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Sustainable storage of Cocoyam Cormels using Ash lined clay pits for post harvest preservation

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This study evaluated the efficacy of plant-derived ash treatments on cocoyam cormels' storage life and nutritional quality. A novel underground cellar with composite walls comprising clay and plant material ash was developed. Various ash treatments, including Iroko tree bark (IR) and feathery Pennisetum Grass (G2), significantly reduced moisture uptake and weight loss (< 28% and 28.98%, respectively) compared to ambient storage (60% weight loss). IR treatment exhibited a lower average temperature and higher thermal gradient. G2 treatment demonstrated a balanced nutritional profile, with low moisture content (9.85%), high dry matter (90.15%) and maintains stable crude protein levels, minimizes protein breakdown, and preserves starch, resulting in high carbohydrate content (77.62%). Principal Component Analysis (PCA) confirmed G2's balanced nutrient composition and minimal moisture uptake. Statistical analysis revealed significant treatment effects on temperature difference and mass loss. These findings suggest that specific plant-derived ash treatments can enhance cocoyam cormels' storage life and maintain nutritional quality, offering a promising solution for post-harvest storage.

Keywords Cocoyam storage, Burnt Ash, Clay-ash composite, Post-harvest management, Root and tuber crops

Root and tuber crops are important food crops in most countries in sub-Saharan Africa[1]. Among the roots and tuber crops, cocoyam is predominantly cultivated in tropical zones[2]. It belongs to the family Araceae, a diverse group of aroids comprising 110 genera, among which Colocasia and Xanthosoma are the two main genera[3–5]. These plants are primarily cultivated for their edible corms, serving as a vital food source in tropical regions[6]. It is rich in protein, minerals, vitamins, and digestible starch, surpassing cassava and yam[7–11]. Nigeria is the largest producer of cocoyam in the world, producing about 5.49 metric tons a year equivalent to 46% of global production and 72% of output in the West –African sub-region[12]. Cocoyam is a versatile crop with various uses, including food, feed, and industrial products. It can be processed into products like fufu, pasta, soup thickeners, baking flours, and beverages. Cocoyam starch has potential industrial applications, such as a binding agent in tablets[13–19]. Its flour has unique properties, making it suitable for weaning foods and potentially replacing corn or wheat starch[7]. Uses also include taro chips and as a vegetable in some regions[11].

Cocoyam storage poses significant challenges, with traditional methods proving inadequate. Common practices include shade, hut, and basket storage, often lined with botanical leaves[20,21]. However, these methods result in substantial losses, with reported mass losses ranging from 30 to 94.9% due to decay, microbial growth, and moisture loss[22,23]. The maximum shelf life of cocoyam is typically 4 weeks when not properly stored[24]. In contrast, refrigerated storage at 11–13 °C and 85–90% relative humidity can extend storage life to 150 days, offering a more effective solution[20]. Additional techniques, such as dipping corms in NaCl solution, can provide

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further protection against fungal infections[20]. Developing sustainable and effective storage solutions is crucial to reducing post-harvest losses and ensuring food security. Despite the availability of improved refrigerated storage techniques, Muleta et al.[25] stated that small holder farmers continue to use the traditional methods of cocoyam storage. Local farmers in sub-Saharan Africa commonly use underground pits for crop preservation. However, traditional pits without treatment can lead to moisture accumulation, as crops absorb moisture from the pit walls and floor, compromising storage effectiveness. Thus the product moisture content increases by directly absorbing moisture from the walls leading to increased pit humidity and early sprouting or decay leading to high mass losses. To prevent this, a hydrophilic compound is needed to be integrated on the pit wall surfaces to absorb moisture from it. Thus, one of the compounds that is hydrophilic and can absorb moisture and lower humidity is ash from plant materials. Plant ash absorbs water due to the hydration of the constituent oxides and charge imbalances[26]. Plastering the inner surface wall of the pit with a mixture of clay with low permeability integrated with botanical plant material ash can prevent moisture ingress from the wall and lower the pit's humidity. The ash in the clay-ash mixture serves as a strength enhancer, water resistor, thermal insulator, and pore filler, improving the overall durability and resistance of the pits inner wall surface. Additionally, ash helps reduce shrinkage, enhance workability, and deter pests. Plant material has been reported to have antimicrobial properties[27]. Previous research has demonstrated the antifungal properties of plant-derived compounds such as alkaloids, tannins, and flavonoids[28,29].

