processes

MDPI

Article

The Effectiveness of Different Household Storage Strategies and Plant-Based Preservatives for Dehulled and Sun-Dried Breadfruit Seeds

Macmanus C. Ndukwu [1], Daniel I. Onwude [2,*], James Ehiem [1], Ugochukwu C. Abada [3], Inemesit E. Ekop [4] and Guangnan Chen [5]

[1] Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture Umudike, P.M.B 7267 Umuahia, Nigeria; ndukwumcu@mouau.edu.ng (M.C.N.); ehiem.james@mouau.edu.ng (J.E.)
[2] Department of Agricultural and Food Engineering, University of Uyo, Akwa Ibom State, P.M.B. 52021 Uyo, Nigeria
[3] Department of Agricultural and Bioresources Engineering, University of Nigeria, 410001 Nsukka, Nigeria; ugochukwu.abada@unn.edu.ng
[4] Department of Agricultural Engineering, Akwa Ibom State University, P.M.B. 1167 Uyo, Nigeria; inemesitekop@aksu.edu.ng
[5] Faculty of Health, Engineering and Sciences, University of Southern Queensland, Toowoomba, QLD 4350, Australia; Guangnan.Chen@usq.edu.au
* Correspondence: onwudedaniel@uniuyo.edu.ng

Abstract: In a tropical rainforest environment, different storage strategies are often adopted in the preservation of primary processed food crops, such as maize, sorghum, etc., after drying and dehulling to increase shelf-life. For breadfruit seeds (*Treculia Africana*), the current challenge is identifying the most appropriate short-term storage and packaging methods that can retain the quality of stored products and extend shelf-life. In this regard, we compared the performance of a plastic container, a weaved silo bag and a locally developed silo bin for the short-term storage of parboiled, dehulled and dried breadfruit seeds treated with locally sourced and affordable alligator pepper (*Zingiberaceae aframomum melegueta*) and bitter kola (*garcinia*) powder as preservatives. We show that the concentration of CO_2 was lower in the silo bin treated with 150 g alligator pepper and higher in the silo bag-treated with 100 g bitter kola nut. A higher CO_2 concentration resulted in limited oxygen availability, higher water vapor, and a higher heat release rate. Non-treated bag storage had the highest average mold count of 1.093×10^3 CFU/mL, while silo bin-stored breadfruit treated with 150 g of alligator pepper had the lowest mold count of 2.6×10^2 CFU/mL. The storage time and botanical treatments influenced both the crude protein and crude fiber content. Average insect infestations were low (0–4.5) in the silo bin with breadfruits treated with alligator pepper powder, as the seeds seemed to continue to desorb moisture in storage, unlike in other treatments. The obtained results revealed the high potential of alligator pepper (*Zingiberaceae aframomum melegueta*) as a botanical insecticide in preventing insect infestation and mold growth in stored breadfruit instead of using synthetic insecticide. An aluminum silo bin with alligator pepper powder is recommended to store dried and dehulled breadfruit seeds as a baseline for other tropical crops.

Keywords: postharvest storage; food packaging and shelf-life; bitter kola; food preservation; alligator pepper; underutilized seeds

Citation: Ndukwu, M.C.; Onwude, D.I.; Ehiem, J.; Abada, U.C.; Ekop, I.E.; Chen, G. The Effectiveness of Different Household Storage Strategies and Plant-Based Preservatives for Dehulled and Sun-Dried Breadfruit Seeds. *Processes* **2021**, *9*, 380. https://doi.org/10.3390/pr9020380

Academic Editor: Lina Cossignani
Received: 14 December 2020
Accepted: 14 February 2021
Published: 19 February 2021

1. Introduction

Breadfruit belongs to the family of *Moraceae* and is a multipurpose tropical agro-forestry tree crop with about 120 varieties. Prominent among them in Nigeria is African breadfruit (*Treculia africana*) [1,2]. The seeds are rich in oil, carbohydrates, proteins, calcium, phosphorus, minerals, and vitamins [1]. African breadfruit seeds are prepared for

consumption by cooking (either fresh or dried), roasting, or breadfruit flour. This highly nutritional but underutilized crop is native to the West Indies, Jamaica, as well as many West African countries, including Nigeria, Ghana and Sierra Leone [3]. In 2011, Nigeria accounted for about 32% of African breadfruits' global production [4]. Food prepared from breadfruit seeds is highly appreciated and sought out because it serves as a common source of calories among over 60 million people in the Central African Republic, southern Nigeria, and southern Cameroun [5]. The processing of this underutilized crop involves the fermentation or dehulling of the fresh fruit to extract the seed, washing, heat treatment, and threshing of the seed to reveal an edible greenish cotyledon [6]. This is then either cooked fresh or dried to a moisture content of about 8–10% wet basis before storage [6]. However, drying unhulled seeds makes dehulling very difficult even if heat treatment is applied. This is because of the adhesive layer that attaches the hull to the kernel [7].

Traditionally, in Nigeria, after drying African breadfruits, various households store dried breadfruits under room conditions in plastic containers, weaved silo bags, bottles, hanging above the cooking attic, spreading on the open floor or on a mat, or keeping them in basins [6,8]. However, storing the dried seeds for a long period is a challenge due to the hygroscopic nature of the seeds even after drying, which makes them prone to quick fungi and insect damage, discoloration, etc. [6,9]. Apart from managing the pest in enclosed storage, temperature increase, high humidity and the reaction of chemical and gaseous constituents from the product can cause considerable deterioration [9]. Investigations were carried out by Adindu and Williams [6] on the nutritional quality of non-dehulled dried breadfruit seed stored in tight plastic buckets, polythene bags, closed and open raffia baskets, and tied jute bags. However, in most homes, breadfruits are parboiled, dehulled and dried before storage, as in rice processing. Therefore, storing pretreated and processed African breadfruit seeds is still a challenge as there is a lack of adequate data for food processors.

Several studies on the different postharvest management practices on stored agro-product exist in the scientific literature [10–12]. However, these studies are limited mainly to grains. Furthermore, many storage approaches have been adopted in the literature for the shelf-life extension of stored products by researchers, ranging from the use of botanical insecticides (oil from Vittallaria paradoxa seed, coconut, mustard seed), to Diatomaceous earth, hermetic bags, metal silos, and charcoal ash [12–19]. However, insight gained from these studies revealed that most of these storage approaches are crop-specific with a particular focus on cereals, including maize, cowpea, wheat, etc. [11–21]. To the best of our knowledge, information on the most suitable storage strategy for primary processed and raw African breadfruit seeds under household conditions is non-existent. Again, the respiratory activities in the interstitial space of the storage ecosystem of biological products influence product storage conditions. Temperature changes in the interstitial space have been adduced to respiratory activities within the storage ecosystem, which is a function of the external conditions. With this knowledge of the interstitial temperature, the gaseous exchange within the space can be accounted for. However, this measurement of the interstitial temperature requires constant measurement and probing of the storage system, which distorts the tightness of the storage system. Therefore, employing a mathematical model that will account for interstitial temperature and all the desired components of gaseous exchange involved in the respiration activities using the external conditions will solve this problem. In this way, the rigorous and cumbersome experimental measurement process is eliminated [22–24]. In addition, using this modeling approach will enhance future optimization and process design [25].

Locally, in Nigeria, dried alligator pepper (*Zingiberaceae aframomum melegueta*) powder has been integrated into the storage bag to drive away insects and pests in maize stored in weaved bags under the market environment [12]. In addition to alligator pepper, bitter kola (*garcinia*) has also been used locally for storage because its extracts have shown antimicrobial, antifungal and anti-pest properties, along with their pungent, peppery and bitter taste [26–31]. Therefore, as food processors reduce the dependency on synthetic insecticides

due to the attendant health challenges, evaluating the efficacy of these affordable edible plant seeds as alternatives become indispensable.

This research aims to identify the most effective storage strategies and treatments for an on-the-shelf postharvest preservation approach for breadfruits seeds, as adopted in Nigeria. A plastic container, a weaved bag and a locally developed silo bin were adopted for the short-term storage of parboiled, dehulled, and sun-dried breadfruit seeds treated with alligator pepper (*Zingiberaceae aframomum melegueta*) and bitter kola (*garcinia*) powder as preservatives. The effectiveness of the storage strategies was evaluated in terms of shelf-life duration, nutritional product quality, mold count and insect enumeration. The result of this study will provide valuable information to improve the all-year-round availability and affordability of breadfruits seeds in major breadfruit-producing countries.

2. Materials and Methods

2.1. Description of Storage Strategies

The experiment was carried out for 3 months (14 weeks) (September–December 2019) at the crop processing and storage laboratory of Michael Okpara University of Agriculture Umudike, Nigeria, 5.53° N, 7.49° E. The local storage strategies adopted include a weaved silo bag, a plastic drum and a locally developed aluminum silo bin. Figure 1 shows the schematic view of the aluminum silo and its components. It consists of a storage container equipped with a wooden stirrer force-fitted into the silo through a sealed bearing. Loading and unloading points were created at the top and bottom of the silo and plastic container. The plastic buckets and aluminum silos were airtight with a side opening for material sampling. The loading and unloading opening of the silo was covered with a metal cover sheet, while that of the plastic drum was sealed with masking tape.

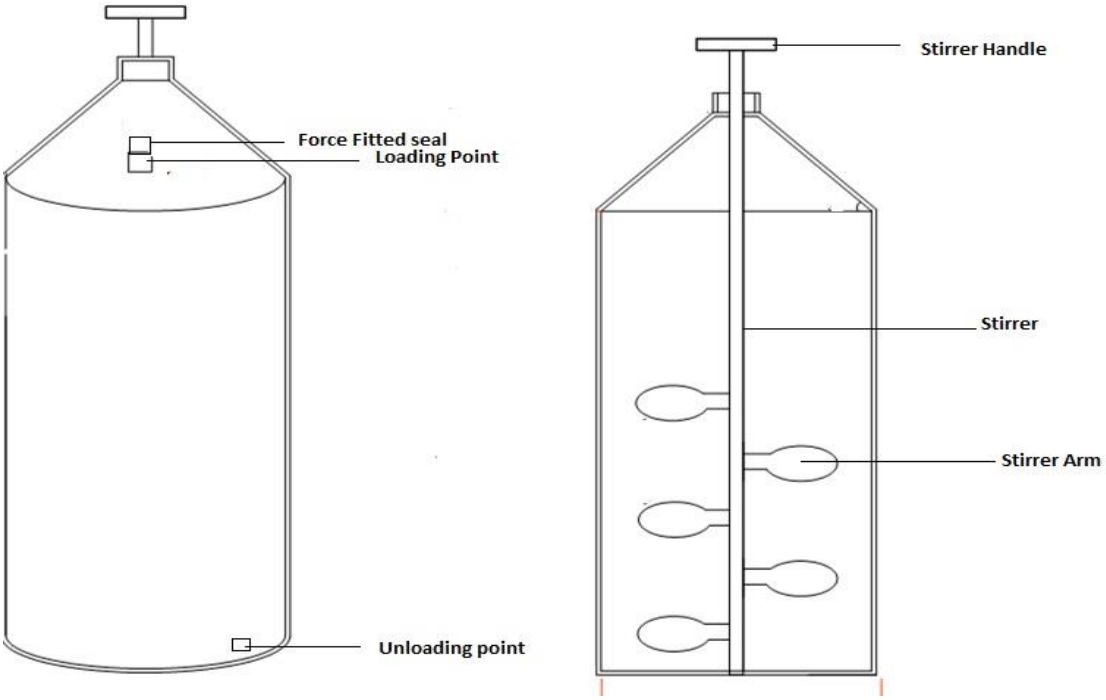


Figure 1. Schematic view of the locally developed aluminum storage silo.

