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RESEARCH PAPER

Effect of modified atmosphere packaging on quality deterioration and shelf life of dried cashew kernels under tropical ambient storage

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Key Message: Vacuum-assisted modified atmosphere packaging using N_2/CO_2 gas mixtures effectively prevented insect infestation, web formation, and kernel damage while maintaining sensory acceptability and extending the shelf life of dried cashew kernels to at least four months under tropical ambient storage conditions.

Abstract

Dried cashew kernels are highly susceptible to moisture uptake, fungal contamination, insect infestation, and rapid quality deterioration during storage, especially under tropical ambient conditions. This study evaluated the effect of vacuum-assisted modified atmosphere packaging (MAP) on the quality attributes and shelf life of dried cashew kernels stored for four months under ambient tropical conditions. Cashew kernels obtained from Mim Cashew and Agricultural Products Ltd., Ghana, were repackaged into 3 kg units at an initial moisture content of 4% and subjected to five packaging treatments: 60% N_2 + 40% CO_2, 40% N_2 + 60% CO_2, 50% N_2 + 50% CO_2, vacuum packaging without gas flushing, and non-vacuum packaging without gas flushing. The experiment was arranged in a completely randomized design with three replications. Physical quality, proximate composition, fungal occurrence, sensory acceptability, and shelf life were evaluated monthly. Packaging treatment significantly affected insect incidence, web formation, kernel damage, sensory acceptability, fungal occurrence, and shelf life. All three gas-flushed MAP treatments recorded zero insects, zero web formation, and zero kernel damage after four months of storage, whereas the non-vacuum control recorded the highest insect count, web presence, and kernel damage. Insect number was strongly and positively correlated with kernel damage ($r = 0.9338$). Shelf life was shortest in the non-vacuum control (1 month) and vacuum-only packaging (3 months), whereas kernels packaged under N_2/CO_2 gas mixtures remained acceptable for at least four months. These findings demonstrate that vacuum-assisted MAP using nitrogen and carbon dioxide can effectively preserve dried cashew kernel quality and extend storage life under tropical ambient conditions. © 2026 The Author(s)

Keywords: Carbon dioxide, Cashew kernel, Modified atmosphere packaging, Shelf life, Tropical storage, Vacuum packaging

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Introduction

Cashew (*Anacardium occidentale* L.) is an economically important tropical crop valued for its kernels, shell liquid, and apple-derived products. In West Africa, and particularly in Ghana, cashew has become a strategic cash crop for income generation, export diversification, and agro-industrial development (Wittern et al., 2023; Otálora et al., 2024). Despite increasing production, local value addition remains constrained by postharvest losses, limited processing efficiency, and inadequate storage systems for preserving kernel quality during marketing and export (Kaur et al., 2021). Cashew kernels are high-value products that must retain desirable colour, flavour, texture, and microbiological safety throughout storage. Their high lipid content, hygroscopicity, and sensitivity to oxygen and ambient humidity make them particularly vulnerable to rancidity, mould growth, insect infestation, flavour deterioration, and commercial downgrading under tropical conditions (Tufail et al., 2019; Donkor et al., 2023; Matusse et al., 2025). Tree nuts generally exhibit reduced storage stability when temperature, oxygen exposure, and relative humidity are poorly controlled (Gama et al., 2018).

Packaging is therefore a critical component of postharvest management. Appropriate packaging reduces exchange of gases and moisture between the product and the surrounding environment and helps preserve nutritional, physical, and sensory quality during storage (Yewle et al., 2022; Gidado et al., 2026). In commercial cashew processing, kernels intended for export are frequently packed under vacuum or flushed with nitrogen, yet storage losses still occur where the package atmosphere is poorly optimized or hygiene prior to sealing is inadequate (Ziegler et al., 2021). Modified atmosphere packaging (MAP) is a widely used preservation strategy in which the gaseous environment surrounding a food product is deliberately altered to delay deterioration and extend shelf life. Carbon dioxide suppresses many aerobic microorganisms and storage pests, while nitrogen functions as an inert filler gas that displaces oxygen and

helps maintain pack integrity (Kaur et al., 2021; Makinya et al., 2021). MAP has improved storage stability in several food systems, and recent work on hazelnut kernels showed that nitrogen-based MAP delayed oxidation and enhanced storability relative to alternative preservation treatments (Worku et al., 2022; Bai et al., 2024). These principles are directly relevant to dried cashew kernels stored under tropical ambient conditions, where heat and humidity accelerate quality deterioration.

Although processors in Ghana use gas flushing in commercial practice, published evidence on the most suitable N_2/CO_2 combinations for dried cashew kernels stored under tropical ambient conditions remains limited. This gap is important because storage failure directly affects processor returns, kernel grade retention, consumer acceptability, and export readiness, particularly for processors operating without cold-chain systems. The present study therefore evaluated the effect of vacuum-assisted modified atmosphere packaging on the physical quality, proximate composition, fungal occurrence, sensory attributes, and shelf life of dried cashew kernels stored for four months under tropical ambient conditions. It was hypothesized that gas-flushed vacuum packaging with N_2/CO_2 mixtures would outperform vacuum-only and non-vacuum packaging in maintaining kernel quality during storage.

Materials and Methods

Study site and sample source

The study was conducted at Mim Cashew and Agricultural Products Ltd., Mim, Brong-Ahafo Region, Ghana, and in the laboratories of the Department of Horticulture and the Department of Crop Science, Faculty of Agriculture, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana. Dried cashew kernels were obtained from Mim Cashew and Agricultural Products Ltd., while nitrogen and carbon dioxide gases (purity ≥ 99.5%) were sourced from Takoradi Gas Ltd., Ghana.

Experimental materials and treatments

The total of 60 kg of dried cashew kernels comprised 45 kg allocated to the 15 experimental packages (five treatments × three replicates × 3 kg per package), while the remaining 15 kg was reserved for initial quality analyses and other experimental requirements. Monthly sampling was conducted according to the established sampling procedure, and the handling of packages during sampling was considered when interpreting changes in packaging atmosphere and product quality. Storage was conducted under ambient tropical conditions with mean temperature ranging from 28–32 °C and relative humidity ranging from 65–85%. Packaging was performed using a vertical vacuum packaging machine equipped with separate gas-charging valves for nitrogen and carbon dioxide. Food-grade gases were used, with nitrogen (N_2) purity ≥ 99.9% and carbon dioxide (CO_2) purity ≥ 99.5%. Air was evacuated from each package and replaced with the desired gas mixture before heat sealing. Gas proportions are reported on a volumetric basis. The cashew kernels were packaged in laminated PA/PE vacuum bags of approximately 80–100 µm thickness and then placed in corrugated fiberboard cartons for storage. The five treatments were: T1 = 40% N_2 + 60% CO_2, T2 = 60% N_2 + 40% CO_2, T3 = 50% N_2 + 50% CO_2, T4 = Vacuum packaging without gas flushing, and T5 = Non-vacuum packaging without gas flushing (Fig. 1). Packages were stored for four months and assessed monthly for physical quality, proximate composition, fungal occurrence, sensory attributes, and shelf life. Cashew kernels were packaged using the vertical vacuum packaging machine under the specified gas-flushed and non-gas conditions, and representative packaged samples were subsequently arranged in storage boxes for ambient storage evaluation (Fig. 2).

