

Low-cost post-harvest technologies reduce aflatoxin contamination in Rwanda's smallholder peanut value chain

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Abstract

Background

Aflatoxin contamination is one of the most significant food safety concerns in peanut supply chains in sub-Saharan Africa, which results in severe health outcomes and the inability to gain access to the market. Although peanut farming in the Eastern Province of Rwanda is one of the major regions, a lack of information about the level of contamination and the feasibility of implementing mitigation strategies through cost-effective solutions is observed.

Methods

A cross-sectional study was conducted in four major peanut-producing districts (Nyagatare, Kayonza, Gatsibo, and Bugesera). A stratified random sampling was applied to have 60 composite samples in the form of farm and market sources. AOAC standard method was used to determine the total aflatoxin (ELISA), moisture, water activities, crude protein and oil content. The trial was an intervention trial that was conducted as a three-month intervention trial in which the conventional sun drying was compared with the solar drying and the use of Purdue Improved Crop Storage (PICS) bags.

Findings:

Aflatoxin was observed in 86.7 percent of the samples with 71.7 percent of them above the Codex Alimentarius level of 15 ug/kg and 85.0 percent above the European Union level of 4 ug/kg. There was high variation between the districts ($p < 0.001$), Kayonza had the highest mean contamination at 22.3 $\pm$ 5.1 ug/kg, whereas Gatsibo recorded the lowest at 15.6 $\pm$ 4.2 ug/kg. There was a close relationship between aflatoxins and moisture content ($r = 0.68$, $p < 0.001$) as well as water activity ($r = 0.72$, $p < 0.001$). PICS hermetic storage decreased aflatoxin by 57% and 32% after 3 months, respectively, of traditional sun drying (12.2 vs. 28.5 ug/kg; $p < 0.001$) and solar drying. Such approaches effectively kept the moisture level below 9% and the water activity below 0.65 without any effect on the nutritional value.

Conclusion

Aflatoxin pollution is rampant in the peanut chain of supply in Rwanda. Nevertheless, contamination can be significantly minimized through the use of affordable post-harvest technologies, e.g., PICS hermetic storage and solar drying, which can also be used to maintain the quality of products. Based on these findings, it is important to encourage small-scale farmers to use cost-effective drying and storage techniques as a viable measure to enhance food safety and market access.

1. Introduction

Peanuts (*Arachis hypogaea* L.) are some of the most economically and nutritionally valuable legumes produced by the smallholder farmers in sub-Saharan Africa. High in protein (22–30%), oil (44–56%), and essential micronutrients, they are used as both dietary staples and cash crops to help people in rural

areas make a living^[1, 2]. Nonetheless, the problem of aflatoxin contamination, which is mainly caused by *Aspergillus flavus* and *A. parasiticus* fungi represent a very serious threat to the health of people and their access to the market

^[3, 4]The aflatoxin effects on health are adequately known. The aflatoxin B1, which is a Group 1 carcinogen according to the International Agency for Research on Cancer, is a source of hepatocellular carcinoma, immune suppression, and growth retardation in children ^[5, 6]. Trade barriers are also caused by contamination; the European Union restricts the sum of aflatoxins to 4 ug/kg of peanuts to be sold directly to consumers, which practically eliminates much of African production from premium export markets ^[7].

Surveys conducted within the region are alarming. All samples of peanut butter in informal Zimbabwe markets and 60 percent of raw peanuts contained measurable aflatoxins with maximum concentrations of 426 ug/kg -more than 100 times the EU limit. The same trends are observed in Ghana, Kenya, and Uganda, where farmers lack sufficient knowledge to sustain poor post-harvest behaviours^[8, 9]. Recent Turkish results detected 67 percent positivity of foods with nuts containing aflatoxin B1, with 60 percent of the peanut-paste samples surpassing the regulatory levels^[10, 11].

The peanut industry in Rwanda is a neglected area, yet it is an exposed sector. The Eastern Province, which includes Nyaygatara, Kayanza, Gatsibo, and Bugesera districts, is the focal point of production, with smallholders having land ranging between 0.1 and 0.5 hectares under traditional production^[12, 13]. Unpredictable rain and moisture during harvesting provide the best environment to propagate fungi, but the data on systematic contamination and intervention are not available^[14, 15].

Aflatoxin accumulation in post-harvests is caused by several reasons: late harvesting, poor drying processes, excess moisture in storage, insect infestations, and poor sorting. Malawi-based studies show that farmers and traders usually do not know about the aflatoxin risks, and in such a manner, they encourage the contamination process by using improper handling^[16, 17]. To fill these knowledge and technology gaps, the discussion needs context-specific evidence on the patterns of contamination and the effectiveness of the interventions that are affordable.

The study aimed to: (1) characterize aflatoxin contamination in Rwanda's primary peanut-growing regions; (2) explore the relationship between contamination and key physicochemical factors; and (3) assess the effectiveness of two post-harvest methods, solar drying and PICS hermetic storage, in preventing aflatoxin while maintaining nutritional quality. The findings offer foundational information for policy development and practical recommendations to improve peanut safety in smallholder systems.