2.2. Sourcing, Heat Treatments and Drying of Breadfruit Seeds

The breadfruit used for this experiment was obtained directly from the farmers in Umudike, southeastern Nigeria. All the seeds were sourced from the same lot as recommended in the International Rules of Seed Testing [32] and there was no requirement for additional homogenization. The seeds were harvested off-season and were not treated with any pesticide. The farmers allow matured fruit to naturally fall from the tree in the

wild, after which it is allowed to ferment from two to three weeks. Fermented fruits were washed with clean water to remove the pulp from the seeds. The seeds were manually selected to remove any bad seed or dirt, after which they were spread on a stainless tray and kept under the sun for three hours. The seeds were parboiled in hot water for 5 min with clean water, after which the water was filtered out. The parboiled seeds were spread under the sun and allowed to cool before manual threshing using a local wooden thresher to reveal the cotyledon. Parboiling the seed unstuck the chaff from the cotyledon for easy separation, and it also kills any larvae of pests from the farm or the fermentation process. Parboiling of the seed for a short time of less than 10 min causes no significant difference in the seed's nutritional composition [33]. The threshed mixture of cotyledon and chaff was separated manually by winnowing using a stainless tray. After winnowing, broken cotyledon was manually removed while the rest was dried under the sun until the moisture content reached about $8 \pm 2.2\%$. Initial moisture content was checked with a grain moisture meter (Kongskilde, series 20849) initially calibrated with a laboratory oven (DHG-9053A Ocean med+ England).

2.3. Preparation of Botanical Treatments

Dried pulverized alligator pepper seed (*Zingiberaceae aframomum melegueta*) at 8% moisture content and dried pulverized bitter kola seed (*Garcinia*) at 10% moisture content were introduced as botanical preservatives. These two plant materials were harvested from the trees in southeastern Nigeria, and care was taken to select seeds of premium quality. Before milling, the two seeds were dried in the sun for 7 days and further in the oven at 40 °C. They were milled separately using a hammer mill (Animal ration shredder hammer mill foliage, Model: TRF 400; 1.5 kW; 10 swinging hammers). The milled seeds were sieved with 90 µm sieve openings and kept in an airtight vessel before application.

2.4. Experimental Test

Each of the storage strategies received two botanical treatments (pest management) consisting of mixing 2 kg of dried breadfruit with 100 and 150 g of dried pulverized alligator pepper (*Zingiberaceae aframomum melegueta*), and 100 and 150 g dried pulverized bitter kola (*Garcinia*), respectively. In addition, a similar experiment without treatment was set up to serve as a control. Therefore, a total of 15 experiments were set up. The treatments were categorized as follows: breadfruits stored in the aluminum silo and treated with various mass of pulverized alligator pepper, labeled as $SLAP_{100}$ and $SLAP_{150}$; breadfruits stored in the aluminum silo and treated with pulverized bitter kola were labeled as $SLBK_{100}$ and $SLBK_{150}$, while SL_0 was the control. In addition, breadfruits stored in the plastic drum and treated with pulverized alligator pepper were labeled as $RBAP_{100}$ and $RBAP_{150}$, and breadfruits stored in the plastic drum and treated with pulverized bitter kola were labeled as $RBBK_{100}$ and $RBBK_{150}$. At the same time, RB_0 serves as the control. In addition, breadfruit stored in the woven bag and treated with pulverized alligator pepper were labeled as $BGAP_{100}$ and $BGAP_{150}$, and breadfruit stored in the woven bag and treated with pulverized bitter kola were labeled as $BGBK_{100}$ and $BGBK_{150}$, while BG_0 served as the control. All containers received 2 kg of heat-treated, dehulled and dried breadfruit seed with the botanical treatment applied once at the beginning of storage. Figure 2 shows the storage strategies.

Figure 2. The different storage strategies for household preservation of breadfruit seeds.

2.5. Weight Loss and Moisture Content

The moisture content (MC) of the seeds was determined using a grain moisture meter (Kongskilde, series 20849) previously calibrated with a laboratory oven for accuracy. MC was respectively measured at 0, 6, and 12 weeks of storage. Weight loss in storage was determined by direct weighing (Camry weighing balance, ACS, 56; China) of the entire sample at the beginning of storage and after 4, 8, and 12 weeks of sampling.

2.6. Enumeration of Insects

The number of adult insects present in the stored product was counted at 6 weeks and 12 weeks of storage by sifting the 100 g sample through a sieve pan. The insects were retrieved and counted manually.

2.7. Total Mold Count

Sabouraud dextrose agar and Yeast extract agar (BDH, London, UK) for fungi and yeast count were used as the media for isolating the microorganisms. The media were prepared according to the manufacturer's instructions by sterilization at a temperature of 121 °C for 15 min in an autoclave. According to the dilution-plating method described by Cowan and Steel [34], the total mold count was determined. Tenfold serial dilution of the sample was prepared with distilled water, and 9 mL measures of diluent were placed into 9 sterile test-tubes. About 1 g of each sample was uniformly mixed and 1.0 mL was transferred into the first tube of diluent. This was done for the remaining dilutions using a fresh pipette for each to obtain different concentrations. Using the third and fifth (10^{-3} and 10^{-5} concentration) dilutions, 0.1 mL amounts of each dilution were pipetted into each of three Petri dishes. The Sabouraud dextrose agar and Yeast extract agar were added using the spread plate method. The plates were incubated at 37 °C for 24 h aerobically. Counts were taken of the colonies in the three plates that were inoculated with the dilutions of 50 and 500 colonies per plate. The discrete colonies were purified by repeated subculturing onto Sabouraud dextrose agar and Yeast extract agar until pure cultures were obtained. Pure mold isolates were streaked onto new culture plates and incubated for 48 h. The pure isolates were stored on Sabouraud dextrose agar. The average number per plate was multiplied by the dilution factor to obtain the viable count per gram of the sample [34]. The cut-off point for contamination was taken as $>10^2$ CFU/mL [35]. The samples were subjected to microbiological analysis to monitor the dynamic changes in the fungal populations. Mold isolates were identified and characterized by microscopic

morphological observations. The morphological characteristics of mold include the shape of colonies, colonial outline, colonial evaluation, color, consistency and size.

2.8. Product Quality

Fresh and stored dried breadfruit seeds were analyzed for ash, carbohydrate, fat, protein, and crude fiber content. Prior to nutritional analysis, the seeds were washed with clean water to remove any traces of the botanicals used for the treatment. The ash content was deduced by the furnace incineration gravimetric method, while the fat content was inferred via the continuous solvent extraction gravimetric method using Soxhlet apparatus as described in the Association of Official Analytical Chemists (AOAC 2007) manual [36]. The crude fiber content was deduced using the Wende method described by James [37], while the crude protein was determined by the Kjedahl method [38]. The carbohydrate content was calculated via the nitrogen-free extraction method as described by James [37].

2.9. Determination of Minerals

The dried breadfruit's mineral content was determined using the dry ash acid extraction method, as described by Carpenter and Hendricks [39]. A 5g measure of each breadfruit sample was burned to ashes in a muffle furnace at 500 °C. The ash produced was dissolved in 10 mL of 2M HCl solution and diluted to 100 mL with distilled water in a volumetric flask and filtered. The filtrate was used for mineral analysis. The mineral analysis was carried out according to Ref. [40] by employing atomic absorption spectroscopy for magnesium (Mg), calcium (Ca), phosphorus (P), iron (Fe) and zinc (Zn), and flame emission photometry for sodium (Na) and potassium (K).

2.10. Data Analysis

All the accumulated data were subjected to two-way ANOVA to test the variation in the mean between different storage approaches, periods and treatments. Turkey's HSD ($p < 0.05$) test was used to detect the mean differences between the examined traits.

3. Mathematical Modeling

3.1. Modeling of Interstitial Gaseous Exchange

According to Abelon et al. [41], the concentration of gas in a storage system is dependent on the degree of consumption or entrance of oxygen, which leads to the total combustion of carbohydrates, so the production or loss of carbon dioxide, water and heat within the storage system is as follows:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6C0_2 + 6H_2O + 2835kJ/mol \quad (1)$$

$$180g + 192g \rightarrow 264g + 108g + 2835kJ/mol \quad (2)$$

The gas exchange between the system and the environment is a function of the partial pressure difference and the permeability of the systems. Assuming uniformly distributed temperature and moisture, and ignoring respiration from insects and carbon dioxide sorption [42], the rate of heat produced during respiration, the water vapor produced and the oxygen consumed were calculated from Equations (1) and (2). These equations were used to deduce Equations (3)–(5) considering the molecular weight of carbohydrate, oxygen, carbon dioxide and water, and the heat produced according to Gaston et al. [42], as follows:

$$Y_{res} = q_h Y_{CO_2} \quad (3)$$

$$Y_{H_2O} = q_w Y_{CO_2} \quad (4)$$

$$Y_{O_2} = q_o Y_{CO_2} \quad (5)$$

where q_h, q_w, and q_o are the parameters deduced from Equation (1), while Y_{CO2} is the CO_2 release rate in mg (CO_2) kg^{-1} (dry matter) in 24 h. The Y_{CO2} was given from a generic equation presented in Ref. [43] for the oxidation of hexose, as follows:

$$\log Y_{CO_2=} q_1 + q_2 T_C - q_3\theta + q_4\theta^2 + q_5 M \quad (6)$$

where q_1, q_2, q_3, q_4 and q_5 are the regression constants presented in Table 1. Equation (6) can be adapted to suit any stored product by adding a non-unite parameter ζ, as follows:

$$\log Y_{CO_2=} \zeta \left(q_1 + q_2 T_C - q_3\theta + q_4\theta^2 + q_5 M\right) \quad (7)$$

The total amount of CO_2 produced or oxygen consumed over the storage period (% v/v) was calculated by the integration of Equation (8) overtime in days, and the result is presented in Equation (9), according to Gaston et al. [42] and Abelon et al. [41].

$$m_{CO_2}(t) = \int_0^t \overline{Y}_{CO_{2(\ t')}} d\ t' \quad (8)$$

$$x_{CO_2=\frac{Y_{CO_2}(t)}{1000M_{CO_2}}} \rho_b \times \frac{RT\ (t)}{\varepsilon\ P_{at}} \quad (9)$$

where M_{CO2} is molecular weight (44 g/mol), T is the intergranular temperature (K), P_{at} is the atmospheric pressure (1 atm = 101 325 Pa), R is the gas constant (8.314J/mol K), ε is the porosity and ρ_b is the bulk density of the stored product (kg/m^3), given as follows:

$$\rho_b = (1-\varepsilon)\rho_{sp} + \varepsilon\rho_a \quad (10)$$

where ϱ_{sp} is the density of the parboiled breadfruit, ε is the porosity of parboiled breadfruit, and ϱ_a is the density of intergranular air (kg/m^3) adapted from the density of a heated space given by Simo-Tagne et al. [44], as follows:

$$\rho_a = \frac{b}{T} \quad (11)$$

where T is the temperature (K) and b is given as 353 (kg K/m^3).