Experimental design

The experiment was arranged in a completely randomized design (CRD) with five packaging treatments and three replications, resulting in fifteen experimental packages in total. Storage was conducted under ambient tropical conditions with mean temperature ranging from 28–32 °C and relative humidity ranging from 65–85%. Samples were assessed monthly over the four-month storage period using destructive sampling. At each monthly interval, sealed packages were randomly selected and opened once for analysis; packages were not re-sealed after opening.

Physical quality assessment

Physical quality was assessed monthly by counting insects present in each package and recording web presence as the number of nuts showing visible webbing. Percentage kernel damage was calculated as the number of damaged kernels divided by the total number of kernels assessed, multiplied by 100 (Shahbazi & Shahbazi, 2022):

$$\text{Percentage kernel damage (\%)} = \frac{\text{Number of damaged kernels}}{\text{Total number of kernels assessed}} \times 100$$

Proximate analysis

A representative composite sample of cashew kernels was milled, and subsamples of 0.5–5 g were used for proximate analyses (moisture, ash, crude fat, crude protein, and crude fibre) following Beshaw et al. (2022). Moisture was determined by oven drying to constant weight at 105 °C. Crude protein was measured by the micro-Kjeldahl method using a nitrogen-to-protein conversion factor of 6.25. Ash was determined by dry ashing in a muffle furnace at 550 °C for 6 h. Crude fibre was determined by sequential acid and alkali digestion, crude fat by Soxhlet extraction with petroleum ether, and carbohydrate was calculated by difference as nitrogen-free extract: 100 − (moisture + crude protein + crude fat + crude fibre + ash). Each determination was performed in triplicate.

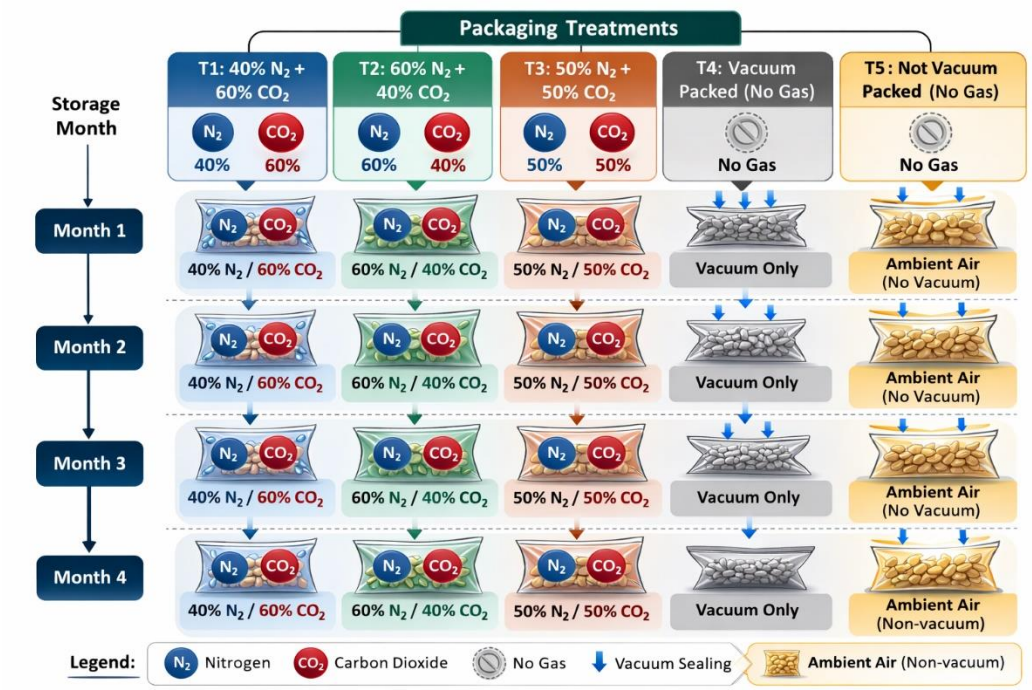


Fig. 1 Study workflow and treatment arrangement for dried cashew kernels packaged under five modified atmosphere and control treatments

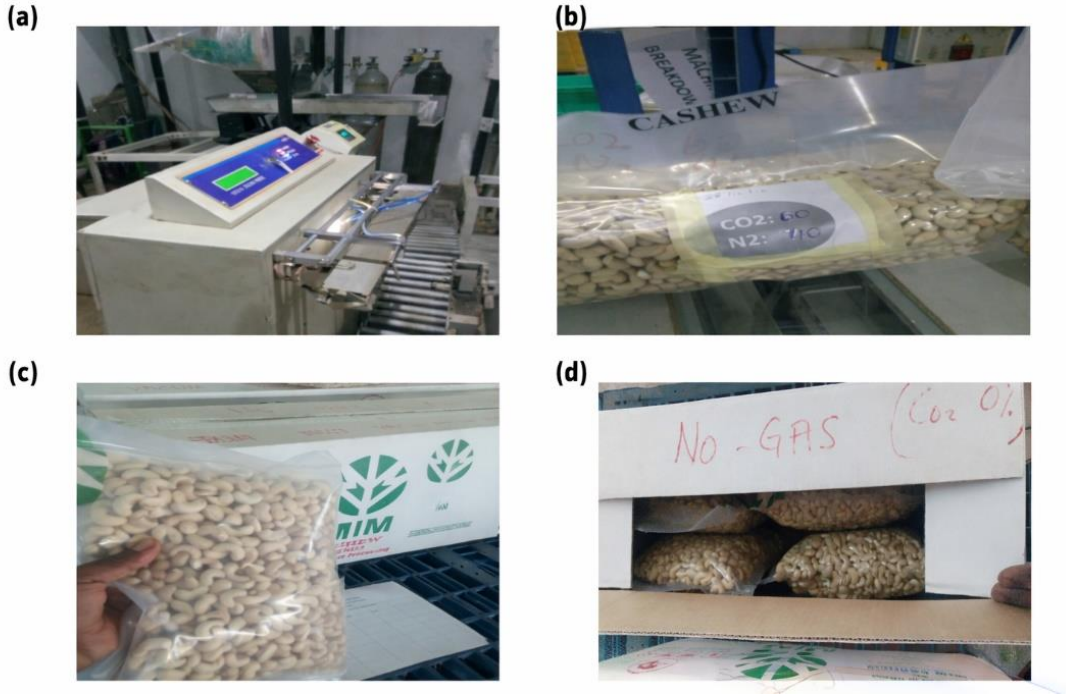


Fig. 2 Experimental packaging and storage setup for dried cashew kernels (a) Vertical vacuum packaging machine used for sealing cashew kernels (b) representative gas-flushed package containing nitrogen and carbon dioxide (c) representative vacuum-packaged sample without gas flushing (d) packaged cashew kernel samples arranged in storage boxes under ambient conditions