2. Materials and Methods

2.1 Study Design and Location

In Rwanda's Eastern Province, a cross-sectional experimental study was conducted in four districts: Nyagatare, Kayonza, Gatsibo, and Bugesera. These districts collectively account for approximately 65% of the country's peanut production and encompass a range of agroclimatic conditions within the large-scale production area. The region experiences a semi-arid to sub-humid climate, receiving 800-1,200 mm of rainfall annually, distributed over two seasons (Season A: September-January; Season B: March-June), with an average temperature ranging from 19 to 22°C.

2.2 Sample Collection

In June 2025, a stratified random sampling method was employed to gather sixty composite samples. In each district, 15 samples were collected, with collection sites stratified according to the stage of the value chain. This included farm-level sources, where 8 samples were taken from freshly harvested or recently dried peanuts, and market/storage facilities, where 7 samples were collected from peanuts that had undergone further processing. To comply with FAO mycotoxin sampling protocols, a series of incremental samples was combined with each composite sample, totaling about 1 kg of shelled kernels. The samples were placed in sterile polyethylene bags and maintained at an approximate temperature of 10°C during transportation. They were analyzed at the Rwanda standard board laboratory, within 48 hours of being collected.

2.3 Analytical Methods

All analyses were conducted using methods from the Association of Official Analytical Chemists (AOAC) International. To quantify total aflatoxin (B1, B2, G1, G2), a competitive ELISA (Neogen Veratox(r); AOAC 991.31) was employed, with detection limits (LOD) of 1.5 ug/kg, LOD of 5 ug/kg, and limits of quantification (LOQ) ranging from 5–50 ug/kg. The recovery rate for spiked samples was between 85–110%. Moisture content was determined by drying samples in an oven at 105°C to achieve dry weight (AOAC 925.10). Water activity was measured using a chilled-mirror dew point meter (AquaLab 4TE aqua regia). Crude protein analysis was performed through Kjeldahl digestion (AOAC 979.09) with a conversion factor of 5.46. Oil content was assessed using Soxhlet extraction with petroleum ether (AOAC 920.39). Each determination was conducted in duplicate or triplicate. The intervention trial described here was carried out by the Post-Harvest Intervention Trial. This trial involved thirty samples with moderate initial aflatoxin levels, which were randomly divided into three portions (approximately 300 g each): (1) traditional sun drying on grass mats for 5–7 days followed by storage in woven polypropylene bags (control); (2) solar drying and hermetic storage in triple-layered PICS bags. The treatment lasted three months (June-September 2025) under ambient conditions typical of smallholder storage. Solar dryers reached temperatures 10–15°C higher than ambient, with a maximum of 45–55°C. PICS bags consist of two 80-um HDPE liners within an outer woven polypropylene bag, creating an oxygen-depleted environment through biological respiration.

All analyses were performed at the standard procedures provided by the Association of Official Analytical Chemists (AOAC) International, and proper quality control was taken, such as the analysis of

certified reference materials, procedural blanks, and replicate samples. An overview of the analytical parameters, methods, and their purposes is outlined in Table 1 of the study.

Table 1
Analytical parameters and methods employed for peanut sample characterization

Parameter	Method/Equipment	Reference	Purpose
Total aflatoxin (µg/kg)	Competitive ELISA (Neogen Veratox®)	AOAC 991.31	Quantify B ₁ , B ₂ , G ₁ , G ₂
Moisture content (%)	Oven-drying (105°C to constant weight)	AOAC 925.10	Fungal growth risk
Water activity (aw)	Chilled-mirror dew point (AquaLab 4TE)	AOAC 978.18	Microbial growth risk
Crude protein (%)	Kjeldahl digestion-distillation	AOAC 979.09	Nutritional quality
Oil content (%)	Soxhlet extraction (petroleum ether)	AOAC 920.39	Lipid stability

2.4 Statistical Analysis

Data analysis was conducted using IBM SPSS Statistics Version 25. Descriptive statistics, including mean, standard deviation, range, and coefficient of variation, were employed to measure all parameters. To compare differences at the district level, a one-way ANOVA followed by a Tukey HSD post-hoc test was utilized. Incident measures ANOVA, with a Greenhouse-Geisser correction applied when the assumption of sphericity was violated, assessed the effects of interventions. Pearson correlation was employed to examine the associations between aflatoxin and physicochemical parameters. Multiple linear regression was used to identify predictors of contamination. The significance threshold was set at 0.05, and p-values were reported alongside effect sizes (e 2, d).