Table 1. Input parameters for the determination of gaseous exchange.

Input Parameters	Values	Source
q_1	−4.0540	[43]
q_2	0.0406	[43]
q_3	−0.0165	[43]
q_4	0–0001	[43]
q_5	0.2389	[43]
ε	0.49 for 5 min blanching	[45]
ϱ_b	632.87 kg/m^3 for 5 min blanching	[45]
ϱ_{sp}	1262.38 kg/m^3 for 5 min blanching	[45]
q_h	10.738 J/mg (CO_2)	[42]
q_w	4.09×10^{-5} kg (H_2O)/mg (CO_2)	[42]
q_o	0.7272 mg (O_2)/kg (dry matter)	[42]

3.2. Intergranular Temperature and Relative Humidity

The building (ambient) temperature and relative humidity were measured with a temperature and humidity clock (DTH-82; TLX, Guandong China). The intergranular dry bulb temperature was determined three times daily with a temperature probe (Extech, Taiwan China) inserted through the small hole made at the top of the silo and plastic container. In contrast, for the bag storage, it was inserted carefully through the body. After each measurement, the hole was sealed correctly. However, the interstitial relative humidity was determined from the vapor pressure equations, according to Abe and Basunia [46] for a stored product, as follows:

$$RH = \frac{h_{vp}}{h_{ds}} \quad (12)$$

where h_{vp} and h_{ds} are the vapor pressure and saturated vapor pressure at the dry bulb temperatures given in Equations (13) and (15), respectively, by Abe and Basunia [46] as follows:

$$h_{vp} = h_{ws} - 0.5(T_{db} - T_{wb}) \times \left(\frac{760}{755}\right) \quad (13)$$

where T_{db} and T_{wb} are the intergranular dry and wet bulb temperature, and h_{ws} is the saturated vapor pressure at the wet bulb temperature, given as:

$$h_{ws} = 4.58 \times 10^{(7.5T_{wb})/(237+T_{wb})} \quad (14)$$

$$h_{ds} = 4.58 \times 10^{(7.5T_{db})/(237+T_{db})} \quad (15)$$

The wet bulb temperature (°C) of the intergranular air was calculated from the empirical relationship presented by Fouda and Melikyan [47] for moist air, as follows,

$$T_{wb} = 2.65(1.97 + 4.3T_{db} + 1000d)^{1/2} - 14.85 \quad (16)$$

where d is the pressure parameter given in Equation (17), as follows,

$$d = \frac{0.622p_{st}}{p_{atm} - p_{st}} \quad (17)$$

where p_{atm} is the atmospheric pressure (Pa) and p_{st} is the saturated vapor pressure at the surface of the storage containers, given as Equation (18) as follows,

$$p_{st} = \exp\left(23.196 - \frac{3816.44}{T - 46.13}\right) \quad (18)$$

where T is the temperature (K).

4. Results and Discussions

4.1. Temperature, Relative Humidity and Moisture Distribution

The initial breadfruit seeds moisture was 10.2% w.b. (wet basis), while the intergranular temperature of bulk seed was recorded as 28.3 °C at the beginning of storage. The intergranular temperature variations among the storage strategies and botanical treatments are shown in Figure 3A–F. The building temperature (ambient temperature) was marginally higher than the intergranular temperatures for the botanically treated seeds, but lower than the temperature of the untreated seeds stored by different methods. This showed the stability of seeds treated botanically. Monitoring the storage temperature in bin silos has been reported as an effective way of measuring stored products' storage conditions [41]. A sharp rise in core temperature is an indication of localized heating as a result of spoilage, as shown in non-treated bin silos (Figure 3A,B), while in the case of bags, it is as a result of gaseous exchange between the core and the environment, which is influenced by the climatic conditions [48]. The mean value for the building temperature was determined as 28.78 °C, while SL_0, $SLAP_{100}$, $SLAP_{150}$, $SLBK_{100}$, $SLBK_{150}$, RB_0, $RBAP_{100}$, $RBAP_{150}$, $RBBK_{100}$, $RBBK_{150}$, BG_0, $BGAP_{100}$, $BGAP_{150}$, $BGBK_{100}$ and $BGBK_{150}$ were recorded as 29.49, 28.59, 28.66, 28.61, 28.69, 29.42, 28.64,28.73, 28.68, 28.62, 29.38, 28.68,28.72, 28.67 and 28.77 °C, respectively, with a mean building relative humidity of 73%. The observed temperature is within the temperature range of seeds stored in bins and silo bags, which is less than 30 °C [48]. It was also observed with the inclusion of non-treated samples that there was a mean temperature increase from 28.25 to 29.46 °C in the first week to a range of 28.62–29.63 °C in the fourth week. However, this average value decreased to a range of 28.59–29.49 °C in the 12th week. Nevertheless, for the storage strategies adopted, the maximum temperature difference between the building (storage room) and the intergranular temperature is less than 1.0 °C. This could be due to the small size of storage [46].

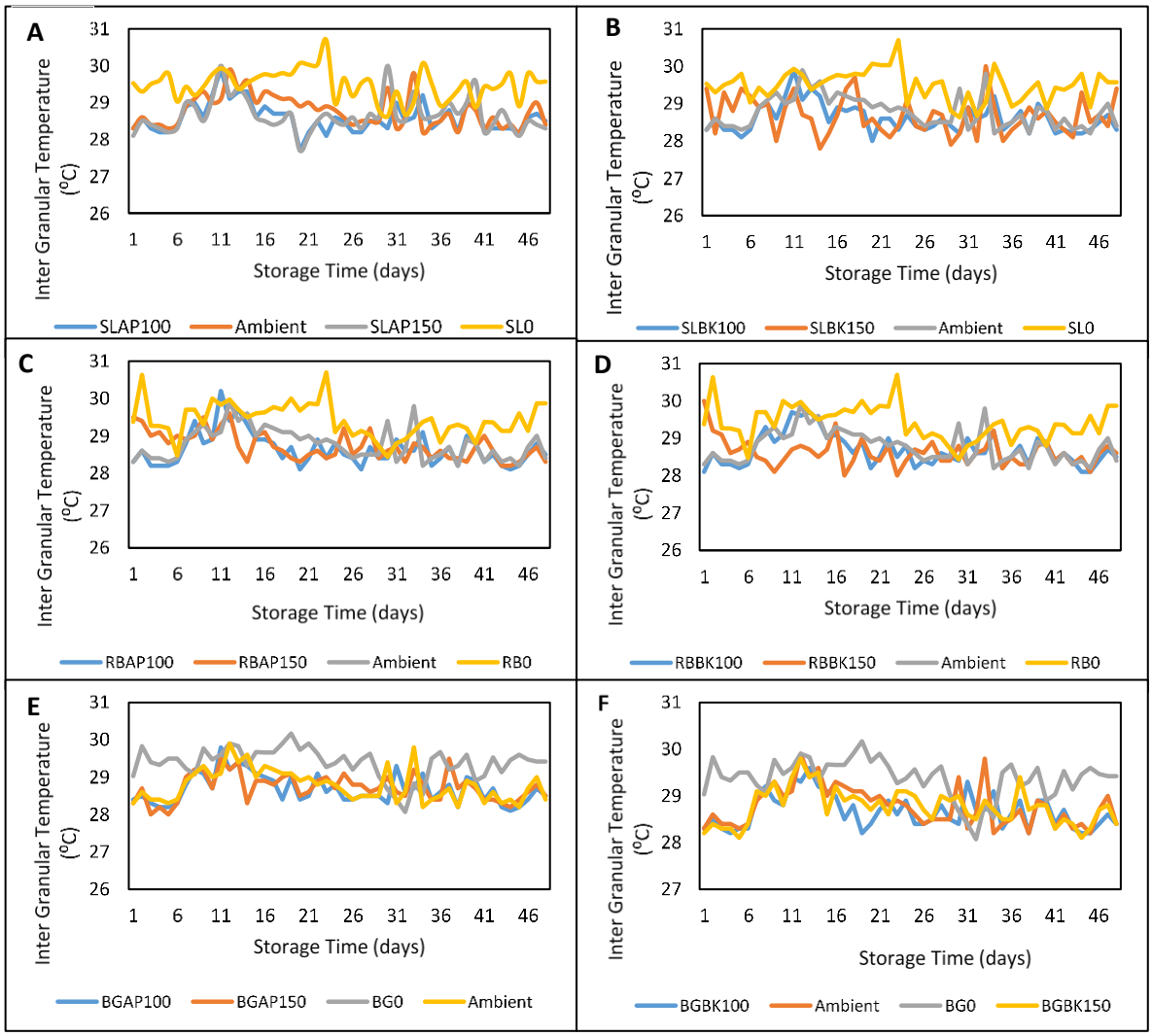


Figure 3. Intergranular temperature of the stored breadfruits for different storage methods and treatments. (**A**) Breadfruit stored in the silo and treated with aligator pepper. (**B**) Breadfruit stored in the silo and treated with bitter kola. (**C**) Breadfruit stored in the rubber and treated with aligator pepper. (**D**) Breadfruit stored in the rubber and treated with bitter kola. (**E**) Breadfruit stored in the bag and treated with bitter kola. (**F**) Breadfruit stored in the bag and treated with aligator pepper.

Stored food's shelf-life can be influenced by the initial product moisture, temperature, and weather variation during storage, which is modified by the building conditions [49–51]. Moisture uptick was recorded for all non-botanical treated stored breadfruits, as shown in Figure 4. The increase ranged from 0.09 to 5.04%, with the product stored in the silo recording the lowest moisture increase, while the silo bag recorded the highest value after 12 weeks of storage. This might result from the marginally increased temperature observed in non-botanical-treated storage compared to the ambient values (Figure 3). However, considering the moisture content of the botanically treated breadfruits, the moisture contents of those treated with alligator pepper decreased consistently. In contrast, those treated with bitter kola increased within the first six weeks but decreased later when checked at 12 weeks. The variation in the seed moisture content of the different storage methods and pest management strategies could be due to the possible condensation of air occasioned by the temperature drop in the intergranular spaces, or between the storage spaces [52]. Besides this, the vapor emitted by biomaterials due to biological processes might have contributed to the uptick in seed moisture [53,54]. On the other hand, seed moisture with alligator pepper tends to drop due to the lower biological activities. Therefore, it can be stated that the alligator pepper can serve as a drying agent in stored

products. A significant ($p < 0.05$) moisture decrease was observed between those treated with alligator pepper when the amount of alligator pepper increased from 100 to 150 g, while it was not significant ($p < 0.05$) when compared, under the same storage method, with those treated with bitter kola. However, a significant difference ($p < 0.05$) exists between the moisture levels measured for those treated with the same amounts of alligator pepper and bitter kola. Again, for different silo storage strategies, there were significant differences ($p > 0.05$) among the same amounts of treated material.