Therefore, by developing and validating a novel, composite underground treated pit cocoyam storage technology that incorporates plant-derived ash coatings in the clay inner walls; this study intends to significantly improve on the prevalent untreated pit cocoyam storage conditions to reduce mass losses and nutritional degradation of cocoyam cormels during post-harvest underground pit storage compared to traditionally untreated pit storage methods. The research gap lies in the lack of effective and sustainable storage solutions for cocoyam cormels. Given the importance of cocoyam, this study hypothesizes that underground pits treated with specific plant-derived ash coatings can reduce mass losses and maintain nutritional quality. The objectives are: (1) to develop and validate a novel composite underground treated pit storage technology, (2) to evaluate the effect of different plant material ash coatings on mass losses and nutritional composition, (3) to assess the impact on thermal gradients and temperature fluctuations, and (4) to identify the most effective treatment for cocoyam storage.

Materials and methods

Experimental materials

Cocoyam (*Colocasia esculenta*) cornmels were sourced from the experimental farm of the National Root Crops Research Institute (NRCRI), Umuike, Abia State, located in the South Eastern region of Nigeria. To produce the plant ash, two locally available grasses which includes Groose Grass (G1) and Feathery Pennisetum ash (G2), and three agro biomass that includes Rice husk (RH), Palm nut shell (PN), and Iroko tree bark (IR) were used. The plant material was dried and burnt in the presence of oxygen. The burnt ashes were collected and sieved using 0.0005 m sieve to achieve uniform size.

Study area

This study was conducted in Olokoro, Umuahia North Local Government Area, Abia State, Nigeria (5.5167°N, 7.4833°E). The region's tropical monsoon climate is characterized by high temperatures (33.4–42.8°C) and heavy rainfall (~ 2,354 mm/year), with relative humidity ranging from 58 to 84%. The fertile Ultisols and Alfisols soils support agricultural activities, making Olokoro suitable for cocoyam cultivation.

Description of the underground storage pit

A cuboidal-shaped pit (0.35 m x 0.33 m), as depicted in Fig. 1, was constructed. The inner walls and base of the storage chamber were lined with a 4 mm thick composite material consisting of a mixture of clay and botanical ash, uniformly applied to ensure a consistent and durable surface. The storage chamber had a volume of 0.112 m^3 and was topped with an overboard rectangular structure, 10 cm thick, to prevent flooding. The overboard was covered with a plastic net, and securely fastened to a wooden frame, as shown in Fig. 1. A total of 18 underground storage structures were arranged in arrays of three, with a 0.5 m gap separating each storage structure, as illustrated in Fig. 2. The arrays were covered with thatched palm leaf roofs, mounted on 2 m wooden sticks, to protect the structures from direct solar radiation and rainfall. The thatched roofs allowed for natural ventilation of the storage structures. The arrays of underground storage chambers occupied a total land area of about 4.93 m^2. The construction process involved digging a cuboidal-shaped pit with the designed dimensions, as shown in Fig. 1. A wet composite mixture of different plant material ash and sieved clay, mixed at 1:5 ratios, was applied to the floor and walls of the pit, with a 4 mm thick layer of clay composite used for plastering. The overboard was laid on top, covered with an insect hole net, and allowed to dry for seven days. Three pits were constructed for each plant material ash type, with the average values used for data analysis. Additionally, three pits were constructed without the ash composite. Therefore, a total of 18 pits were built. A beveled palm leaf roof was installed 2 m above a wooden stand to provide protection from rain interference. Additionally, a 30-centimeter high mound wall was constructed around the entire layout to safeguard the pits against flooding.

Cocoyam storage and data collection

A three-month storage experiment was conducted using the eighteen underground clay composite pits, developed with and without five different plant materials, to store Colocasia esculenta cocoyam cormels. Throughout the storage period, various parameters were monitored at regular intervals. The weight change was determined weekly with Camry analogue weighing scale with a maximum weight of 20 kg. The temperature and humidity of the pit and ambient were determined hourly using a Lutron SD card real-time data logger (MHB – 382SD) while