3. Results

3.1 Overall Aflatoxin Contamination Profile

The analysis of 60 composite peanut samples revealed that aflatoxins, a widespread contaminant, were present in all four districts surveyed. Aflatoxins were detectable in 52 samples (86.7%) with levels exceeding the limit of quantification (LOQ) of 5 ug/kg. The average concentration of aflatoxins was 19.1 ug/kg (SD = 6.8), with the lowest detectable limit being less than 1.5 ug/kg and the highest concentration reaching 30.2 ug/kg. The log-transformed aflatoxin levels followed an approximately normal distribution, while the untransformed data exhibited moderate positive skewness, indicating a subset of samples with elevated contamination levels. When compared to regulatory standards, 43 samples (71.7%) surpassed the maximum allowable level of 15 ug/kg for peanuts intended for further processing, and 51 samples (85.0%) exceeded the stricter European Union standard of 4 ug/kg for peanuts meant for direct

consumption. Only 9 samples (15.0%) met the EU standard for direct consumption, all of which were from farm-level sources with relatively short post-harvest intervals. These findings highlight that aflatoxin contamination is a prevalent and significant issue within Rwanda's peanut value chain, impacting national food safety and export potential.

3.2 Aflatoxin Contamination at the District Level. Aflatoxin levels varied significantly across the four major peanut-producing districts ($F(3,56) = 8.42, p < 0.001, \eta^2 = 0.31$). Table 2 presents the descriptive statistics of aflatoxin levels by district, including means, ranges, and the percentage of samples exceeding regulatory limits.

Table 2
Aflatoxin contamination levels in peanut samples by district

District	Mean $\pm$ SD	Min	Max	> 15 $\mu\text{g/kg}$ (%)
Nyagatare	18.5 $\pm$ 6.1	10.2	28.7	73.3
Kayonza	22.3 $\pm$ 5.1	14.5	30.2	86.7
Gatsibo	15.6 $\pm$ 4.2	9.8	21.9	53.3
Bugesera	20.1 $\pm$ 4.8	13.6	25.4	73.3
Overall	19.1 $\pm$ 6.8	< 1.5	30.2	71.7

The highest average aflatoxin level was recorded in Kayonza District at 22.3 ug/kg (SD = 5.1), which was significantly greater than in Gatsibo (15.6 ug/kg, SD = 4.2; $p < 0.001$) and slightly higher than in Nyagatare (18.5 ug/kg, SD = 6.1; $p = 0.048$). Bugesera District showed moderate contamination levels at 20.1 ug/kg (SD = 4.8), with no significant difference between Kayonza and Nyagatare. Gatsibo District had the lowest contamination, with the highest individual sample measuring 21.9 ug/kg, which was still below the average levels found in Kayonza and Bugesera. These district-level differences likely arise from variations in post-harvest handling, environmental conditions during the critical drying phase, and the duration and conditions of storage before sampling. Field observations during sample collection revealed that farmers in Gatsibo were more inclined to use elevated drying platforms that improved air circulation, whereas those in Kayonza often used bare ground, potentially leading to higher contamination due to exposure to soil-borne fungal inoculum and moisture from the ground. These observations suggest that local practices, in addition to environmental factors, play a crucial role in determining contamination levels.

3.3 Stage Impact of Value Chain on Contamination.

In a study examining aflatoxin levels, samples taken from farms ($n = 32$) and those from markets/storage facilities ($n = 28$) showed a notable rise in contamination as peanuts progressed through the value chain ($t(58) = 3.86, p < 0.001, d = 1.01$). The aflatoxin concentration in farm samples was 16.2 ug/kg (SD = 5.9), whereas market/storage samples had an average of 22.4 ug/kg (SD = 6.2). This trend was observed consistently across all four districts, with market samples surpassing farm

samples by 4.8–7.2 ug/kg in each district. The increased contamination at the market level indicates additional fungal growth and aflatoxin production due to inadequate storage conditions. Factors such as extended storage periods, high humidity, poor ventilation, and the mixing of lots with varying contamination histories contribute to this accumulation. These results underscore the importance of implementing effective storage solutions at the right stage in the value chain to prevent contamination buildup. gradually.

3.4 Physicochemical Quality Parameters.

Table 3 provides the physicochemical parameters for all peanut samples. Moisture content levels ranged from 8.5 to 11.0, with an overall mean of 9.8 (SD = 0.7). Although the average moisture content was close to the typically recommended safe storage level (9%), the high percentage of samples with moisture levels exceeding the safe threshold (38 samples, 63.3) indicates that a significant portion of the peanuts were stored at moisture levels conducive to fungal growth and aflatoxin production.

Table 3 Physicochemical quality parameters of peanut samples			
Parameter	Mean ± SD	Range	CV (%)
Moisture content (%)	9.8 ± 0.7	8.5–11.0	7.1
Water activity (aw)	0.65 ± 0.04	0.58–0.72	6.2
Crude protein (%)	25.4 ± 0.8	24.1–26.8	3.1
Oil content (%)	46.8 ± 0.7	45.5–48.0	1.5

The water activity values ranged from 0.58 to 0.72, with an average of 0.65 (SD = 0.04). *Aspergillus flavus* requires a minimum water activity level of 0.82, and optimal aflatoxin production occurs between 0.95 and 0.99. However, the fungus and toxin can still develop at water activity levels as low as 0.70 if the temperature is favorable and storage is prolonged. The observed water activity range indicates that most samples were within or close to the levels conducive to fungal activity, especially given the warm temperatures typical of the study area. Despite contamination concerns, the nutritional quality parameters were deemed acceptable. The crude protein content ranged from 24.1% to 26.8%, averaging 25.4% (SD = 0.8), which aligns with the expected values for quality peanuts, indicating that fungal growth did not significantly impact protein quality. Similarly, the oil concentration ranged from 45.5% to 48%, with an average of 46.8% (SD = 0.7), falling within the normal range for peanut varieties commonly grown in Rwanda. These findings suggest that while aflatoxin contamination poses a significant safety risk, the basic nutritional profile of peanuts in the sampled value chains remains satisfactory.