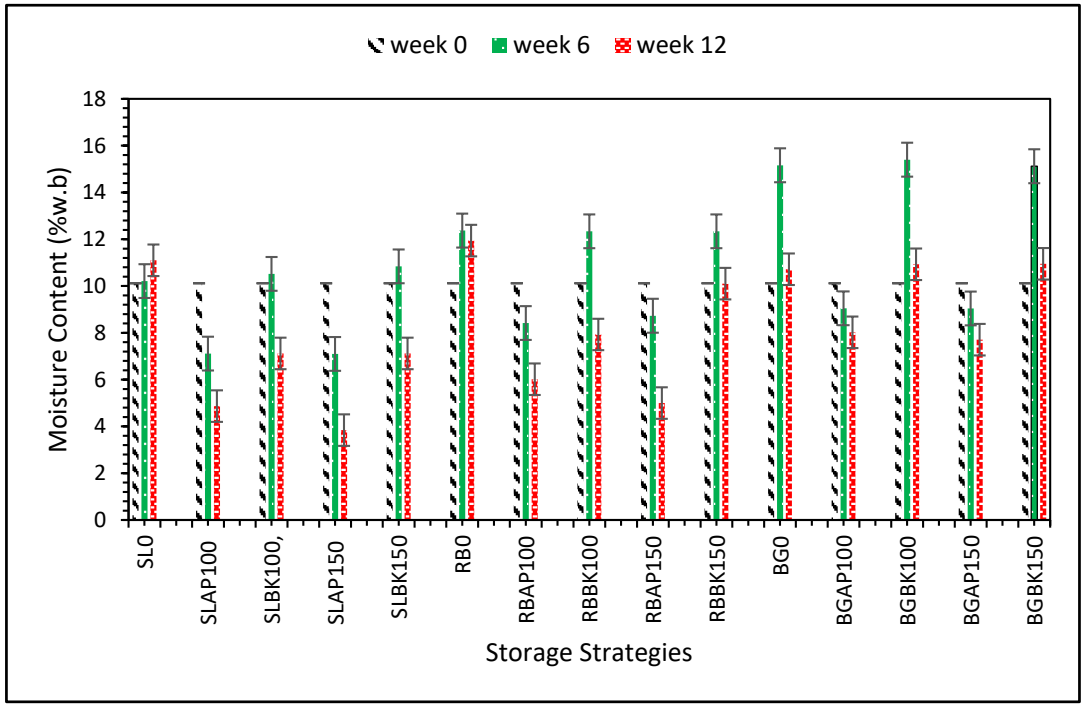


Figure 4. Variation in moisture content for different storage strategies within selected weeks.

The ambient relative humidity is shown in Figure 5. The weather pattern highly influences relative humidity in the storage room. The room relative humidity will increase during the ambient peak humidity, while the temperature drops, and vice versa. The ambient relative humidity ranged from 71 to 76%, with an average value of 73%. This is relatively high, which is common in most tropical rainforest zones, making it difficult to achieve stability in natural storage because of the influence of relative humidity on microbial developments. The value of the ambient relative humidity will also influence the interstitial humidity due to environmental interactions between the storage space and the external environment. In addition, the internal heat of the storage product can also affect the relative humidity of the intergranular space.

The interstitial relative humidity was predicted using Equations (12)–(18), and is presented in Figure 6A–F for different storage strategies. The simulated relative humidity and wet bulb temperature were deduced from the measured interstitial temperature, and therefore varied as the interstitial temperature varied. In addition, from Figure 4, we can see that the products desorb or adsorb moisture from the interacting environment due to the storage strategies and management approach adopted, which might have affected the intergranular temperature vis-a-vis the interstitial relative humidity profile. For all the storage strategies, the interstitial relative humidity ranged from 29.86 to 34.25%. The lower relative humidity obtained is a result of the dried nature of the product. However, due to the high ambient relative humidity and temperature, it is possible to have water accumulate on the walls of the silo bin and the plastic containers. The introduction of alligator pepper, in particular, seemed to function as a drying agent for the product.

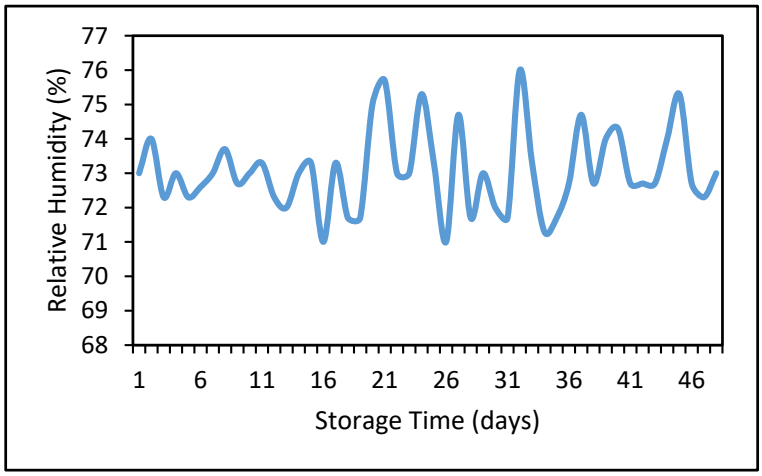
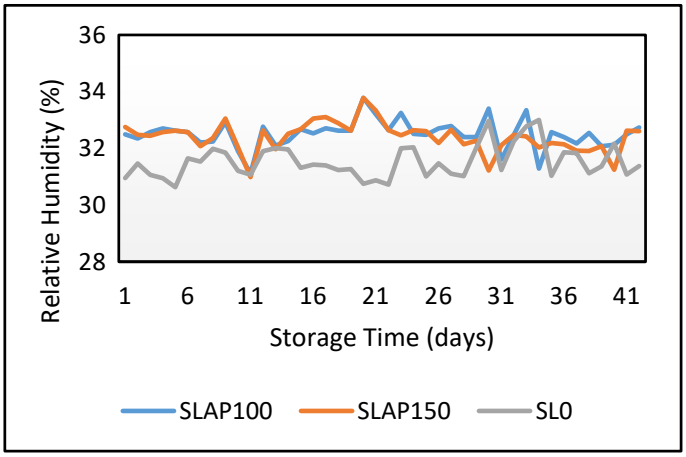
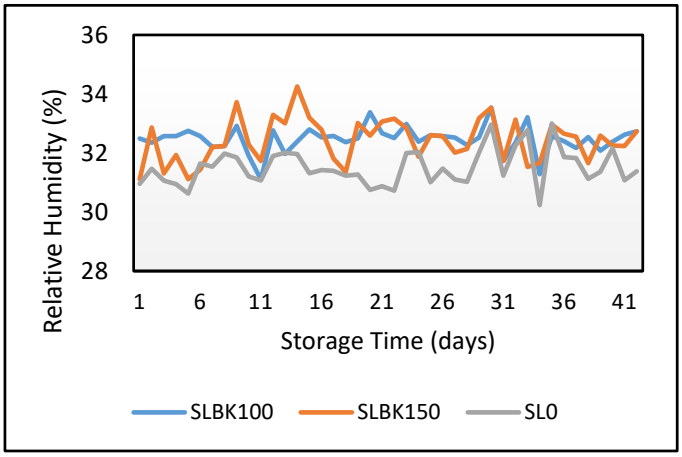


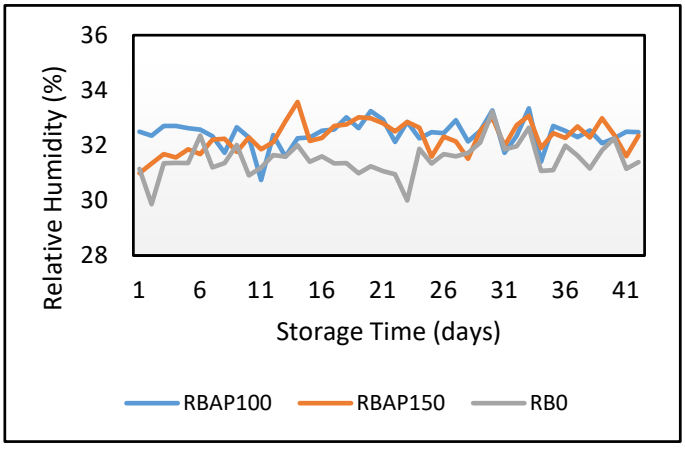
Figure 5. Ambient relative humidity during the storage of breadfruit seeds.



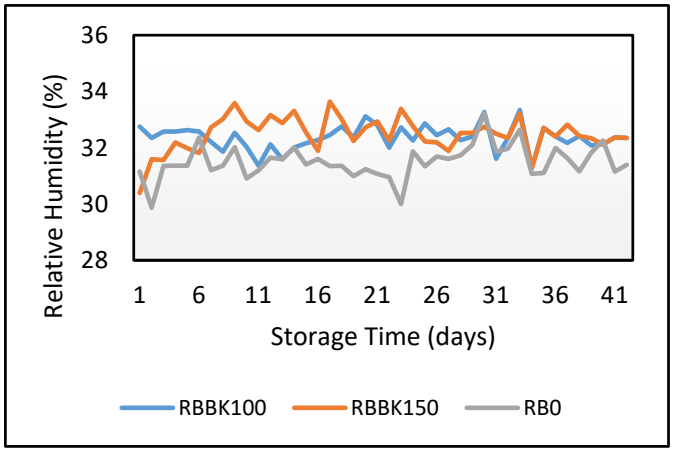
(**a**)



(**b**)



(**c**)



(**d**)

Figure 6. *Cont.*

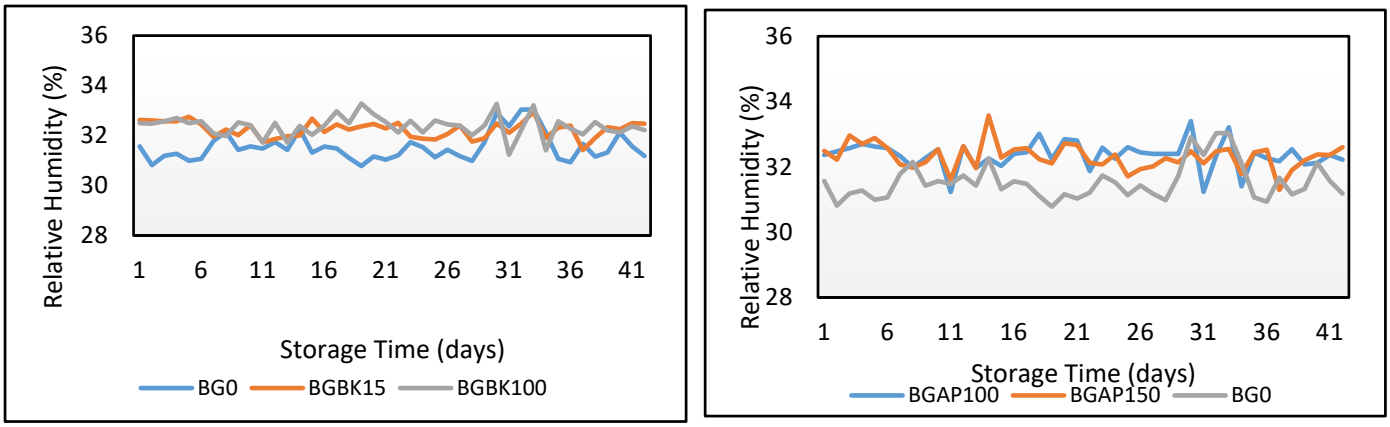


Figure 6. Relative humidity of different storage methods and treatments. (**a**) Breadfruit stored in the silo and treated with aligator pepper. (**b**) Breadfruit stored in the silo and treated with bitter kola. (**c**) Breadfruit stored in the rubber and treated with aligator pepper. (**d**) Breadfruit stored in the rubber and treated with bitter kola. (**e**) Breadfruit stored in the bag and treated with aligator pepper. (**f**) Breadfruit stored in the bag and treated with bitter kola.