Fungal occurrence assessment

For fungal analysis, 10 g of sample was aseptically weighed and homogenized in 90 mL of sterile diluent, followed by serial dilution and plating on Potato Dextrose Agar (PDA). Plates were incubated at 28 °C for 5–7 days, and fungal colonies were identified morphologically and microscopically. Fungal occurrence was reported as percentage isolation frequency according to Beshaw et al. (2022). The study assessed fungal occurrence only and did not quantify mycotoxins. Results are expressed as percentage isolation frequency (% occurrence) of each fungal genus or species per treatment. The fungal taxa identified were *Aspergillus flavus*, *Aspergillus niger*, *Aspergillus ochraceus*, and Penicillium spp.

Sensory evaluation

A panel of 30 semi-trained members comprising staff and students of the Department of Horticulture, Faculty of Agriculture, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana was selected based on familiarity with cashew consumption and availability. Panelists were oriented to the sensory attributes (colour, aroma, taste, texture, and overall acceptability) and to the use of a 9-point hedonic scale, where 1 = dislike extremely and 9 = like extremely. Samples were randomized, coded with three-digit numbers, and presented monadically. Panelists were briefed on the scoring procedure before each session, provided with water for palate cleansing between samples, and scores of 5 or above were considered acceptable. Participation was voluntary, informed consent was obtained, and responses were treated confidentially.

Shelf-life determination

Shelf life was defined as the number of months a sample remained acceptable based on combined assessment of mould growth, web formation, insect infestation, and sensory panel judgement. A sample was classified as unacceptable once it failed any one of these criteria.

Statistical analysis

All data were subjected to one-way analysis of variance (ANOVA) using Statistix 9.1. Where significant treatment effects were detected, means were separated using Tukey's honestly significant difference (HSD) test at $p \leq 0.01$. Data were checked for normality and homogeneity of variance prior to ANOVA. Pearson correlation coefficients were calculated between insect number and kernel damage. Microsoft Excel was used for supplementary plotting.

Results

Effect of packaging on physical deterioration

Packaging method significantly affected insect number, web formation, and kernel damage ($p \leq 0.01$). All three gas-flushed MAP treatments recorded zero insects, zero web formation, and zero kernel damage after four months of storage. In contrast, the non-vacuum control recorded the highest mean insect count (2.33), web presence (4.67), and kernel damage (4.67%), while vacuum packaging without gas flushing showed intermediate deterioration (Table 1). Insect number was strongly and positively correlated with kernel damage ($r = 0.9338$), indicating that insect infestation was a primary driver of physical quality deterioration (Fig. 3). Representative evidence of physical deterioration in the non-vacuum treatment is presented in Fig. 4.

Table 1 Physical deterioration indicators of dried cashew kernels after four months of storage under different packaging treatments

Packaging treatment	Number of insects	Web presence	Kernel damage (%)
60% N_2 + 40% CO_2	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c
40% N_2 + 60% CO_2	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c
50% N_2 + 50% CO_2	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c
Vacuum packaged (no gas flush)	1.00 ± 0.39b	1.33 ± 0.40b	1.67 ± 0.48b
Non-vacuum packaged (no gas flush)	2.33 ± 0.90a	4.67 ± 1.42a	4.67 ± 1.35a

Means are presented as mean ± SD, and values followed by different letters within a column indicate significant differences at $p \leq 0.01$ (Tukey's HSD)

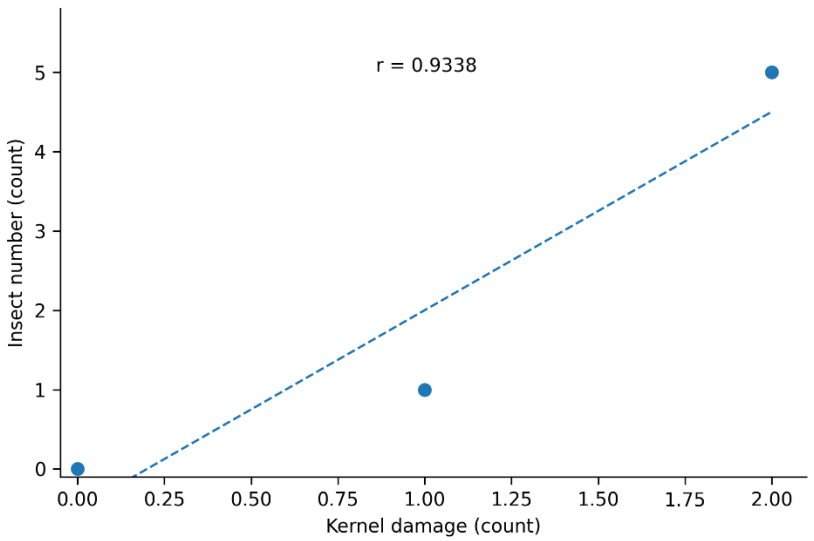


Fig. 3 Correlation between insect infestation and kernel damage, showing a strong positive relationship ($r = 0.9338$).