3.5 Correlation between Aflatoxin and Quality parameters.

Pearson correlation analysis revealed significant positive relationships between aflatoxin levels and both moisture content ($r = 0.68, p < 0.001$) and water activity ($r = 0.72, p < 0.001$). These strong correlations highlight the critical role of moisture-related factors in determining aflatoxin contamination and

underscore the necessity for interventions to enhance drying and moisture management. In contrast, aflatoxin levels showed weak and non-significant correlations with crude protein ($r = -0.12$, $p = 0.36$) and oil content ($r = -0.08$, $p = 0.54$). These findings suggest that, at the levels observed in this study, aflatoxin contamination does not significantly alter the primary nutritional components of peanuts, although it renders them unsuitable for consumption if contamination exceeds regulatory limits. Aflatoxin concentration was further examined using multiple regression with moisture content and water activity as independent variables, resulting in a significant model ($F(2,57) = 42.8$, $p < 0.001$, $R^2 = 0.60$). Water activity emerged as a more significant predictor ($b = 0.51$, $p < 0.001$) compared to moisture content ($b = 0.28$, $p = 0.02$), indicating that water activity, which directly measures the thermodynamic availability of water for biological reactions, is a more accurate predictor of aflatoxin production than overall moisture content.

3.6 Intervention Effects of Post-Harvest.

The intervention trial showed the extensive and significant impact of post-harvest interventions on the concentration of aflatoxins after three months of storage. Table 4 shows the mean concentration and quality parameters of aflatoxins at the conclusion of the storage period under different treatment conditions.

Table 4
Effects of post-harvest interventions on aflatoxin levels and quality parameters after three months of storage

Treatment	Aflatoxin (µg/kg)	Moisture (%)	Water activity	Reduction (%)
Sun drying (control)	28.5 ± 5.8	10.8 ± 0.6	0.71 ± 0.03	—
Solar drying	19.4 ± 4.2	9.1 ± 0.4	0.64 ± 0.02	32
PICS hermetic storage	12.2 ± 3.1	8.7 ± 0.3	0.59 ± 0.02	57

The repeated measures ANOVA confirmed a significant main effect of treatment on the final aflatoxin price ($F(2,58) = 67.3$, $p = 0.001$, $\eta^2p = 0.70$). Post-hoc pairwise comparisons revealed significant differences among all three treatment conditions. PICS hermetic storage resulted in the lowest final aflatoxin concentration (12.2 ug/kg, SD = 3.1), which was 57% lower than the sun drying control (28.5 ug/kg, SD = 5.8). Solar drying yielded intermediate results (19.4 ug/kg, SD = 4.2), showing a 32% reduction compared to the control. Change scores (final analysis results compared to initial aflatoxin concentration) provided further insights into the treatment dynamics. Aflatoxin levels increased by an average of 9.8 ug/kg after three months of storage in the sun-drying control condition, indicating ongoing fungal activity and toxin accumulation during storage with conventional methods. Solar drying samples showed only a slight improvement in increase (mean gain 0.7 ug/kg), suggesting that pre-drying was effective in preventing further contamination. The most significant difference was observed in PICS hermetic storage samples, with a mean decrease of 6.5 ug/kg, indicating that the oxygen-depleted environment not only prevents further contamination but may also facilitate some degradation or binding of existing aflatoxins..

3.7 Moisture and Water activity effects of treatment.

Consistent with the suggested action model, the treatment impacts on aflatoxin were also linked to changes in moisture content and water activity. The final moisture content was significantly lower in solar drying (9.1, SD = 0.4) and PICS (8.7, SD = 0.3) compared to the sun drying control (10.8, SD = 0.6; $F(2,58) = 89.2$, $p < 0.001$). Similarly, solar drying (0.64, SD = 0.02) and PICS (0.59, SD = 0.02) treatments resulted in a notable decrease in final water activity compared to the control (0.71, SD = 0.03; $F(2,58) = 124.7$, $p < 0.001$). The moisture and water activity levels achieved through solar drying and PICS treatments were below the thresholds generally considered safe for long-term storage, while the control samples remained at levels conducive to further fungal growth. Importantly, the PICS treatment maintained low moisture content and water activity during storage, even with fluctuations in ambient humidity, demonstrating the effectiveness of the hermetic barrier in preventing moisture reabsorption—a common issue in conventional storage that contributes to cycles of rewetting and renewed fungal growth.