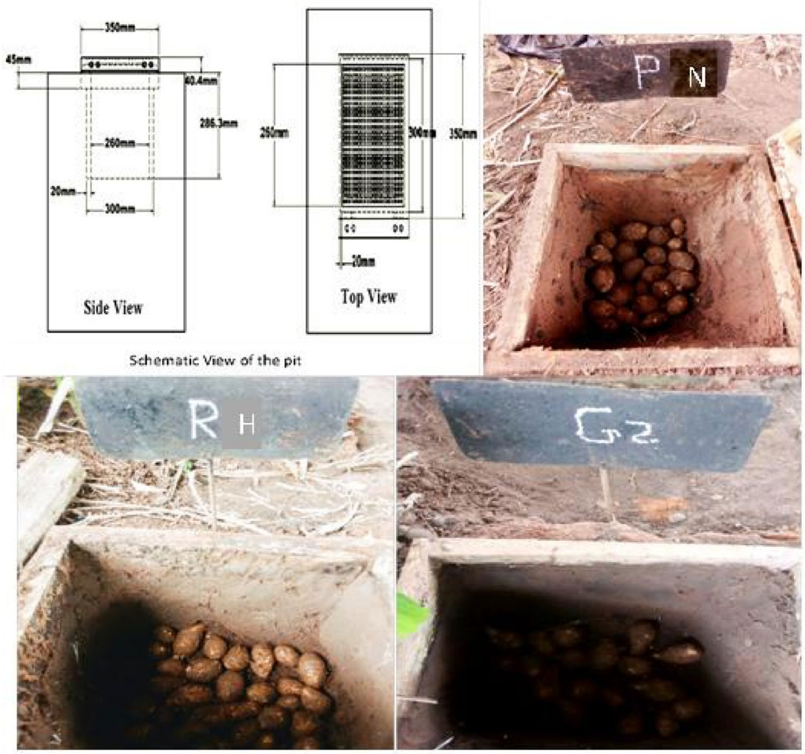

Fig. 1. Schematic view of the underground cellar showing inner wall of PN, TH and G2.

Fig. 2. Design layout of the underground clay-composite storage chambers.

the moisture content was determined monthly with and oven method. Additionally, the proximate composition, mineral content, and vitamin profile of the cocoyam were also analyzed every four weeks to evaluate the effects of storage on its nutritional quality.

Experimental uncertainty analysis

Experimental measurements are inherently subject to various sources of uncertainty, including fluctuations in reading values, instrumentation, and calibration methods[30,31]. To assess the reliability of the experimental data, measurements of temperature, relative humidity, and product mass were taken. The uncertainty associated with each measurement (Ux) was calculated using the following Eq. 1.

$$U_x = \left[\left(\frac{\partial R}{z_1}\right) w_1{}^2 + \left(\frac{\partial R}{z_2}\right) w_1{}^2 + \ldots + \left(\frac{\partial R}{z_2}\right) w_n{}^2 \right]^{1/2} \quad (1)$$

1

Where w_1, w_2, and w_n represent the experimental uncertainties in variables z_1, z_2, and z_n. The calculated percentage of experimental uncertainties is presented in Table 1, which falls within the reported range of total experimental uncertainty in literature[32].

Percentage weight loss

To determine the percentage weight loss of cocoyam due to decay, the cocoyam was separated into decayed and undecayed samples. Their various numbers were counted, weighed, and recorded. The percentage mass loss is determined as follows[25].

$$\text{Weight Loss } (\%) = ((M_1 n_d) - (M_2 n_u)) \,/\, M_2(n_d + n_u) \times 100 \quad (2)$$

Where: - M_1 = Mass of Undecayed cocoyam, - M_2 = Mass of Decayed cocoyam, - n_d = Number of Decayed cocoyam, - n_u = Number of Undecayed cocoyam.

Thermal evaluation of the pit

Two thermal indices were used to evaluate the stability of temperature within the pits. Thermal gradient (TG) measures the rate of temperature change with depth. It analyzes temperature variations within the pit to identify any thermal gradients while the Temperature Fluctuation Index (TFI) determines the range and frequency of temperature fluctuations. The thermal gradient is determined with Eq. 3 as follows.

$$TG = (T_{max} - T_{min}) \,/\, d \quad (3)$$

Where: T_{max} = Maximum temperature (°C) recorded in the pit, T_{min} = Minimum temperature (°C) recorded in the pit and d = Depth of the pit (m).

The Temperature Fluctuation Index (TFI) is determined as follows.

$$TFI = (\sigma \,/\, T_{avg}) \times 100 \quad (4)$$

Where: σ = Standard deviation of temperature readings (°C), T_{avg} = Average temperature over the measurement period (°C).

Proximate analysis of the Cocoyam

The proximate composition of the cocoyam was determined every four weeks to ascertain the quality of the stored cocoyam. This is done to establish the impact of various treated storage pits on the quality of stored cocoyam. The AOAC (2012), (2000) and (1990) methods were used to determine crude protein (AOAC 990.03), fat content (AOAC 920.39), crude fiber (AOAC 993.21), total ash (AOAC 923.03), carbohydrates (AOAC 2011.25), mineral content (AOAC 985.35), vitamin B content (AOAC 2012.01) and Vitamin C (AOAC 967.21). The entire chemicals used for the screening were of analytical grade[33–35].