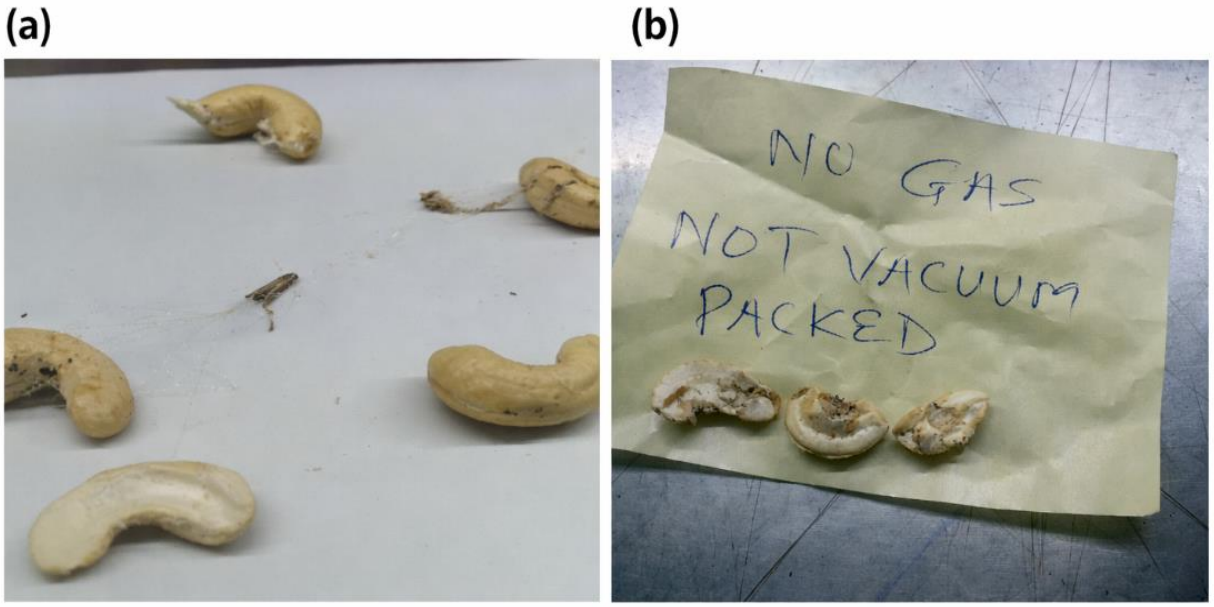


Fig. 4 Representative physical deterioration observed in stored dried cashew kernels (a) Infested cashew kernels showing insect presence and webbing (b) damaged kernels from the non-gas, non-vacuum packaged treatment after storage

Effect of packaging on proximate composition

Packaging treatment influenced the proximate composition of dried cashew kernels after storage (Table 2). Moisture content did not differ significantly among treatments, ranging from 4.47% to 5.26%, suggesting that the packaging film provided broadly comparable moisture-barrier performance during the storage period. Crude protein was highest in the 50% N_2 + 50% CO_2 and non-vacuum treatments (23.35% and 21.98%, respectively), whereas crude fat was found to be the highest in non-vacuum treatment (51.67%) and the lowest in the vacuum-only treatment (15.67%). Because carbohydrate was calculated by difference, interpretation of this parameter should be made alongside the individual proximate components rather than in isolation.

Fungal occurrence in stored dried cashew kernels

The dominant fungi identified were *Aspergillus flavus*, *Aspergillus niger*, *Aspergillus ochraceus*, and *Penicillium spp. Aspergillus flavus* isolation frequency was highest in the 60% N_2 + 40% CO_2 treatment (66.97%), while *Aspergillus niger* was most prevalent in the 50% N_2 + 50% CO_2 treatment (67.00%). *Aspergillus ochraceus* was detected only in the 40% N_2 + 60% CO_2 treatment (33.66%), and *Penicillium spp.* were absent in the vacuum-only and non-vacuum treatments. These data represent percentage isolation frequency rather than CFU-based fungal load (Table 3). The variation in fungal isolation frequency suggests that modified atmospheric packaging influenced the occurrence and distribution of fungal species in stored dried cashew kernels.

Table 2 Proximate composition of dried cashew kernels after four months of storage under different packaging treatments

Packaging treatment	Moisture (%)	Crude protein (%)	Crude fat (%)	Crude fibre (%)	Ash (%)	Carbohydrate (%)
60% N_2 + 40% CO_2	4.95±0.57	17.67±0.50^{b}	47.50±0.81^{b}	5.96±0.51^{bc}	2.67±0.03^{a}	21.25±0.35
40% N_2 + 60% CO_2	5.26±0.60	19.58±0.56^{b}	49.50±0.85^{ab}	5.49±0.47^{c}	1.88±0.02^{c}	18.29±0.30
50% N_2 + 50% CO_2	4.47±0.51	23.35±0.67^{a}	20.67±0.35^{c}	8.74±0.75^{a}	2.36±0.03^{b}	40.41±0.66
Vacuum packaged (no gas flush)	4.72±0.54	18.43±0.53^{b}	15.67±0.27^{d}	7.94±0.68^{ab}	2.41±0.03^{b}	50.83±0.83
Non-vacuum packaged (no gas flush)	4.78±0.55	21.98±0.63^{a}	51.67±0.88^{a}	6.43±0.55^{bc}	1.88±0.02^{c}	13.26±0.22

Means are presented as mean ± SD, and values followed by different letters within a column indicate significant differences at $p \leq 0.01$ (Tukey's HSD). Carbohydrate was calculated by difference as nitrogen-free extract: 100 − (moisture + crude protein + crude fat + crude fibre + ash). Values are means of three replications.

Sensory acceptability and shelf life

The link between physical deterioration and sensory rejection is direct. The non-vacuum treatment experienced the highest insect infestation and kernel damage (Table 4), which inevitably compromised colour, texture, and flavour. In contrast, the complete absence of insect activity and physical damage in gas-flushed treatments preserved the sensory integrity of kernels over the full four-month period.

Table 3 Fungal occurrence (% isolation frequency) in dried cashew kernels after four months of storage under different packaging treatments

Packaging treatment	*A. flavus* (%)	*A. niger* (%)	*A. ochraceus* (%)	*Penicillium spp.* (%)
60% N_2 + 40% CO_2	66.97±1.08^a	33.18±0.40^b	0.00^b	33.33±1.15^a
40% N_2 + 60% CO_2	33.77±0.54^b	0.00^c	33.66±1.28^a	33.66±1.16a
50% N_2 + 50% CO_2	33.67±0.54^b	67.00±0.81^a	0.00±0.00^b	0.00±0.00^b
Vacuum packaged (no gas flush)	0.00±0.00^c	33.67±0.54^b	0.00±0.00^b	0.00±0.00^b
Non-vacuum packaged (no gas flush)	0.00±0.00^c	33.78±0.41^b	0.00±0.00^b	0.00±0.00^b

Values represent percentage isolation frequency of fungal taxa. Means within a column followed by different letters indicate significant differences at $p \leq 0.01$ (Tukey's HSD).

Table 4 Shelf life of dried cashew kernels packaged by different methods under ambient tropical storage

Packaging treatment	Month 1	Month 2	Month 3	Month 4	Shelf life (months)
Non-vacuum (no gas flush)	+	–	–	–	1
Vacuum pack (no gas flush)	+	+	+	–	3
60% N_2 + 40% CO_2	+	+	+	+	4
40% N_2 + 60% CO_2	+	+	+	+	4
50% N_2 + 50% CO_2	+	+	+	+	4

+ = acceptable (mean hedonic score ≥ 5 on a 9-point scale); − = unacceptable. Acceptability was determined by a 30-member semi-trained sensory panel based on colour, aroma, firmness, taste, and overall acceptability.