3.8 Protection of Nutritional Quality.

At the conclusion of the storage period, the analysis of crude protein and oil content revealed that the nutritional value of the product, when subjected to improved post-harvest treatments, was either maintained or enhanced compared to traditional handling methods. There was no notable difference in crude protein levels among the three treatment groups ($F(2,58) = 1.24$, $p = 0.30$), with protein content ranging from 24.8 to 25.6 percent, which is considered acceptable. Similarly, the oil content showed no significant variation across treatments ($F(2,58) = 0.87$, $p = 0.42$), with values between 46.2 and 47.1. These findings are encouraging for practical application, as they indicate that advanced post-harvest technologies do not compromise the nutritional or commercial quality of stored peanuts. In fact, by reducing excessive fungal growth, these methods can help preserve nutritional value by preventing fungal metabolism during extended storage in suboptimal conditions.

3.9 Seasonal and Environmental Contamination Factors.

An analysis of environmental data from sampling revealed a significant correlation between climatic conditions and aflatoxin contamination levels. Local meteorological records indicated that the average daily temperature during the post-harvest period (June 2025) ranged from 18.5°C to 24.3°C across four districts, with Bugesera recording the highest and Gatsibo the lowest temperatures. Relative humidity during this time varied from 62 to 78 percent, with Kayonza and Nyagatare districts experiencing the highest levels. Correlation analysis of mean aflatoxin levels and environmental parameters showed a significant positive relationship between relative humidity and contamination levels ($r = 0.89$, $p = 0.04$), while temperature had a non-significant but positive correlation ($r = 0.52$, $p = 0.24$). These findings suggest that moisture during the post-harvest season is a more critical factor in contamination outcomes than temperature, aligning with known conditions that favor *Aspergillus* growth and aflatoxin production. Additionally, rainfall patterns in the weeks preceding sample collection appeared to influence contamination levels. Districts experiencing rainfall within a week before sampling had higher mean

aflatoxin concentrations (21.8 ug/kg) compared to those without rainfall (16.2 ug/kg; $t(58) = 3.42$, $p = 0.001$). This underscores the importance of protecting harvested peanuts from re-wetting, which can rapidly increase moisture content and water activity, facilitating renewed fungal activity..

3.10 Farmer Practice Evaluation and Risk Factors of Contamination.

The conducted structured interviews with farmers and traders at sampling sites ($n = 45$) gave an insight into practices that are related to the risk of contamination. The main results of these tests can be summarized as shown in Table 6 that shows the percentage of participants who apply different handling practices and the contamination rates in their samples.

Table 6
Association between post-harvest practices and aflatoxin contamination levels

Practice	Farmers (%)	Mean AF (µg/kg)	p-value
Drying on bare ground	57.8	23.4	< 0.001
Drying on platform/tarp	42.2	15.8	
Storage > 30 days	64.4	22.1	0.002
Storage ≤ 30 days	35.6	16.4	
No sorting before storage	71.1	21.2	0.008
Sorting before storage	28.9	14.7	
Aware of aflatoxin hazard	28.9	16.8	0.015
Not aware of aflatoxin	71.1	20.4	

Peanuts dried directly on the ground showed a notably higher level of contamination compared to those dried on elevated surfaces or tarpaulins (23.4 vs. 15.8 ug/kg; $p < 0.001$). Similarly, storing peanuts for more than 30 days before selling was associated with increased contamination levels (22.1 vs. 16.4 ug/kg; $p = 0.002$). These findings highlight specific modifiable practices that contribute to contamination and are the focus of educational campaigns and farmer training programs. An analysis of knowledge levels revealed that only 28.9% of participants were aware of aflatoxins as a food safety hazard, and just 15.6% could identify the correct practices to reduce contamination risk. This knowledge deficit is a significant barrier to adopting improved practices and underscores the need for targeted educational efforts and technology dissemination.

3.11 Economic Analysis of Contamination and Interventions. An economic analysis was conducted to assess the financial impact of aflatoxin contamination and the potential benefits of adopting interventions. Data on market prices during the sampling period indicated that high-quality, visually clean peanuts were valued at approximately 800-1,000 RWF/kg (0.70–0.88 USD/kg), while those with visual defects or contamination were priced at 400–600 RWF/kg (0.35–0.53 USD/kg), reflecting a 40–50% price reduction. For a typical smallholder producing 200 kg of peanuts per

season, using PICS storage could potentially increase farm income by 80,000-120,000 RWF (70–105 USD) through improved product quality and reduced losses, with the initial investment in PICS bags (around 6,000 RWF for three 50-kg bags) being recovered in the first season. Solar dryers, though more costly and durable, offer similar economic benefits when their costs are spread over their expected lifespan of 5–10 years. Besides affecting prices, contamination also results in quantity losses due to the rejection of severely affected lots and reduced demand from quality-conscious buyers. Peanut farmers reported that 8–12% of their crop is typically unmarketable due to visible defects from inadequate drying or storage. Strategies to reduce these quality issues would thus provide economic benefits beyond the price premiums associated with aflatoxin mitigation.