Experimental design

Complete Randomized Design (CRD) was used to design the experiment. Plant ash with five levels was also considered in this research work. It was considered as the treatment and the experiment was replicated three times. Then five levels of a factor (plant ash) were denoted by.

Control	Above ground/ambient storage
G0	Non ash treated storage pit with only clay wall
G1	Treated with Groose Grass (elousine indica) ash
G2	Treated with Feathery Pennisetum Grass (pennisetum polystachion)ash

S/No	Parameter	Calculated overall percentage uncertainty (%)
1	Temperature of air	± 1.14
2	Relative Humidity of air	± 2.04
3	Mass of cocoyam	± 1.11
4	Moisture Content of cocoyam	± 3.12

Table 1. Percentage uncertainties.

Control	Above ground/ambient storage
PN	Treated Palm nut shell ash
IR	Treated with Iroko tree back ash
RH	Treated with Rice husk ash

Data analysis

The study employed several multivariate analysis techniques to interpret the statistical relationship between variables. Analysis of Variance (ANOVA) was deployed to determine the significant effects of various pit treatments while Post Hoc Analysis test was carried out to deduce the variations among means at 0.05 significant levels[36,37]. The study also applied principal component analysis (PCA) to reduce the dimensionality of the dataset and extract significant Principal components. The coveraint matrix and principal components score can be illustrated in Eqs. 5 and 6[38].

$$\Sigma = (1/n-1) * (X - \mu)^T * (X - \mu) \quad (5)$$

Where: Σ = covariance matrix, X = data matrix, μ = mean vector, n = number of observations.

$$S = X * V / \sqrt{\lambda} \quad (6)$$

Where: S = principal component scores.

All statistical analysis was done in an open-source R environment version 4.2.2 using the following packages; ggplot2, tidyverse, agricolae, and betareg.

Results and discussion

Effects of plant Ash on storage temperature an relative humidity

The temperature and relative humidity profiles of the treated underground pits and ambient conditions were monitored over 12 weeks, as illustrated in Figs. 3 and 4, respectively. The results showed that the untreated pit (G0) had the highest average temperature (27.64ºC) while iroko tree (IR) treated pit had the lowest (27.28ºC) compared to other treated pit and ambient. This might be as a result of cooling effect provided by the ash coating preventing hot spot developing within the layers of hipped cocoyam cormels. However, the average temperature of the pits ranged from 27.28 to 27.64 °C as shown in Fig. 7. The values of treated pit were 0.21–0.27 °C lower than the untreated pit (G0). The treated pits consistently maintained the pit temperature lower than the ambient despite the respiratory activities of cocoyam that generates heat into the pits and also coupled with the air exchange between the surroundings and the pits through the top pit net cover. This shows the temperature buffering effects of the ash coatings as untreated pits average temperature value was above the ambient. The average temperatures of the untreated pits were only significantly different ($p < 0.05$) with PN, IR and G2 treated pits. The ability of the storage environment of agricultural products to maintain lower temperatures and buffer external temperature fluctuations is crucial for extending the storage life of the product by providing a surrounding air that is dry and at a lower temperature than the ambient, thereby providing a cooling effect on the stored product[39]. Researchers have emphasized the importance of temperature control in reducing post-harvest losses in cocoyam[40]. This is particularly important in regions with high ambient temperatures, where temperature control can be challenging and a small temperature change between the ambient and the storage room can prove significant in the storage life of agricultural products. The study's results suggest that specific plant ashes can create a more stable microenvironment within the pits, which is beneficial for the long-term storage of cocoyam[41]. The study's findings underscore the importance of selecting appropriate treatments to optimize storage conditions[42]. These

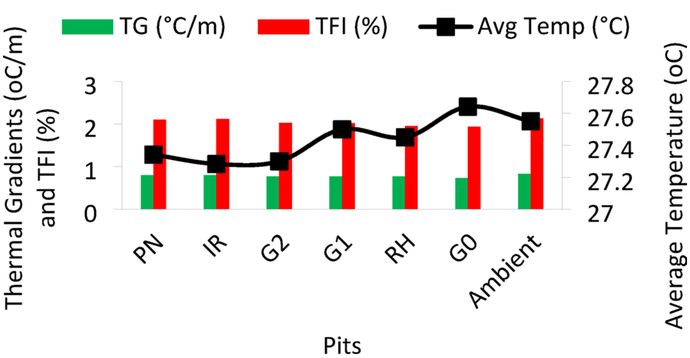

Fig. 3. Comparison of Average temperature and thermal gradients for (PN) Palm nut shell ash-clay walled storage pit, (G1) Groose Grass (elousine indica) ash-clay walled storage pit, (G2) Feathery Pennisetum Grass ash-clay walled storage pit, (RH) Rice husk ash-clay walled storage pit, (IR) Iroko tree back ash-clay walled treated pit (G0) non ash clay walled storage pit, (Ambient) Ambient condition. PN, IR and G2 ash-clay walled storage pit showed lower temperature compared tom others.