Discussion

The superior performance of gas-flushed treatments can be attributed to the protective effects of modified atmospheres, which create unfavourable conditions for insect survival and help minimize biological deterioration during storage (Cao et al., 2019; Atef et al., 2026). Carbon dioxide at concentrations of 40–60% is widely recognized as insecticidal and fungistatic, impairing the aerobic metabolism of storage insects and inhibiting many aerobic spoilage organisms (Walker et al., 2018). Nitrogen, as an inert balancing gas, displaces residual oxygen and limits oxidative reactions that could otherwise sustain insect activity (Athanassiou & Sakka, 2022; Rumbos et al., 2023; Ren et al., 2026). Although the additional vacuum step further reduces oxygen availability before gas flushing, the gas-flushed treatments showed better performance than vacuum-only packaging under the storage conditions investigated. This difference suggests that factors other than initial oxygen concentration may have contributed to the observed packaging performance (Faria et al., 2012). Under tropical ambient conditions, where insect pressure is high throughout the year, the combined effect of oxygen reduction and elevated CO_2 provides a clear protective advantage for cashew kernel quality and marketability (Liberal et al., 2025; Zanjurne et al., 2025).

During the present research study, crude fat content of cashew kernels exhibited considerable variation among the packaging treatments after four months of storage. The highest crude fat content (51.67%) was recorded in non-vacuum-packaged kernels without gas flushing, followed by kernels packaged under 40% N_2 + 60% CO_2 (49.50%) and 60% N_2 + 40% CO_2 (47.50%). In contrast, substantially lower values were observed in kernels packaged under 50% N_2 + 50% CO_2 (20.67%) and vacuum packaging without gas flushing (15.67%). These differences were retained following verification of the original analytical measurements. The observed variation is noteworthy because cashew kernels are naturally rich in lipids, and their proximate composition is influenced by genotype, geographical origin, growing conditions, maturity, and processing history. Lima et al. (2015) reported lipid contents ranging from 39.88% to 47.10% among nine Brazilian cashew genotypes, demonstrating that genetic and biological variation can influence the initial composition of cashew kernels. The same study reported protein contents ranging from 17.50% to 24.49%, indicating that considerable variation in both protein and lipid proportions can occur among cashew genotypes. Thus, the initial characteristics and homogeneity of the raw material are important considerations when interpreting treatment-related differences in proximate composition. Hence, the relatively high crude fat concentrations observed in the non-vacuum and gas-flushed treatments indicate that a substantial proportion of extractable lipids remained in these samples after storage. However, the considerably lower values recorded under vacuum packaging and the 50% N_2 + 50% CO_2 atmosphere require a distinction between total lipid content and lipid oxidative stability. Total crude fat represents the fraction of lipid extracted using the analytical procedure, whereas oxidative stability describes the susceptibility of extracted lipids to chemical deterioration during storage (Münch et al., 2024; Kasaai, 2025). These parameters are related to nutritional quality but are not interchangeable. Lipid oxidation primarily involves the reaction of oxygen with unsaturated fatty acids, resulting in the formation of lipid hydroperoxides and subsequent secondary oxidation products (Wang et al., 2023; Jaldani et al., 2024). Although advanced deterioration can influence the chemical characteristics and extractability of lipids, a decrease in crude fat content cannot automatically be interpreted as evidence of lipid oxidation (Münch et al., 2024). Therefore, the lower crude fat concentrations observed in the present study should be considered differences in measured extractable lipid content rather than direct evidence of oxidative degradation.

In the present study, the treatment containing 50% N_2 + 50% CO_2 exhibited the highest crude protein content (23.35%). Similarly, vacuum-packaged kernels exhibited 18.43% protein. These observations suggest differences in the relative distribution of the measured proximate components. However, because proximate composition is expressed as a percentage of the sample mass, an increase in the percentage of one constituent may correspond to a decrease in the relative percentage of another constituent without indicating actual synthesis or loss of that component. In particular, the higher protein percentage under 50% N_2 + 50% CO_2 should not be interpreted as an increase in the absolute protein quantity during storage. Rather, it represents a higher proportion of protein in the analyzed sample. Establishing actual changes in protein or lipid mass would require initial composition measurements and a mass-balance assessment throughout storage. In the present study, carbohydrate was estimated by subtracting moisture, crude protein, crude fat, crude fibre, and ash from 100. Consequently, the carbohydrate content is mathematically dependent on the measured values of the other proximate constituents. For example, the 50% N_2 + 50% CO_2 treatment exhibited 40.41% carbohydrate, whereas vacuum-packaged kernels exhibited 50.83% carbohydrate. These relatively high carbohydrate percentages are consistent with their comparatively low measured crude fat contents. However, this inverse relationship should not be considered an independent physiological response to packaging because the carbohydrate values were calculated rather than directly measured. Similar approaches have been employed in the determination of cashew kernel proximate composition (Greenfield & Southgate, 2003; Lima et al., 2015; Dakuyo et al., 2022; Zanjurne et al., 2025). Therefore, the observed carbohydrate differences should be interpreted in the context of the overall proximate composition rather than as direct evidence of carbohydrate accumulation during storage.

The influence of modified-atmosphere packaging on lipid stability has been investigated extensively in other tree nuts, including almonds, walnuts, and hazelnuts. Massantini et al. (2022) investigated the storage of early-ripe almond kernels under nitrogen, carbon dioxide, and atmospheric conditions and demonstrated that the effectiveness of modified atmospheres depended on the storage temperature and gas composition. Nitrogen packaging at 4°C was particularly effective in maintaining the chemical, physical, and sensory characteristics of the almond kernels. These findings demonstrate the importance of oxygen displacement and temperature management in preserving lipid-rich nuts. Similarly, Bai et al. (2024) investigated nitrogen-based modified-atmosphere packaging of dried hazelnut kernels and demonstrated that 100% N_2 packaging delayed lipid oxidation during prolonged storage. Their evaluation included peroxide value, free fatty acids, and conjugated dienes, providing evidence that modified atmospheres can influence lipid stability even when changes in total crude fat are not necessarily the principal indicator of preservation. In walnut kernels, Yurdunuseven Yildiz & Karaca (2024) examined the effects of packaging techniques, including normal atmosphere, nitrogen atmosphere, and vacuum packaging, at different storage temperatures. Their findings indicated that packaging technique alone did not significantly determine oxidative stability, whereas storage temperature and walnut variety had important influences on oxidation. This observation is particularly relevant to the present study because it demonstrates that the effectiveness of vacuum and gas-flushed packaging cannot be interpreted independently of other storage-related factors. Furthermore, recent research on shelled pecans by Yang et al. (2025) demonstrated that cultivar, packaging system, and storage temperature collectively influenced lipid deterioration. Nitrogen-flushed modified-atmosphere packaging provided substantial protection during prolonged storage, whereas higher temperatures and cultivar-dependent differences were associated with increased free fatty acids and secondary oxidation products. These findings suggest that the nutritional and oxidative stability of tree nuts is determined by interactions among raw-material characteristics, packaging atmosphere, and storage conditions rather than by gas composition alone.