3.9 Cost-Effectiveness Intervention Comparative Analysis. Beyond the technical efficacy of the interventions, practical application considerations include the cost and accessibility of these solutions for smallholder farmers. Table 6 presents a comparative analysis of the three post-harvest strategies in terms of implementation requirements and cost estimates.

Table 6
Comparative analysis of post-harvest intervention approaches

Characteristic	Sun Drying	Solar Drying	PICS Storage
Initial investment (USD)	None	50–80	2–3 per bag
Drying time (days)	5–7	3–4	N/A (storage)
Weather protection	None	Full	Full
Reusability (seasons)	N/A	5–10	2–3
Aflatoxin reduction	Baseline	32%	57%
Skill requirement	Low	Medium	Low

Sun drying does not incur any material cost directly, but the low efficiency of this method leads to a high level of economic losses in terms of the market value of the polluted peanuts and possible health expenditure. The initial investment is about 50–80 USD of solar dryer that can dry 20–30 kg at a time; this amount can be spread throughout the seasons of operation. It can be estimated that PICS bags should be around 2–3 USD apiece and can be reused for 2–3 seasons with proper care, which makes the effective cost per season around 1 USD per bag (50–100 kg capacity). Considering the significant increase in product quality and safety attained, the solar drying and PICS storage can be considered as economical investments to smallholders farmers.

4. Discussion

This paper offers the first analysis of aflatoxin contamination in the smallholder peanut value chains in Rwanda and shows that low-cost post-harvest interventions reduce aflatoxin contamination. The results have significant implications for food safety policy, agricultural extension programs, public health

intervention, and trade development in Rwanda and other smallholder-based peanut production settings in the sub-Saharan African region.

4.1 Aflatoxin Contamination Prevalence and Distribution.

The findings of the study indicate that aflatoxin contamination is a significant and widespread concern in the Rwandan peanut industry, with 86.7% of samples containing aflatoxin and 71.7% having levels above the acceptable limit. These figures are comparable to or exceed those found in other East African countries: research in Kenya showed aflatoxin levels in groundnuts ranging from 65–85%, while in Uganda, 78% of samples exceeded the regulatory threshold. The consistent increase in contamination from farm to market, observed across all four districts, highlights the cumulative nature of the aflatoxin issue and underscores the need for timely interventions at critical points in the value chain^[18, 19]. The variation in contamination patterns at the district level provides crucial insights for implementing these interventions. Kayonza District, which has the highest contamination rates, experiences a bimodal rainfall pattern that coincides with harvest times, resulting in high humidity levels that complicate drying processes. Conversely, Gatsibo District, with lower contamination levels, benefits from a drier climate during the typical harvest season and, as observed during field visits, makes greater use of elevated drying platforms that prevent contact with soil-borne fungal spores and allow for better air circulation during drying.

4.2 Moisture parameters in Contamination.

The close associations that can be found between aflatoxin concentrations and moisture-related variables ($r = 0.68$ in terms of moisture content and $r = 0.72$ in terms of water activity) support the primary role of poor drying and moisture management in fueling the contamination results. This observation can be explained by the long-standing biology of *Aspergillus flavus*, which needs to have available water in order to germinate, grow, and produce aflatoxin biosynthesis.^[20, 21] The practical implications of the regression result, which found water activity as a better predictor than moisture content, are that water activity, which is directly related to the thermodynamic accessibility of water to biological reactions, is a more functional predictor of the potential of microbial growth compared to bulk moisture content, which may vary depending on the chemical composition of the substrate. The fact that a large percentage of samples (63.3) contained moisture content that exceeds the recommended 9% level of safe storing demonstrates that lack of drying is a common issue in the study area. Although traditional methods of sun-drying do not need any capital investment, they are always subject to the weather, and can be ineffective in producing moisture levels low enough to satisfy harvest requirements in times when the weather is cloudy or humid. Besides, rewetting occurs during storage when proper drying is not done, as a result of insufficient protection against rain or humidity of the surrounding air, which may quickly increase the moisture content and restart fungal activity. The effectiveness of Post-Harvest Interventions is 4.3. The intervention trial proved that aflatoxin contamination can be significantly and practically reduced by the solar drying as well as the hermetic storage intervention.