4.2. Insect Enumeration

At the beginning of the storage period, no insect infestations were observed, but after four weeks, *Tribolium casteneum* (Figure 7) was observed in all storage strategies except for the untreated and alligator pepper-treated breadfruits stored in silo, as shown in Table 2. These values significantly ($p < 0.05$) increased by 12 weeks of storage, with infestations now noticed in all storage strategies. However, during the counting of the insects, it was observed that not all the insects were alive, even though the ratio of dead and living insects was not separated; the total insects in the infestations were enumerated together. Quantifying the ratio of dead and living insects for future insect mortality prediction in the treated samples could be a future gap to be filled.

Nonetheless, silo storage treatment with alligator pepper demonstrated lower total insect infestation, followed by rubber containers, while infestations were very high in bag storage. It has been reported that metal silos can eliminate insects from the stored product due to a shortage of oxygen [19]. However, since the silo is not fully filled and there is the possibility of space between the bearing and the stirring shaft, air could have been introduced into the silo. This is because as little as 15% oxygen is enough for insects to thrive [55]. Therefore, from this study, we deduce that none of the storage strategies could stop the proliferation of insects beyond four weeks.

Figure 7. *Tribolium casteneum* on the stored breadfruit seeds after four weeks.

Table 2. Average live and dead insects (*Tribolium casteneum*) for different storage strategies for selected weeks.

Sample	4 Weeks	12 Weeks
SL_0	0.0 ± 0.0	3.3 ± 0.8
$SLAP_{100}$	0.0 ± 0.0	4.5 ± 0.5
$SLAP_{150}$	0.0 ± 0.0	3.0 ± 0.4
$SLBK_{100}$	3.2 ± 1.5	8.2 ± 2.5
$SLBK_{150}$	3.4 ± 1.2	7.4 ± 0.9
RB_0	2.1 ± 0.5	4.0 ± 1.5
$RBAP_{100}$	2.4 ± 1.1	5.0 ± 1.5
$RBAP_{150}$	5.2 ± 1.5	9.4 ± 0.5
$RBBK_{100}$	4.4 ± 1.1	10.3 ± 3.6
$RBBK_{150}$	2.0 ± 0.3	6.2 ± 0.4
BG_0	3.0 ± 0.7	6.0 ± 0.2
$BGAP_{100}$	4.1 ± 1.5	6.0 ± 1.5
$BGAP_{150}$	2.8 ± 0.6	6.4 ± 0.7
$BGBK_{100}$	2.0 ± 0.2	7.3 ± 1.6
$BGBK_{150}$	3.2 ± 0.4	9.4 ± 1.8

4.3. Microbial Analysis

The mold counts after 4, 8 and 12 weeks of storage are presented in Table 3. The mold counts increased as the weeks went by. While the increase in carbon dioxide or the lower oxygen levels slowed the insect infestation on a modified atmosphere-stored product, this was not efficient in stopping mold proliferation. However, the mold's ability to attack the product tissues can be delayed [48,56]. From the results presented in Table 3, we see that treating the product with 100 g of alligator pepper and bitter kola increased the mold count. However, when the treatments were increased to 150 g, the fungi count decreased under the same storage condition. However, non-treated bag storage had the highest average mold count of 1.093×10^3 CFU/mL, while silo-stored breadfruit treated with 150 g alligator pepper had the lowet mold count of 0.26×10^3 CFU/mL. The lower mold count observed in alligator pepper-treated samples can be associated with its lower moisture content compared to others, as shown in Figure 4. When products treated with 100 g botanicals were compared to non-treated products for silo and plastic container storage, we saw that non-treated products had lower mold count. This implies that the botanicals, being biological material, are subject to decay over time, and might have contributed to the increased mold count. Three mold species were predominantly isolated from the mold analysis for each storage strategy, i.e., *Aspergillus niger*, *Aspergillus sp* and *Rhodotorula sp*. However, *Aspergillus sp*, was predominantly isolated for most of the storage methods and treatments. The predominance of *Rhodotorula sp* in the plastic container ($RBAP_{100}$), unlike other storage methods, might be due to its opportunistic infection nature and affinity to plastic, as reported in the literature [57]. However, none of the storage strategies could stop mold growth after four weeks of storage completely.

Table 3. Average fungi counts for different storage strategies and dominant mold species detected.

Sample	Mean Mold Count ($\times 10^3$ CFU/mL)	Dominant Mold Specie Detected
SL_0	0.443 ± 0.00312	*Aspergillus niger*
$SLAP_{100}$	0.577 ± 0.00249	*Aspergillus niger*
$SLAP_{150}$	0.26 ± 0.00196	*Aspergillus sp*
$SLBK_{100}$	0.49 ± 0.00330	*Aspergillus niger*
$SLBK_{150}$	0.33 ± 0.00312	*Aspergillus sp*
RB_0	0.347 ± 0.00220	*Aspergillus niger*
$RBAP_{100}$	0.703 ± 0.00401	*Rhodotorula sp*
$RBAP_{150}$	0.677 ± 0.00596	*Aspergillus sp*

Table 3. *Cont.*

Sample	Mean Mold Count ($\times 10^3$ CFU/mL)	Dominant Mold Specie Detected
$RBBK_{100}$	0.833 ± 0.00605	*Aspergillus sp*
$RBBK_{150}$	0.697 ± 0.00420	*Aspergillus sp*
BG_0	1.093 ± 0.00681	*Aspergillus niger*
$BGAP_{100}$	0.93 ± 0.0040	*Aspergillus sp*
$BGAP_{150}$	0.36 ± 0.00157	*Aspergillus sp*
$BGBK_{100}$	0.283 ± 0.00159	*Aspergillus sp*
$BGBK_{150}$	0.59 ± 0.00467	*Aspergillus sp*

4.4. Proximate Analysis and Mineral Composition

Proximate composition assessment was carried out at the beginning, and after 6 weeks and 12 weeks of storage, and the concentrations of crude protein, fat, ash, and carbohydrates are presented in Table 4. The maximum decrease in crude protein concentration from the initial value was about 30.22% in the silo storage-treated samples with and without alligator pepper, and the reduction was about 75.27% for those treated with bitter kola within the first six weeks of storage. A similar magnitude of depreciation in crude protein was observed for other treatments with the same storage methods. Storage time influenced the nutritional composition. The chemical process occurs during the storage of crops due to either respiration or chemical decomposition, reducing the nutritional values [58]. Among storage methods with the same types of botanical treatments, crude protein values were not significant ($p < 0.05$), but they were significant ($p > 0.05$) when compared among the different botanical treatments of the same storage method (Table 4). The crude fiber increased for all storage strategies, while crude fat decreased. The loss in crude fat for botanical treatment with and without alligator pepper was steeper, reaching a 61.42 to 65.64% loss in crude fat for all storage strategies. Samples treated with bitter kola lost between 25.4 and 34.84%, which shows that the bioconversion effect of bitter kola on crude fat is high, and might have contributed to the smaller reduction observed than in the non-treated samples. The ash content increased for those treated with or without alligator pepper, but decreased for those treated with bitter kola. However, the carbohydrate and crude fiber contents did not significantly ($p > 0.05$) change for all treatments. The mineral compositions of sodium (Na), magnesium (Mg), calcium (Ca), phosphorus (P), potassium (K), iron (Fe) and zinc (Zn) of the stored products remained inferior to the initial values, except for phosphorous, which increased as shown in Table 5. The values of P, K, and Fe were higher in the alligator pepper-treated products stored in the silo than in other storage methods. This might be due to more negligible microbial and fungi attacks on products treated with alligator pepper. Alligator pepper contains alkaloids, tannins, saponin, steroids, cardiacglycoside, flavonoid and terpenoids, among other antimicrobial and antifungal agents [27]. Therefore, due to the antimicrobial and antifungal potency, alligator pepper-treated products stored in the silo will contain higher mineral contents than products stored using other methods in this study. Similar observations have been made by Ubani et al. [59] in the storage of oilseeds. An adequately stored oil seed with 6–8% moisture content always shows chemical and mineral stability [59].

Table 4. Proximate composition of stored breadfruits with different storage strategies.

Storage Method	Crude Protein (%)	Crude Fiber (%)	Crude Fat (%)	Ash (%)	Carbohydrates (%)	KcalEV
Initial values (0 weeks)	10.72 ± 1.5	4.69 ± 1.15	6.17 ± 1.02	2.21 ± 0.08	78.11 ± 1.5	342.79 ± 23.3
6 weeks						
SL_0	7.48 ± 0.15	5.20 ± 0.35	2.38 ± 0.00	2.42 ± 0.10	75.40 ± 3.3	352.94 ± 18.9
$SLAP_{100}$	7.49 ± 0.02	5.21 ± 0.45	2.39 ± 0.51	2.43 ± 0.00	75.39 ± 2.5	352.95 ± 34.2
$SLAP_{150}$	7.49 ± 0.11	5.22 ± 0.05	2.39 ± 0.45	2.43 ± 0.05	75.37 ± 4.1	352.95 ± 40.3
$SLBK_{100}$	2.66 ± 0.05	5.15 ± 0.85	4.61 ± 0.15	1.18 ± 0.01	76.19 ± 6.8	356.87 ± 42.2
$SLBK_{150}$	2.65 ± 0.05	5.36 ± 0.63	4.6 ± 0.72	1.17 ± 0.01	76.21 ± 4.5	356.84 ± 52.0
RB_0	7.26 ± 0.24	5.14 ± 0.44	2.32 ± 0.43	2.36 ± 0.04	74.51 ± 2.5	347.96 ± 11.20
$RBAP_{100}$	7.24 ± 0.35	5.13 ± 0.41	2.33 ± 0.11	2.35 ± 0.05	74.54 ± 3.7	348.03 ± 1.80
$RBAP_{150}$	7.22 ± 0.05	5.12 ± 0.51	2.33 ± 0.86	2.34 ± 0.06	74.56 ± 4.3	348.09 ± 11.11
$RBBK_{100}$	2.48 ± 0.15	5.06 ± 0.53	4.55 ± 0.54	1.15 ± 0.01	74.42 ± 8.5	348.49 ± 18.9
$RBBK_{150}$	2.47 ± 0.01	5.09 ± 0.51	4.56 ± 0.51	1.16 ± 0.02	74.40 ± 6.5	348.52 ± 36.7
BG_0	7.20 ± 0.16	5.1 ± 0.57	2.24 ± 0.36	2.3 ± 0.00	74.10 ± 5.7	345.36 ± 44.4
$BGAP_{100}$	7.22 ± 0.22	5.11 ± 0.41	2.23 ± 0.29	2.31 ± 0.10	74.10 ± 7.5	345.31 ± 51.9
$BGAP_{150}$	7.23 ± 0.42	5.11 ± 0.81	2.22 ± 0.33	2.31 ± 0.08	74.09 ± 5.5	345.26 ± 45.8
$BGBK_{100}$	2.42 ± 0.02	4.92 ± 0.64	4.41 ± 0.22	1.13 ± 0.02	72.00 ± 3.6	337.29 ± 61.8
$BGBK_{150}$	2.43 ± 0.02	4.92 ± 0.53	4.4 ± 0.51	1.14 ± 0.02	71.99 ± 1.8	337.28 ± 21.1
12 weeks						
SL_0	9.14 ± 0.11	5.49 ± 0.27	2.27 ± 0.08	2.53 ± 0.12	76.68 ± 8.5	363.71 ± 5.59
$SLAP_{100}$	9.15 ± 0.08	5.50 ± 0.47	2.28 ± 0.04	2.53 ± 0.05	76.69 ± 4.5	363.86 ± 2.51
$SLAP_{150}$	9.16 ± 1.01	5.5 ± 0.52	2.29 ± 0.27	2.52 ± 0.03	76.69 ± 6.3	364.01 ± 6.53
$SLBK_{100}$	3.21 ± 0.07	5.41 ± 0.35	4.27 ± 0.22	1.7 ± 0.01	78.31 ± 8.8	364.45 ± 10.1
$SLBK_{150}$	3.2 ± 0.030	5.41 ± 0.05	4.25 ± 0.31	1.71 ± 0.05	78.31 ± 6.1	364.29 ± 18.24
RB_0	9.03 ± 0.080	5.37 ± 0.75	2.21 ± 0.44	2.3 ± 0.06	76.06 ± 7.4	360.25 ± 27.7
$RBAP_{100}$	9.04 ± 1.12	5.38 ± 0.11	2.21 ± 0.18	2.32 ± 0.01	76.05 ± 4.6	360.19 ± 8.8
$RBAP_{150}$	9.04 ± 1.09	5.39 ± 0.64	2.2 ± 0.59	2.33 ± 0.01	76.04 ± 9.2	360.12 ± 38.2
$RBBK_{100}$	3.15 ± 0.02	5.32 ± 0.62	4.17 ± 0.15	1.05 ± 0.01	78.39 ± 4.0	363.69 ± 41.2
$RBBK_{150}$	3.16 ± 0.25	5.31 ± 0.29	4.18 ± 0.52	1.06 ± 0.03	78.38 ± 3.5	363.78 ± 19.34
BG_0	7.05 ± 0.15	5.3 ± 0.880	2.14 ± 0.43	2.14 ± 0.10	77.62 ± 6.1	357.94 ± 10.8
$BGAP_{100}$	7.06 ± 0.15	5.32 ± 0.12	2.13 ± 0.50	2.15 ± 0.02	77.62 ± 7.3	357.90 ± 15.5
$BGAP_{150}$	7.06 ± 1.20	5.33 ± 0.32	2.12 ± 0.59	2.16 ± 0.02	77.62 ± 5.8	357.8 ± 12.35
$BGBK_{100}$	2.21 ± 0.00	5.23 ± 0.09	4.03 ± 0.06	1.01 ± 0.03	78.60 ± 6.2	359.45 ± 28.3
$BGBK_{150}$	2.21 ± 0.03	5.21 ± 0.86	4.02 ± 0.17	1.00 ± 0.02	78.61 ± 1.5	359.46 ± 22.97