The potential contribution of carbon dioxide to lipid preservation should also be considered. Carbon dioxide has relatively high solubility in several food matrices, and its dissolution and diffusion depend on temperature, pressure, food composition, and matrix structure (Chaix et al., 2014). In modified-atmosphere packaging, absorbed CO_2 can alter the equilibrium between the gas phase and the food matrix, while nitrogen primarily functions as an inert gas that displaces oxygen and helps maintain package volume. A combination of these gases may therefore influence the atmosphere surrounding the kernels and the conditions under which oxidative reactions occur. However, CO_2 solubility should not be considered a direct explanation for the lower crude fat content recorded in the 50% N_2 + 50% CO_2 treatment. The present experiment did not include measurements of lipid oxidation products or gas absorption into the kernel matrix; consequently, the specific contribution of CO_2 to the observed crude fat differences remains uncertain. Another important factor influencing the effectiveness of modified-atmosphere packaging is the headspace-to-product ratio (Martin et al., 2023; Florit et al., 2025a, 2025b). The volume of gas available within a package relative to the mass of the packaged kernels determines the amount of oxygen displaced and the potential for changes in gas composition during storage (Schmackler et al., 2024). A relatively large headspace may provide a greater gas reservoir, whereas a smaller headspace may result in more pronounced changes in gas composition as CO_2 dissolves into the product or oxygen enters through the packaging material. Similarly, residual oxygen remaining after vacuum application or gas flushing may contribute to lipid oxidation, even when the nominal packaging atmosphere contains a high proportion of nitrogen or carbon dioxide (Dold et al., 2024; Lindstad et al., 2025). The effectiveness of gas flushing is also influenced by the efficiency of the packaging equipment, initial air removal, film permeability, and package-sealing integrity (Schmackler et al., 2024).

The absence of a consistent MAP-associated reduction in fungal occurrence is scientifically noteworthy. Fungal contamination of dried cashew kernels appears to be

governed substantially by pre-existing contamination levels at the time of packaging, moisture gradients within the kernel mass, and fungal ecology rather than by packaging atmosphere alone (Adetunji et al., 2019; Liberal et al., 2025; Olou et al., 2026). *Aspergillus species* are well-recognized contaminants of stored tree nuts and are capable of growth at very low water activity, which limits the protective effect of reduced oxygen per se (Gama et al., 2018). The presence of *Aspergillus ochraceus* and *Penicillium spp.* in gas-flushed treatments further suggests that residual oxygen and localized moisture pockets may support fungal survival even under modified atmospheres. These findings demonstrate the importance of achieving low initial contamination and low moisture content before packaging and highlight that MAP should be regarded as one component of an integrated postharvest management system rather than a stand-alone mycological control measure. The proximate profile observed in this study is broadly consistent with values reported by Rico et al. (2016), who documented crude fat contents of 43–48% and crude protein contents of 17–19% in raw cashew kernels from different origins. The wider variation observed among treatments in the present study may reflect storage atmosphere, packaging integrity, and kernel batch variability. Accordingly, the proximate-composition results are useful for describing post-storage composition, but treatment effects should be interpreted cautiously, particularly for carbohydrate, which was derived by difference. These findings have practical relevance for cashew processors, warehouse managers, and exporters operating under tropical ambient conditions in Ghana, where cold-chain infrastructure is limited. A four-month acceptable storage window under ambient conditions represents a meaningful operational advantage, enabling processors to accumulate sufficient stock for export batches and bridge the gap between seasonal harvest peaks and market demand. These findings are in line with the broader evidence that appropriate atmosphere management helps preserve quality and delay deterioration in storage-sensitive foods (Gama et al., 2018; Bai et al., 2024).

Conclusion

Vacuum-assisted modified atmosphere packaging using nitrogen and carbon dioxide substantially improved the storage stability of dried cashew kernels under tropical ambient conditions. Compared with vacuum-only and non-vacuum packaging, no insect infestation, web formation, or associated kernel damage was observed in the gas-flushed MAP samples during the four-month observation period. Gas-flushed MAP also improved sensory acceptability and extended the shelf life of dried cashew kernels to at least four months. The three N_2/CO_2 mixtures tested performed equally well in controlling physical deterioration and all outperformed vacuum-only and non-vacuum packaging on the measured physical and sensory criteria. Based on these findings, dried cashew kernels intended for ambient tropical storage should be dried to 4% moisture content and packaged under vacuum with 40–60% N_2/CO_2 gas mixtures. Fungal occurrence was not consistently reduced by MAP, indicating that pre-packaging hygiene, initial moisture management, and integrated postharvest practices remain critical components of any storage strategy. Further work should verify the proximate-composition dataset using confirmed raw laboratory values, standardize the fungal reporting metric, and assess storage durations beyond four months under monitored temperature and relative humidity conditions.

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Declarations

i. Ethics approval and consent to participate: This study did not involve human participants, human data, or animal studies; therefore, ethical approval was not required.

ii. Competing interests: The authors declare that they have no conflict of interest regarding the publication of this manuscript.

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References

Adetunji, M. C., Aroyeun, S. O., Osho, M. B., Sulyok, M., Krska, R., & Mwanza, M. (2019). Fungal metabolite and mycotoxins profile of cashew nut from selected locations in two African countries. *Food Additives & Contaminants: Part A, Chemistry, Analysis, Control, Exposure & Risk Assessment*, *36*(12), 1847–1859. https://doi.org/10.1080/19440049.2019.1662951

Atef, R., Ahmed, S. S., Abo-Shnaf, R., & Hassan, M. F. (2026). Impact of modified atmosphere on two mite species *Glycyphagus domesticus* (Astigmatina: Glycyphagidae) and *Caloglyphus oudemansi* (Astigmatina: Acaridae) infesting stored wheat grains. *Journal of Stored Products Research*, *115*, 102877. https://doi.org/10.1016/j.jspr.2025.102877

Athanassiou, C. G., & Sakka, M. K. (2022). Using nitrogen for the control of stored product insects: One single application for multiple purposes. *Agrochemicals*, *1*(1), 22–28. https://doi.org/10.3390/agrochemicals1010004

Bai, X., Dag, D., Jung, J., & Zhao, Y. (2024). Investigation of antioxidant edible coating and modified atmosphere packaging for enhancing storability of hazelnut kernels. *Journal of Agriculture and Food Research*, *17*, 101246. https://doi.org/10.1016/j.jafr.2024.101246

Bai, X., Dag, D., Jung, J., & Zhao, Y. (2024). Investigation of antioxidant edible coating and modified atmosphere packaging for enhancing storability of hazelnut kernels.