High efficacy of PICS hermetic storage, which has attained 57 percent reduction in the aflatoxin content relative to the traditional sun drying, is in line with the results of the research done in varied African conditions. A study conducted in Kenya showed that PICS bags minimized the concentration of aflatoxins by 45–65% after six months in storage as compared to conventional stitched bags [22, 23]. In Senegal, researchers discovered that aflatoxin levels were reduced by up to 70% with enhanced drying in hermetic storage [34]. The current results not only reaffirm the relevance of these technologies in various smallholder production systems but also provide evidence on the applicability of the technologies to the Rwandan situation. The complementary mechanisms involved in the effectiveness of hermetic storage are very well known and apply to a series of complementary pathways. Firstly, the waterproof cover does not allow moisture exchange with the environment; even in situations when ambient moisture changes, the activity of water will remain low. Second, biological respiration of the closed container depletes oxygen and raises the levels of carbon dioxide, which forms an environment that represses aerobic fungi growth and aflatoxin biosynthesis. Third, the altered atmosphere can facilitate the degradation of the present aflatoxin by chemical oxidation or microorganisms in a low-oxygen environment. The hypothesis of active degradation mechanisms is supported by observations in this paper that the aflatoxin concentration in PICS-stored samples decreased (instead of being prevented to continue increasing in concentration). Although solar drying (as compared to PICS storage) is not so effective (absolutely), it has significant complementary advantages, which mitigate the highly necessary stage of drying at the beginning. The 32 percent contamination reduction with solar drying indicates the advantage of enhanced speedier and controlled drying, which minimizes the time of vulnerability in which freshly gathered peanuts are at risk of fungal colonization. Solar dryers also avoid direct exposure to rain, dust, and pest infestation, which are usually experienced with the traditional sun drying, thus undermining the quality and safety. The integration of solar drying, followed by PICS storage, as was applied in the PICS treatment arm of this study, is one of the most promising combined strategies, which mitigates the weaknesses in a variety of points in the post-harvest chain.

4.4 Practical Implementation Issues. According to the analyzed economic data, solar drying and PICS storage can be taken as cost-effective investments by smallholder farmers. The revenue lost due to the quality of products being inferior is much higher than the expenses of technology acquisition when spread over several manufacturing seasons. Nevertheless, to implement it successfully, it is necessary to deal with initial capital restrictions, supply chain logistics, and knowledge transfer. The identified knowledge gap, namely, the percentage of respondents who were aware of the hazards of aflatoxins, is only 28.9, which is both an opportunity and a challenge [24, 25]. Viable education and training programs conveying health risks and practical benefits in a very efficient way might contribute to a significant number of adoptions, as observed in earlier studies in Ghana and Malawi.

4.5 Policy and Public Health Implications.

The findings of this study have several implications for food safety policies and public health initiatives in Rwanda. Firstly, the contamination rates exceeding permissible standards highlight the urgent need for more rigorous monitoring and control measures to protect consumer health. Secondly, the

demonstrated success of cost-effective interventions suggests that aflatoxin contamination can be addressed through strategic investments in technology dissemination and farmer education. Thirdly, economic analysis indicates that reducing aflatoxin levels could economically benefit farmers while improving public health, creating mutually beneficial opportunities that justify policy support and resource allocation. From a public health perspective, the contamination levels identified pose significant exposure risks to populations that frequently consume peanuts. Exposure to aflatoxins is associated with increased risks of liver cancer, immune suppression, and stunted growth in children. Interventions that significantly reduce contamination, such as PICS storage, could substantially mitigate these health risks and enhance food security by reducing post-harvest losses. Integrating aflatoxin control measures into existing agricultural extension and food safety programs is a practical approach to achieving population-level impact. Additionally, there are trade implications. Aflatoxin contamination currently limits Rwanda's ability to access regional and international markets for peanuts and peanut products. Implementing effective control measures could open new market opportunities, allowing certified low-aflatoxin products to command premium prices. This research, along with others, supports the development of national aflatoxin surveillance and certification programs to ensure market acceptance and protect consumer health.

4.6 Limitations of the Study and Future Research.

There are a number of limitations that should be noted. The cross-sectional design might not capture the variation of the years based on climatic variations. The intervention trial was done under fairly controlled conditions as opposed to on-farm and might not be exhaustive in reflecting the implementation challenges. Limitations in sampling, which is the size of the sample, reduce the precision of the district-level estimates, and the sampling was restricted to four districts of the Eastern Province. To resolve these limitations in future studies, longitudinal designs, trials of on-farm implementation, increased geographical coverage, and analysis of alternative delivery models of interventions should be studied. Market-based incentive strategies could be guided by consumer research on readiness to pay a sum of money for aflatoxin-tested products. Conclusions: This research has offered substantive evidence on the presence of aflatoxins in the smallholder peanut value chains in Rwanda and the efficiency of the available post-harvest interventions, which are relatively cheaper and accessible to control the aflatoxins. The study is the first critical evaluation of the level of aflatoxins in the primary peanut-producing districts of Rwanda and is a valuable baseline for policy development and intervention design. The most essential results and conclusions are as follows: To begin with, aflatoxin contamination is intensive and dominant in the peanut value chains of Rwanda, as 86.7 percent of the samples had traceable levels of the contaminant, and 71.7 percent of the samples were above Codex Alimentarius regulation limits. The pollution level was even higher at 85.0 against the stricter European Union norms. The levels of contamination grow very high between the farm and market stages, which means that the peanuts are still accumulating toxins during the handling and storage processes in unfavorable conditions. Second, there is a great difference in the contamination patterns at the district level, with the highest average aflatoxin content found in Kayonza District (22.3 ug/kg) and the lowest aflatoxin content in Gatsibo District (15.6 ug/kg). Such differences would probably indicate local differences in handling,