Table 5. Variation in the mineral compositions of the stored breadfruits using different strategies.

Storage Method	Na	Mg	Ca	P	K	Fe	Zn
Initial values	9.32 ± 0.85	1.71 ± 0.11	1.40 ± 0.40	1.13 ± 0.01	11.34 ± 2.5	1.88 ± 0.22	2.03 ± 0.42
6 weeks							
SL_0	1.01 ± 0.00	1.14 ± 0.05	1.25 ± 0.13	1.38 ± 0.21	2.06 ± 0.85	0.42 ± 0.10	0.83 ± 0.00
$SLAP_{100}$	1.02 ± 0.00	1.14 ± 0.22	1.25 ± 0.10	1.38 ± 0.20	2.05 ± 0.25	0.41 ± 0.00	0.82 ± 0.04
$SLAP_{150}$	1.02 ± 0.01	1.13 ± 0.12	1.24 ± 0.13	1.37 ± 0.10	2.04 ± 0.56	0.04 ± 0.01	0.81 ± 0.01
$SLBK_{100}$	1.93 ± 0.01	1.31 ± 0.08	1.86 ± 0.08	4.17 ± 0.73	10.33 ± 3.6	2.38 ± 0.09	0.53 ± 0.01
$SLBK_{150}$	1.92 ± 0.01	1.30 ± 0.22	1.85 ± 0.20	4.15 ± 0.87	10.31 ± 2.5	2.37 ± 0.05	0.52 ± 0.00
RB_0	0.92 ± 0.02	1.10 ± 0.05	1.20 ± 0.00	1.29 ± 0.02	2.01 ± 0.08	0.40 ± 0.04	0.80 ± 0.01
$RBAP_{100}$	0.92 ± 0.03	1.13 ± 0.03	1.21 ± 0.84	1.28 ± 0.02	2.02 ± 0.50	0.41 ± 0.05	0.80 ± 0.00
$RBAP_{150}$	0.91 ± 0.01	1.13 ± 0.15	1.22 ± 0.25	1.27 ± 0.05	2.02 ± 0.15	0.42 ± 0.05	0.80 ± 0.00
$RBBK_{100}$	1.92 ± 0.05	1.27 ± 0.06	1.82 ± 0.09	4.01 ± 1.50	10.12 ± 3.33	2.31 ± 0.25	0.52 ± 0.10
$RBBK_{150}$	1.93 ± 0.03	1.27 ± 0.18	1.81 ± 0.16	4.0 ± 1.55	10.13 ± 2.50	2.32 ± 0.21	0.52 ± 0.00
BG_0	0.84 ± 0.10	1.10 ± 0.11	1.12 ± 0.08	1.20 ± 0.11	1.93 ± 0.25	0.32 ± 0.00	0.72 ± 0.08
$BGAP_{100}$	0.83 ± 0.03	1.11 ± 0.01	1.12 ± 0.33	1.22 ± 0.00	1.92 ± 0.53	0.32 ± 0.00	0.72 ± 0.11

Table 5. *Cont.*

Storage Method	Na	Mg	Ca	P	K	Fe	Zn
$BGAP_{150}$	0.82 ± 0.02	1.12 ± 0.07	1.12 ± 0.06	1.23 ± 0.02	1.91 ± 0.51	0.31 ± 0.00	0.71 ± 0.13
$BGBK_{100}$	1.81 ± 0.04	1.27 ± 0.08	1.81 ± 0.06	3.92 ± 0.84	10.02 ± 1.5	2.24 ± 0.80	0.46 ± 0.01
$BGBK_{150}$	1.80 ± 0.02	1.26 ± 0.11	1.82 ± 0.12	3.92 ± 0.11	10.01 ± 2.5	2.23 ± 0.53	0.46 ± 0.00
12 weeks							
SL_0	1.02 ± 0.00	1.13 ± 0.05	1.25 ± 0.13	1.34 ± 0.21	2.03 ± 0.85	0.43 ± 0.10	0.81 ± 0.00
$SLAP_{100}$	1.07 ± 0.00	1.21 ± 0.17	1.35 ± 0.34	1.61 ± 0.04	2.17 ± 0.35	0.44 ± 0.00	0.88 ± 0..23
$SLAP_{150}$	1.06 ± 0.01	1.20 ± 0.16	1.34 ± 0.18	1.60 ± 0.06	2.15 ± 0.80	0.43 ± 0.00	0.88 ± 0.01
$SLBK_{100}$	2.08 ± 0.00	1.36 ± 0.31	1.95 ± 0.19	4.31 ± 1.80	10.82 ± 2.11	2.45 ± 0.06	0.61 ± 0.02
$SLBK_{150}$	2.07 ± 0.01	1.34 ± 0.05	1.94 ± 0.28	4.32 ± 0.04	10.82 ± 2.6	2.44 ± 0.04	0.61 ± 0.06
RB_0	0.92 ± 0.02	1.12 ± 0.05	1.20 ± 0.00	1.29 ± 0.02	2.01 ± 0.08	0.40 ± 0.04	0.80 ± 0.01
$RBAP_{100}$	0.92 ± 0.08	1.12 ± 0.00	1.18 ± 0.03	1.24 ± 0.05	1.94 ± 0.03	0.35 ± 0.00	0.83 ± 0.01
$RBAP_{150}$	0.91 ± 0.2	1.10 ± 0.08	1.17 ± 0.03	1.22 ± 0.00	1.93 ± 0.11	0.33 ± 0.01	0.82 ± 0.01
$RBBK_{100}$	2.01 ± 0.6	1.22 ± 0.16	1.82 ± 0.12	3.92 ± 0.94	9.87 ± 1.34	2.20 ± 0.12	0.46 ± 0.00
$RBBK_{150}$	2.01 ± 0.08	1.21 ± 0.08	1.83 ± 0.17	3.10 ± 0.11	9.85 ± 0.98	2.20 ± 0.43	0.46 ± 0.01
BG_0	0.84 ± 0.10	1.10 ± 0.11	1.12 ± 0.08	1.20 ± 0.11	1.93 ± 0.25	0.32 ± 0.00	0.72 ± 0.08
$BGAP_{100}$	0.75 ± 0.23	0.84 ± 0.13	1.01 ± 0.03	1.11 ± 0.02	1.72 ± 0.44	0.25 ± 0.00	0.64 ± 0.09
$BGAP_{150}$	0.73 ± 0.11	0.83 ± 0.20	1.00 ± 0.00	1.10 ± 0.07	0.72 ± 0.35	0.24 ± 0.02	0.64 ± 0.11
$BGBK_{100}$	1.63 ± 0.21	1.04 ± 0.00	1.63 ± 0.01	3.62 ± 1.1	8.68 ± 2.87	2.02 ± 0.50	0.40 ± 0.05
$BGBK_{150}$	1.64 ± 0.10	1.02 ± 0.02	1.62 ± 0.02	3.61 ± 0.03	8.66 ± 2.08	2.00 ± 0.42	0.40 ± 0.02

4.5. Analysis of Gaseous Exchange

The gaseous concentrations in the stored product showed changes as the days progressed. The CO_2 concentration at the beginning of storage was 0, but increased to 0.13–0.14 (% v/v) in the first week of storage, as shown in Figure 8A. The CO_2 concentration ranged from 0.16 to 0.47 (% v/v) at the sixth weeks, and 0.57 to 3.98 (% v/v) in the twelfth week for all treatments in the silo bin storage. Other storage strategies ranged from 0.12–1.09 (% v/v) to 1.09–9.6 (% v/v) for plastic container, and 0.19–6.55 (% v/v) to 5.12–10.81 (% v/v) for silo bag, respectively. The concentration of CO_2 was lower in the silo bin-treated samples with 150 g of alligator pepper, and higher in the silo bag-treated samples with 100 g bitter kola. A higher CO_2 concentration results in limited oxygen availability as more oxygen is consumed, higher water vapor production, and a higher heat release rate, as shown in Figure 8B–D for blanched and dehulled breadfruits storage. The concentration of CO_2 and O_2 availability depends on the respiratory capacity of the stored seed, the infiltration of external O_2 and the loss of CO_2 to the storage building [41].