Journal of Agriculture and Food Research, 17, 101246. https://doi.org/10.1016/j.jafr.2024.101246

Beshaw, T., Demssie, K., Tefera, M., & Guadie, A. (2022). Determination of proximate composition, selected essential and heavy metals in sesame seeds (*Sesamum indicum* L.) from the Ethiopian markets and assessment of the associated health risks. *Toxicology Reports*, *9*, 1806–1812. https://doi.org/10.1016/j.toxrep.2022.09.009

Cao, Y., Xu, K., Zhu, X., Bai, Y., Yang, W., & Li, C. (2019). Role of modified atmosphere in pest control and mechanism of its effect on insects. *Frontiers in Physiology*, *10*, 206. https://doi.org/10.3389/fphys.2019.00206

Chaix, E., Guillaume, C., & Guillard, V. (2014). Oxygen and carbon dioxide solubility and diffusivity in solid food matrices: A review of past and current knowledge. *Comprehensive Reviews in Food Science and Food Safety*, *13*(3), 261–286. https://doi.org/10.1111/1541-4337.12058

Dakuyo, R., Konaté, K., Sanou, A., Kaboré, K., Sama, H., Bazié, D., Diao, M., & Dicko, M. H. (2022). Comparison of proximate and phytonutrient compositions of cashew nuts and apples from different geographical areas of Burkina Faso. *BioMed Research International*, *2022*, 1800091. https://doi.org/10.1155/2022/1800091

Dold, J., Götzendörfer, L., Hollmann, C., & Langowski, H. C. (2024). A non-destructive measuring device in the mid-infrared range for measuring the CO_2 concentration in the headspace of food packaging. *Journal of Food Engineering*, *375*, 112063. https://doi.org/10.1016/j.jfoodeng.2024.112063

Donkor, L., Kontoh, G., Yaya, A., Bediako, J. K., & Apalangya, V. (2023). Bio-based and sustainable food packaging systems: relevance, challenges, and prospects. *Applied Food Research*, *3*(2), 100356. https://doi.org/10.1016/j.afres.2023.100356

Faria, M. R., Hotchkiss, J. H., & Wraight, S. (2012). Application of modified atmosphere (gas flushing and active packaging) for extending the shelf life of *Beauveria bassiana* conidia at high temperatures. *Biological Control*, *61*(1), 78–88. https://doi.org/10.1016/j.biocontrol.2011.12.008

Florit, F., Fiorati, A., Rota, R., & De Nardo, L. (2025a). Generalized toolbox for a priori equilibrium modified atmosphere packaging design. Part I: Model development. *Food Packaging and Shelf Life*, *47*, 101434. https://doi.org/10.1016/j.fpsl.2025.101434

Florit, F., Fiorati, A., Rota, R., & De Nardo, L. (2025b). Generalized toolbox for a priori equilibrium modified atmosphere packaging design. Part II: Validation. *Food Packaging and Shelf Life*, *47*, 101384. https://doi.org/10.1016/j.fpsl.2024.101384

Gama, T., Wallace, H. M., Trueman, S. J., & Hosseini-Bai, S. (2018). Quality and shelf life of tree nuts: A review. *Scientia Horticulturae*, *242*, 116–126. https://doi.org/https://doi.org/10.1016/j.scienta.2018.07.036

Gidado, M. J., Gunny, A. A. N., Ali, A., Korsten, L., & Devi, M. (2026). Environmental and external determinants of postharvest storage: Impacts, challenges, and sustainable mitigation strategies. *Food Chemistry Advances*, *11*, 101290. https://doi.org/10.1016/j.focha.2026.101290

Greenfield, H., & Southgate, D. A. T. (2003). *Food composition data: Production, management and use* (2nd ed.). Rome, Italy: Food and Agriculture Organization of the United Nations.

Jaldani, S., Sarfaraz Khabbaz, E., Jooyandeh, M., & Farhoosh, R. (2024). Kinetics of simultaneous change in the concentration of total lipid hydroperoxides and total conjugated dienes during peroxidation of canola, sunflower, and olive oils. *Food Chemistry*, *435*, 137605. https://doi.org/10.1016/j.foodchem.2023.137605

Kasaai, M. R. (2025). Oxidative and hydrolytic deteriorations of lipids and several alternative pathways for their protections: An overview. *Food Nutrition Chemistry*, *3*(1), 238. https://doi.org/10.18686/fnc238

Kaur, J., Aslam, R., & Saeed, P. A. (2021). Storage structures for horticultural crops: a review. *Environment Conservation Journal*, *22*(SE), 95–105. https://doi.org/10.36953/ECJ.2021.SE.2210

Liberal, A., Fernandes, Â., Moreira, J., Fernandes, N., Gonçalves, A., Ferreira, I. C. F. R., & Barros, L. (2025). Microbial and pest contamination in nuts: Radio frequency disinfestation and controlled atmosphere preservation—A review. *Food Control*, *175*, 111328. https://doi.org/10.1016/j.foodcont.2025.111328

Liberal, Â., Fernandes, Â., Moreira, J., Fernandes, N., Gonçalves, A., Ferreira, I. C. F. R., & Barros, L. (2025). Microbial and pest contamination in nuts: Radio frequency disinfestation and controlled atmosphere preservation – A review. *Food Control*, *175*, 111328. https://doi.org/10.1016/j.foodcont.2025.111328

Lima, J. R., Nobre, A. C. O., Magalhaes, H. C. R., & Souza, R. N. M. (2015). Chemical composition and fatty acid profile of kernels from different Brazilian cashew tree genotypes. *African Journal of Food Science*, *9*(7), 390–394. https://doi.org/10.5897/AJFS2015.1316

Lindstad, A. J., Li, K. D., Sharmin, N., & Pettersen, M. K. (2025). Suitability of cellulose-based trays with PE/EVOH coating for modified atmosphere packaging of salmon, chicken, and beef. *Journal of Food Science*, *90*, e70505. https://doi.org/10.1111/1750-3841.70505

Makinya, K. J., Wagacha, J. M., Odhiambo, J. A., Likhayo, P., Edoh-Ognakossan, K., Tefera, T., Abass, A., & Mutungi, C. M. (2021). The importance of store hygiene for reducing post-harvest losses in smallholder farmers' stores: Evidence from a maize-based farming system in Kenya. *Journal of Stored Products Research*, *90*, 101757. https://doi.org/10.1016/j.jspr.2020.101757

Martin, D., Joly, C., Dupas-Farrugia, C., Adt, I., Oulahal, N., & Degraeve, P. (2023). Volatilome analysis and evolution in the headspace of packed refrigerated fish. *Foods*, *12*(14), 2657. https://doi.org/10.3390/foods12142657