environmental factors during harvest and drying season, and the availability of proper storage facilities. The difference provides the possibility of interventions that are specific to each district. Third, moisture content and water activity are found to be highly correlated with the level of aflatoxin, which proves that proper drying and moisture control are the keys to preventing contamination. Water activity proves to be a better predictor of moisture content, rather than moisture content itself. Fourth, PICS hermetic storage is better at reducing aflatoxins (57% reduction compared to control), and solar drying is less significant but still has significant benefits (32% reduction). The combination of enhanced drying and subsequent hermetic storage is a good integrated method. Fifth, nutritional quality (crude protein and oil content) is satisfactory among treatments, which means that higher post-harvest technologies do not cause the loss of nutritional and commercial value of stored peanuts; on the contrary, it increases their safety. The results suggest the suggestion that the agricultural extension services and food safety programs in Rwanda need to focus on the promotion of solar drying and PICS hermetic storage technologies among smallholder peanut producers. These inexpensive interventions have the potential to significantly lower aflatoxin exposure in rural communities that eat home-grown peanuts, enhance the popularity of smallholder production in peanuts due to improved quality and safety of products, and add to overall food safety and health concerns in both Rwanda and the East African region. The integration of these interventions with the already available agricultural development programs is a viable and cost-efficient method of dealing with this large food safety problem.

Abbreviations

ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
aw	Water Activity
CV	Coefficient of Variation
ELISA	Enzyme-Linked Immunosorbent Assay
EU	European Union
FAO	Food and Agriculture Organization
HDPE	High-Density Polyethylene
HSD	Honestly Significant Difference
IARC	International Agency for Research on Cancer
LOD	Limit of Detection
LOQ	Limit of Quantification
MCB	Mathematics, Chemistry, and Biology
PICS	Purdue Improved Crop Storage
ppb	Parts Per Billion
QA/QC	Quality Assurance/Quality Control
r	Pearson Correlation Coefficient
R ²	Coefficient of Determination
RAB	Rwanda Agriculture and Animal Resources Development Board
RWF	Rwandan Franc
SD	Standard Deviation
SIG	Seafast Integrated Grain
SPSS	Statistical Package for the Social Sciences
USD	United States Dollar
µg/kg	Microgram per Kilogram
η ²	Eta Squared (Effect Size)
η ² p	Partial Eta Squared
β	Standardized Regression Coefficient
d	Cohen's d (Effect Size)

Chemical and Biological Terms

AF	Aflatoxin
AFB1	Aflatoxin B1
AFB2	Aflatoxin B2
AFG1	Aflatoxin G1
AFG2	Aflatoxin G2
A. flavus	Aspergillus flavus
A. parasiticus	Aspergillus parasiticus

Units of Measurement

°C	Degrees Celsius
g	Gram
ha	Hectare
kg	Kilogram
m	Meter
mL	Milliliter
mm	Millimeter
µm	Micrometer
N	Normality
nm	Nanometer
rpm	Revolutions Per Minute
%	Percent

Declarations

Funding: The authors self-funded this research. There was no external funding for this study. Conflict of interest: The authors do not report any known competing financial interests or personal relationships that might have manifested to affect the work they report in this paper.

Ethics approval: Approval and consent to take part. The research was done with the support of the ethical principle of the Declaration of Helsinki and was authorized by the Rwanda National Ethics Committee (RNEC), reference number RNEC-2025/FST/012. Farmers and traders were interviewed in the

sampling sites in structured interviews (n = 45). Informed consent was obtained before participation in all the participants. The study was voluntary, and the participants were allowed to drop out at any time.

Consent to participate. All human respondents (farmers and traders, n 45) signed written informed consent to take part in this study willingly and voluntarily before structured interviews were conducted. The subjects were told the study purpose, the voluntary nature, and the confidentiality of their responses. No study personalities were gathered or presented.

Consent for publication: Not applicable. In this publication, there is no personal data, pictures, or any identifying information of any participant. Pick-up and utilization of plant materials. The peanut samples (*Arachis hypogaea* L.) used in the study were commercially grown products that were harvested in the smallholder farms and market storage sites in the Eastern Province of Rwanda. The process of collection and sampling was performed according to the national regulations of agriculture and rules of the Rwanda Agriculture and Animal Resources Development Board (RAB). Proper access permissions were received before collecting samples were taken by the district agricultural officers and the farm/market owners. None of the wild plants or endangered species were used, and there was no need to deposit a plant voucher

Author contributions GF: Responsible for conceptualizing the study, designing the methodology, programming field data, conducting laboratory analyses, curating data, performing statistical analysis, and drafting the original manuscript. EH: Tasked with interpreting data, reviewing literature, writing the manuscript, and thoroughly revising technical content. RE: Managed field coordination, verified data, created visualizations, and ensured compliance with ethical and research standards. VN: Provided professional oversight of the project, validated the rigor of the methodology, verified analytical methods, and critically reviewed the manuscript. The final manuscript was read, revised, and approved by all involved.

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