Storage strategies with higher moisture content showed higher CO_2 concentration, higher O_2 consumption with more water vapor, and higher energy release rate. As such, a greater tendency to spoilage from fungi infestation could have resulted in the higher fungi count observed in Table 2. This is in tandem with other similar studies that reported that higher moisture content increases the CO_2 concentration of stored bio-products [48,60]. In the first week of storage, the moisture content was almost the same. The observed CO_2 concentration showed no significant difference ($p < 0.05$), but a significant difference was observed as the storage time increased to 6 weeks and 12 weeks. Higher respiration occurs due to the increased moisture content and depletion of oxygen, as observed in Figure 8B,C. For the weeks analyzed, respiration reached its peak at 6 weeks and decreased in the 12th week, which was reflected in the high oxygen depletion peaking in the same week (6) before going down in week 12 for all storage strategies. Due to the lower moisture content of the silo bin with alligator pepper, they also had lower respiration heat and CO_2 concentration values. At the same time, the bag storage method had a higher CO_2 concentration due to the higher moisture content, which resulted probably from environmental interference.

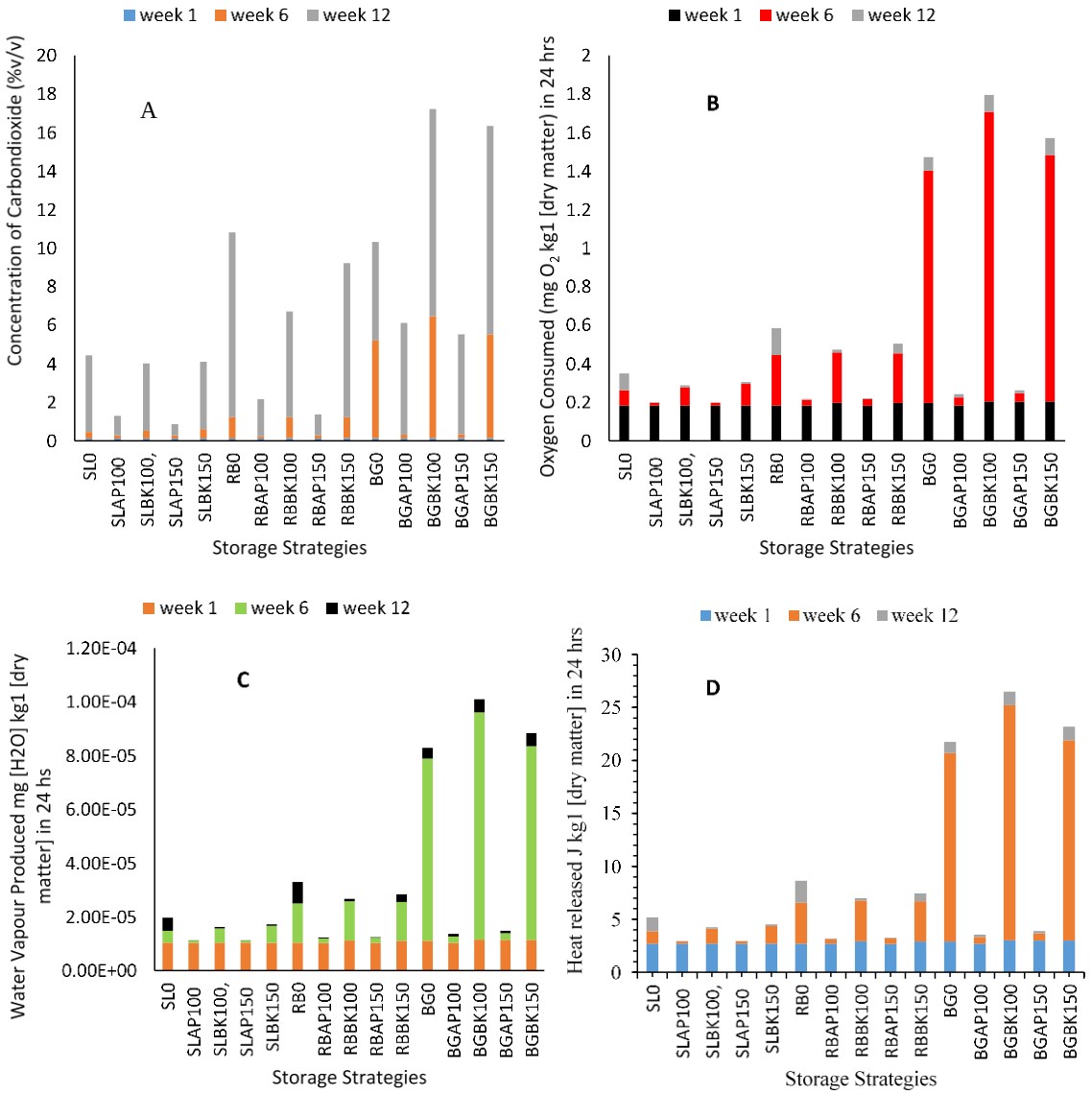


Figure 8. Gaseous exchange of breadfruit seeds for different storage strategies. (**A**) CO_2 concentration. (**B**) O_2 consumption. (**C**) Water vaper production. (**D**) Heat release.

5. Conclusions

The present study evaluates the effectiveness of different local storage methods and botanical treatments to preserve blanched, dehulled, and dried breadfruit seeds under small-scale household conditions in a tropical rainforest environment with very high ambient humidity. Non-treated bag storage had the highest average mold count of 1.093×10^2 CFU/mL, while silo bin-stored breadfruit treated with 150 g of alligator pepper had the lowest mold count of 0.26×10^2 CFU/mL. *Aspergillus niger*, *Aspergillus sp* and *Rhodotorula sp* were the predominant mold species isolated; however, *Aspergillus sp* was dominant. The storage time influenced both the nutritional and mineral quality; regardless, products stored in a plastic container and weaved silo bags were inferior compared to those stored in the aluminum silo bin. Insect infestations were low in alligator pepper-treated seeds, as the seed continued to desorb moisture in storage, unlike other treatments. Silo bins had a comparatively lower *Tribolium casteneum* attack, and this did not happen until after 2 months. The concentration of CO_2 was lower in the silo bin samples treated with 150 g alligator pepper, and higher in the silo bag-treated samples with 100 g bitter kola nut. A higher CO_2 concentration resulted in limited oxygen availability, higher water vapor production, and a higher heat release rate. The analysis of the various results showed that

adopting the mini silo bin storage with treated alligator pepper can help in the short-term storage of blanched breadfruit, achieving better quality and an extended shelf-life, which most households aim to achieve.

Author Contributions: M.C.N.: conceptualization, methodology, supervision, project administration, data analysis, writing—original draft, review and editing. D.I.O.: methodology, review and editing. J.E.: review and editing: U.C.A.: review and editing. I.E.E.: review and editing. G.C.: review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: The authors acknowledge Ndkuwu's 2018/2019 undergraduate project students and Postgraduate Diploma students for helping in data collection for this project.

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

References

1. Onyekwelu, J.C.; Fayose, O.J. Effect of storage methods on germination and proximate composition of Treculia africana seeds. In Proceedings of the Conference on International Agricultural Research for Development, University of Kassel-I-Witzen-hausen and University of Gottigen, Tropentag, October 2007.
2. Osuji, J.O.; Owei, S.D. Mitotic index studies on Treculia africana Decne in Nigeria. *Aust. J. Agric. Eng.* **2010**, *1*, 25–28.
3. Osukoya, O.; Nwoye-Ossy, M.; Olayide, I.; Ojo, O.; Adewale, O.; Kuku, A. Antioxidant activities of peptide hydrolysates obtained from the seeds of Treculia africana Decne (African breadfruit). *Prep. Biochem. Biotechnol.* **2020**, *50*, 504–510. [CrossRef]
4. Adewole, E.; Ogunmodede, O.T.; Adeniran, O.A.; Talabi, J.; Lajide, L. Rheological properties and fatty acid of seedless bread fruit (Artocarpus altilis). *Arch. Appl. Sci. Res.* **2011**, *3*, 80–86.
5. Okafor, V.C.; Chinweuba, D.C.; Ejesu, P.K.; Nwakuba, R.N. Some Selected Physical Properties of Parboiled Breadfruit Seeds (Treculia africana). *Greener J. Sci. Eng. Technol. Res.* **2016**, *6*, 19–26. [CrossRef]
6. Adindu, M.N.; Williams, J.O. Effect of storage on dehydrated African breadfruit seeds (Treculia africana Decne). *Plant Foods Hum. Nutr.* **2004**, *58*, 1–8. [CrossRef]
7. Nwabueze, T. Kernel extraction and machine efficiency in dehulling parboiled african breadfruit (Treculia africanadecne) whole seeds. *J. Food Qual.* **2009**, *32*, 669–683. [CrossRef]
8. Ugwu, C.S.; Iwuchukwu, J.C. Processing and preservation of African bread fruit (Treculia africana) by women in Enugu North agricultural zone, Enugu State, Nigeria. *Afr. J. Agric. Res.* **2013**, *8*, 984–994. [CrossRef]
9. Ijeh, I.I.; Ejike, E.C.; Nkwonta, O.M.; Njoku, B.C. Effect of Traditional Processing Techniques on the Nutri-tional and Phytochemical Composition of African Bread-Fruit (Treculia africana) Seeds. *J. Appl. Sci. Environ. Manag.* **2010**, *14*, 169–173.
10. Mugo, N.C.; Nderi, M.J.; Kimondo, M. Effect of Diatomaceous Earths on Mortality, Progeny and Weight Loss Caused by Three Primary Pests of Maize and Wheat in Kenya. *Int. J. Sci. Technol. Soc.* **2015**, *3*, 76. [CrossRef]
11. Amadou, L.; Baoua, I.B.; Baributsa, D.; Williams, S.B.; Murdock, L.L. Triple bag hermetic technology for control-ling a bruchid (Spermophagus sp.) (Coleoptera: Chrysomelidae) in stored Hibiscus sabdariffa grain. *J. Stored Prod. Res.* **2016**, *69*, 22–25. [CrossRef]
12. Nwaubani, S.I.; Otitodun, G.O.; Ajao, S.K.; Opit, G.P.; Ala, A.A.; Omobowale, M.O.; Ogwumike, J.C.; Abel, G.I.; Ogundare, M.O.; Braimah, J.A.; et al. Assessing efficacies of in-sect pest management methods for stored bagged maize preservation in storehouses located in Nigerian markets. *J. Stored Prod. Res.* **2020**, *86*, 101566. [CrossRef]
13. Ramzan, M. Efficacy of edible oils against pulse beetle, callosobruchus maculatus. *J. Insect Sci.* **1994**, *7*, 37–39.
14. Uddin, R.O.; Abdulazeez, R.W. Comparative efficacy of neem (Azadirachta indica), False sesame (Ceratotheca sesamoides) Endl. And the Physic nut (Jatropha curcas) in the protection of stored cowpea (Vigna unguiculata) L. Walp against the seed beetle Callosobruchus maculatus (F.). *Ethiop. J. Environ. Stud. Manag.* **2013**, *6*, 827–834. [CrossRef]
15. Kalsa, K.K.; Subramanyam, B.; Demissie, G.; Mahroof, R.; Gabbiye, N. Efficacy of filter cake against Sitophilus granarius L. and Rhyzopertha Dominica F. In stored wheat. In Proceedings of the 1st All Africa Post-harvest Congress and Exhibition, Nairobi, Kenya, 29 March 2017; pp. 118–120.
16. Adarkwah, C.; Obeng-Ofori, D.; Ulrichs, C.; Schöller, M. Insecticidal efficacy of botanical food by-products against selected stored-grain beetles by the combined action with modified diatomaceous earth. *J. Plant Dis. Prot.* **2016**, *124*, 255–267. [CrossRef]
17. Tadesse, T.M.; Subramanyam, B. Efficacy of filter cake and Triplex powders from Ethiopia applied to concrete arenas against Sitophilus zeamais. *J. Stored Prod. Res.* **2018**, *76*, 140–150. [CrossRef]
18. Kalsa, K.K.; Subramanyam, B.; Demissie, G.; Mahroof, R.; Worku, A.; Gabbiye, N. Evaluation of postharvest preservation strategies for stored wheat seed in Ethiopia. *J. Stored Prod. Res.* **2019**, *81*, 53–61. [CrossRef]