Massantini, R., Cristofori, V., & Frangipane, M. T. (2022). Storage of the early ripe almonds under modified atmosphere to preserve kernel qualitative and sensory traits. *Agriculture*, *12*(7), 974. https://doi.org/10.3390/agriculture12070974

Matusse, C., Bila, J., Macuamule, C., Sampaio, A., Venâncio, A., & Rodrigues, P. (2025). Evaluation of corn drying and storage techniques to mitigate damage and total aflatoxin contamination in Mozambique. *Journal of Stored Products Research*, *114*. https://doi.org/10.1016/j.jspr.2025.102794

Münch, K., ten Klooster, S., van Kouwen, I., Berton-Carabin, C., & Schroën, K. (2024). Incomplete lipid extraction as a possible cause for underestimation of lipid oxidation in emulsions. *European Journal of Lipid Science and*

Technology, *126*, e2300229. https://doi.org/10.1002/ejlt.202300229

Olou, A. O., Kindossi, J. M., Sare, O. E. B. N., Akogou, F., Afe, O. H. I., Mehouel, F., & Cao Diogo, R. V. (2026). HACCP-based risk assessment of cashew nut processing in Benin focusing on the critical role of drying in microbial safety and aflatoxin control. *Journal of Food Safety*, *46*(5), e70094. https://doi.org/10.1111/jfs.70094

Otálora, A., Mora, M. A., Palencia, M., Combatt, E. M., Arrieta, Á. A., & Jarma Orozco, A. (2024). 'Cashew, anacardo or marañón' (*Anacardium occidentale*): An overview about its crop, economic aspects and nutritional relevance. *Journal of Science with Technological Applications*, *16*, 1–10. https://doi.org/10.34294/j.jsta.24.16.9

Ren, H., Pu, Q., Yang, X., Kashyap, S., & Liu, S. (2026). Regulatory mechanisms of nitrogen homeostasis in insect growth and development. *Insect Science*, *33*(4), 1224–1244. https://doi.org/10.1111/1744-7917.70059

Rico, R., Bulló, M., & Salas-Salvadó, J. (2016). Nutritional composition of raw fresh cashew (Anacardium occidentale L.) kernels from different origin. *Food Science and Nutrition*, *4*(2), 329–338. https://doi.org/10.1002/fsn3.294

Rumbos, C. I., Sakka, M. K., Vassilakos, T. N., & Athanassiou, C. G. (2023). Effect of nitrogen on stored-product insect control at industrial scale. *Insects*, *14*(6), 518. https://doi.org/10.3390/insects14060518

Schmackler, T., Müller, K., Tybussek, T., Jesdinszki, M., & Sängerlaub, S. (2024). Evaluation of market-available snack chip packaging: Modified atmosphere packaging, water activity, mechanical properties, and efficiency of packaging material use. *Chemie Ingenieur Technik*, *96*(3), 329–339. https://doi.org/10.1002/cite.202300110

Shahbazi, R., & Shahbazi, F. (2022). Effects of cushion box and closed let-down ladder usage on impact damage to corn kernel during handling. *Food Science & Nutrition*, *11*(5), 2243–2253. https://doi.org/10.1002/fsn3.3137

Tufail, T., Saeed, F., Ul Ain, H. B., Niaz, B., Afzaal, M., Din, A., & Rasul Suleria, H. A. (2019). Cashew nut allergy; immune health challenge. *Trends in Food Science & Technology*, *86*, 209–216. https://doi.org/10.1016/j.tifs.2019.02.014

Walker, S., Jaime, R., Kagot, V., & Probst, C. (2018). Comparative effects of hermetic and traditional storage devices on maize grain: Mycotoxin development, insect infestation and grain quality. *Journal of Stored Products Research*, *77*, 34–44. https://doi.org/10.1016/j.jspr.2018.02.002

Wang, D., Xiao, H., Lyu, X., Chen, H., & Wei, F. (2023). Lipid oxidation in food science and nutritional health: A comprehensive review. *Oil Crop Science*, *8*(1), 35–44. https://doi.org/10.1016/j.ocsci.2023.02.002

Wittern, J., Luckmann, J., & Grethe, H. (2023). Cashew processing in Ghana – A case for infant industry support? *Food Policy*, *119*, 102448. https://doi.org/10.1016/j.foodpol.2023.102448

Worku, A. F., Kalsa, K. K., Abera, M., Tenagashaw, M. W., & Habtu, N. G. (2022). Evaluation of various maize storage techniques on total aflatoxins prevalence and nutrient preservation. *Journal of Stored Products Research*, *95*, 101913. https://doi.org/10.1016/j.jspr.2021.101913

Yang, V. E., Kerr, W. L., Pegg, R. B., & Kerrihard, A. L. (2025). Effect of packaging and storage temperature on shelled pecan chemical quality indicators and their impact on consumer acceptance. *Food Packaging and Shelf Life*, *50*, 101543. https://doi.org/10.1016/j.fpsl.2025.101543

Yewle, N., Chandra Swain, K., Mann, S., & Guru, P. N. (2022). Performance of hermetic bags in green gram [*Vigna radiata* (L.) R. Wilczek] storage for managing pulse beetle (*Callosobruchus chinensis*). *Journal of Stored Products Research*, *95*, 101896. https://doi.org/10.1016/j.jspr.2021.101896

Yurdunuseven Yildiz, A., & Karaca, H. (2024). The protective role of shell, packaging technique and storage temperature in lipid oxidation in walnuts of different varieties. *Postharvest Biology and Technology*, *210*, 112747. https://doi.org/10.1016/j.postharvbio.2023.112747

Zanjurne, R. R., Shirke, G. D., Salvi, S. P., Waikar, G. A., Sanap, P. B., & Adhau, A. S. (2025). Studies on packaging of dehydrated tender cashew (*Anacardium occidentale* L.) kernel. *International Journal of Advanced Biochemistry Research*, *9*(10S), 868–874. https://doi.org/10.33545/26174693.2025.v9.i10Sk.5931

Zanjurne, R. R., Shirke, G. D., Salvi, S., Waikar, G., Sanap, P. B., & Adhau, A. S. (2025). Studies on packaging of dehydrated tender cashew (*Anacardium occidentale* L.) kernel. *International Journal of Advanced Biochemistry Research*, *9*(10S), 868–874. https://doi.org/10.33545/26174693.2025.v9.i10Sk.5931

Ziegler, V., Paraginski, R. T., & Ferreira, C. D. (2021). Grain storage systems and effects of moisture, temperature and time on grain quality - A review. *Journal of Stored Products Research*, *91*, 101770. https://doi.org/10.1016/j.jspr.2021.101770

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