19. Korunić, Z.; Liška, A.; Lucić, P.; Hamel, D.; Rozman, V. Evaluation of diatomaceous earth formulations enhanced with natural products against stored product insects. *J. Stored Prod. Res.* **2020**, *86*, 101565. [CrossRef]
20. Tefera, T.; Mugo, S.; Likhayo, P. Effects of insect population density and storage time on grain damage and weight loss in the due to the maize weevil Sitophilus zeamais and larger grain borer Prostephanus truncatus. *Afr. J. Agric. Res.* **2011**, *6*, 2249–2254.
21. Crop Production and Global Environmental Issues. In *Crop Production and Global Environmental Issues*; Springer International Publishing: Cham, Switzerland, 2015; pp. 153–168.
22. Ndukwu, M.C.; Manuwa, S.I.; Olukunle, O.J.; Oluwalana, I.B. Mathematical model for direct evaporative space cooling systems. *Niger. J. Technol.* **2013**, *32*, 403–409.
23. Ndukwu, C.; Manuwa, S.; Olukunle, O.; Oluwalana, B. A simple model for evaporative cooling of a storage space in a tropical climate. *Sci. J. Agric. Eng.* **2013**, *3*, 27–39.
24. Igboayaka, E.C.; Ndukwu, M.C.; Ernest, I.C. A Modelling approach for determining the throughput capacity and en-ergy consumption of a cassava tuber shredder. *J. Chin. Adv. Mater. Soc.* **2018**, *6*, 801–816. [CrossRef]
25. Onwude, D.I.; Chen, G.; Eke-Emezie, N.; Kabutey, A.; Khaled, A.Y.; Sturm, B. Recent Advances in Reducing Food Losses in the Supply Chain of Fresh Agricultural Produce. *Processes* **2020**, *8*, 1431. [CrossRef]
26. Onunkwo, G.C.; Egeonu, H.C.; Adikwu, M.U.; Ojile, J.E.; Olowosulu, A.K. Some Physical Properties of Tablet-ted Seed of Garcinia kola (HECKEL). *Chem. Pharm. Bull.* **2004**, *52*, 649–653. [CrossRef] [PubMed]
27. Doherty, F.V.; Olaniran, O.O.; Kanife, U.C. Antimicrobial Activities of Aframomum Melegueta (Alligator Pepper). *Int. J. Biol.* **2010**, *2*, 126. [CrossRef]
28. Gbadamosi, I.T.; Moody, J.O.; Lawal, A.M. Phytochemical screening and proximate analysis of eight ethnobotani-cals used as antimalaria remedies in Ibadan, Nigeria. *J. Appl. Biosci.* **2011**, *44*, 2967–2971.
29. Arekemase, M.O.; Aliyu, M.B.; Kayode, R.M.; Ajiboye, A.E.; Ajijolakewu, A.K. Antimicrobial Effects of Garcinia Kola (Bitter Kola) on Some Selected Pathogens from University of Ilorin Teaching Hospital Ilorin, Nigeria. *J. Asian Sci. Res.* **2012**, *2*, 159–169.
30. Ea, M.; Ka, O.; Uk, I. Physico-Chemical and Nutritive Properties of Bitter Kola (Garcinia Kola). *J. Nutr. Food Sci.* **2013**, *3*, 1–4. [CrossRef]
31. Badmos, A.A.; Ahmad-el, I.A.; Annongu, A.A.; Yusuff, A.T.; Kayode, R.M.O.; Salami, K.O.; Ahutu, I.A.; Lawal, A.O. Preservative effects of aqueous and ether extracts of Aframomum melegueta on West African soft cheese. *Bang. J. Anim. Sci.* **2017**, *46*, 51–55. [CrossRef]
32. ISTA. International Rules for seed testing. In *International Seed Testing Association (ISTA)*; Zürichstr. 50; ISTA: Bassersdorf, Switzerland, 2014.
33. Badifu, G.I.O.; Akuboil, P.I.; Akpapunam, M.A. Chemical, Functional and Organoleptic Evaluation of African-Breadfruit (Treculia a.fricanil Ikne) Kernel Flour for Making Cooki. *Tanzan. J. Agric. Sci.* **2000**, *3*, 31–38.
34. Cowan, S.T. Steel, Microscopic Examination of Micro-organisms. In *Microbiological Methods*; Collins: Cambridge, UK, 1990.
35. Chessbrough, M. District Laboratory Practice. In *Tropical Countries*; Cambridge University Press: Cambridge, UK, 2002; Part 2.
36. Association of Official Analytical Chemists (AOAC). *Official Methods of Analysis*, 18th ed.; AOAC: Rockville, MD, USA, 2007.
37. James, C.S. Analytical Chemistry of Foods. *Anal. Chem. Foods* **1995**, 140–144. [CrossRef]
38. Association of Official Analytical Chemists (AOAC). Copper catalyst kjeldahl method (984.13). In *Official Methods of Analysis*, 15th ed.; AOAC: Rockville, MD, USA, 1990.
39. Carpenter, C.E.; Hendriide, D.G. Mineral Analysis. In *Food Analysis*, 3rd ed.; Kluwer Academy, Plenum Publisher: New York, NY, USA, 2003; pp. 191–198.
40. Ensminger, L.G. The Association of Official Analytical Chemists. *Clin. Toxicol.* **1976**, *9*, 471. [CrossRef]
41. Abalone, R.; Gastón, A.; Bartosik, R.E.; Rodríguez, J.C. Mathematical Modelling of Oxygen and Carbon Diox-ide Composition in the Interstitial Atmosphere of Silo-Bags". In Proceedings of the International Commission of Agricultural and Biological Engineers, Section V, Conference "Technology and Management to Increase the Efficiency in Sustainable Agricultural Systems", Rosario, Argentina, 1–4 September 2009.
42. Gastón, A.; Abalone, R.; Bartosik, R.E.; Rodríguez, J.C. Mathematical modelling of heat and moisture transfer of wheat stored in plastic bags (silo-bags). *Biosyst. Eng.* **2009**, *104*, 72–85. [CrossRef]
43. White, N.D.G.; Sinha, R.N.; Muir, W.E. Intergranular carbon dioxide as an indicator of biological activity associ-ated with the spoilage of stored wheat. *Can. Agric. Eng.* **1982**, *24*, 35–42.
44. Simo-Tagne, M.; Ndukwu, M.C.; Zoulalian, A.; Bennamoun, L.; Kifani-Sahban, F.; Rogaume, Y. Numerical analysis and validation of a natural convection mix-mode solar dryer for drying red chilli under variable conditions. *Renew. Energy* **2020**, *151*, 659–673. [CrossRef]
45. Obi, O.F.; Okechukwu, M.E. Parboiling duration effects on physical properties of African breadfruit seed. Agricultural Engineering International. *CIGR J.* **2020**, *22*, 186–193.
46. Abe, T.; Basunia, M.A. Simulation of temperature and moisture content changes during storage of rough rice in cy-lindrical bins owing to weather variability. *J. Agric. Eng. Res.* **1996**, *65*, 223–233. [CrossRef]
47. Fouda, A.; Melikyan, Z. A simplified model for analysis of heat and mass transfer in a direct evaporative cooler. *Appl. Therm. Eng.* **2011**, *31*, 932–936. [CrossRef]
48. Bartosik, R.; Rodríguez, J.; Cardoso, L. Storage of corn, wheat soybean and sunflower in hermetic plastic bags. In Proceedings of the 2008 International Grain Quality & Technology Congress Proceedings, Chicago, IL, USA, 15–18 July 2008.

49. Nithya, U.; Chelladurai, V.; Jayas, D.; White, N. Safe storage guidelines for durum wheat. *J. Stored Prod. Res.* **2011**, *47*, 328–333. [CrossRef]
50. Martin, D.T.T.; Baributsa, D.; Huesing, J.E.E.; Williams, S.B.B.; Murdock, L.L.L. PICS bags protect wheat grain, Trit-icum aestivum (L.), against rice weevil, Sitophilus oryzae (L.) (Coleoptera: Curculionidae). *J. Stored Prod. Res.* **2015**, *63*, 22–30. [CrossRef]
51. Angelovič, M.; Krištof, K.; Jobbágy, J.; Findura, P.; Križan, M. The effect of conditions and storage time on course of moisture and temperature of maize grains. *BIO Web Conf.* **2018**, *10*, 02001. [CrossRef]
52. Sun, D.-W.; Woods, J. The Moisture Content/Relative Humidity Equilibrium Relationship of Wheat—A Review. *Dry. Technol.* **1993**, *11*, 1523–1551. [CrossRef]
53. Ben, D.C.; Lieu, B.; Liem, R.; Van, P. Effect of hermetic storage in the super bag on seed quality and milled rice quality of different varieties in Bac Lieu. *Vietnam Agric. Eng.* **2006**, *31*, 55–56. [CrossRef]
54. Njoroge, A.; Affognon, H.; Mutungi, C.; Manono, J.; Lamuka, P.; Murdock, L. Triple bag hermetic storage delivers a lethal punch to Prostephanus truncatus (Horn) (Coleoptera: Bostrichidae) in stored maize. *J. Stored Prod. Res.* **2014**, *58*, 12–19. [CrossRef]
55. Dowell, F.; Dowell, C. Reducing grain storage losses in developing countries. *Qual. Assur. Saf. Crop. Foods* **2017**, *9*, 93–100. [CrossRef]
56. Navarro, S.; Donahaye, J. Innovative environmentally friendly technologies to maintain quality of durable agricultural produce. In *Environmentally Friendly Technologies for Agricultural Produce Quality*; Yeoshua, S.B., Ed.; CRC Press: Boca Ratón, FL, USA, 2005; pp. 203–226.
57. Bakker, N.D. All You Need to Know about Rhodotorula. Available online: https://www.yeastinfection.org/all-you-need-to-know-about-rhodotorula/ (accessed on 20 August 2020).
58. Paraginski, R.T.; Rockenbach, B.A.; Dos Santos, R.F.; Elias, M.C.; De Oliveira, M. Quality of second-crop corn according to the period between harvest and drying. *Rev. Bras. Eng. Agric. Ambient.* **2015**, *19*, 358–363. [CrossRef]
59. Ubani, O.N.; Williams, J.O.; Okpadokun, J.S.; Akano, D.A.; Ikeorah, J.N. *Storage of Melon Seeds in Various Containers. Nigerian Stored Products Research Institute 22nd Annual Report*; Technical Report No. 7; NSPRI: Ilorin, Nigeria, 1991; pp. 55–58.
60. Weinberg, Z.G.; Yan, Y.; Chen, Y.; Finkelman, S.; Ashbell, G.; Navarro, S. The effect of moisture level on high moisture maize (Zea mays L.) under hermetic storage conditions—In vitro studies. *J. Stored Prod. Res.* **2008**, *44*, 136–144. [CrossRef]