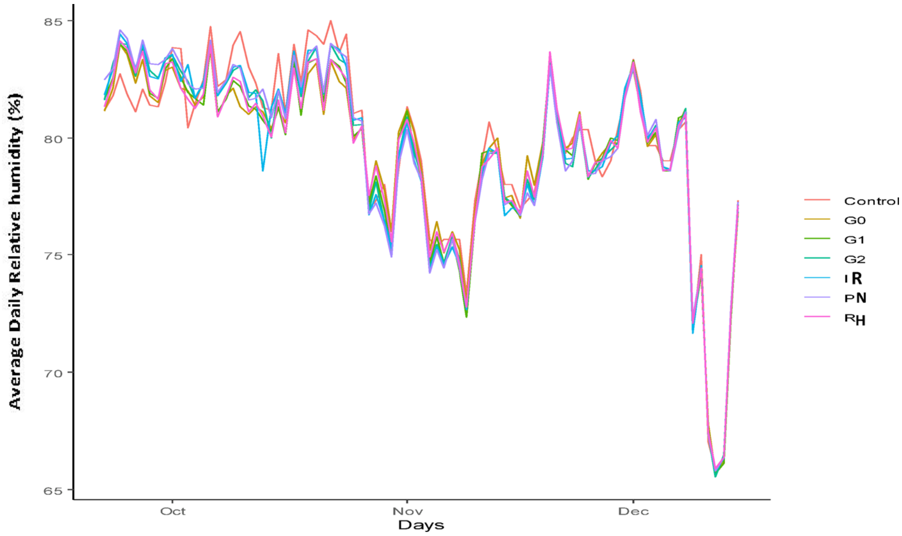

Fig. 4. Comparison of Average relative humidity for (PN) Palm nut shell ash-clay walled storage pit, (G1) Groose Grass (elousine indica) ash-clay walled storage pit, (G2) Feathery Pennisetum Grass ash-clay walled storage pit, (RH) Rice husk ash-clay walled storage pit, (IR) Iroko tree back ash-clay walled treated pit (G0) non ash clay walled storage pit, (control) Ambient condition.

findings provide valuable insights into the use of plant ash treatments for improving cocoyam storage[43,44]. Because of the closeness of the pit temperatures, a further analysis in terms of thermal gradients (TG) and temperature fluctuation index (TFI) were evaluated to determine the stability of each pit in response to variation in the fluctuation in temperature conditions. Thermal gradient measures the rate of temperature change with depth. It analyzes temperature variations within depths to identify any thermal gradients while the Temperature Fluctuation Index determines the range and frequency of temperature fluctuations. Figure 7 also reveals minimal thermal gradients across pits, ranging from 0.7346 to 0.7958 °C/m, indicating slight temperature variations with depth which is reflected on the low overall range of TFI (1.94–2.12%). This suggests reduced thermal fluctuations within the pits indicating that the pits effectively buffer against external temperature fluctuations. This buffering effect enhances thermal stability. The significant differences in thermal gradients and average temperatures among the treatments and ambient conditions suggest that specific plant ashes can effectively regulate the microenvironment within the pits. For example, the Feathery pennispetum (G2) and Iroko tree bark (IR) ash treatments demonstrated the lowest average temperature and moderate thermal gradient, making them ideal suitable for temperature control. The analysis of variance revealed that treatments like G1, and RH demonstrated consistent temperature control too, while PN and IR showed identical TG suggesting treatment-specific temperature regulation. Post-hoc Tukey's HSD tests indicated significant differences between pits and ambient for thermal gradient and also for average temperature. The temperature fluctuation index (TFI) was lower than the ambient highlighting the potential of plant ash treatments to mitigate thermal fluctuations, which is crucial for cocoyam storage. Reduced temperature variability can slow respiration and minimize sprouting, thereby extending the storage life of cocoyam. Treatment-specific temperature control strategies accounted for a significant portion of the total variability in thermal gradient and average temperature. The study's statistical analyses reinforce the importance of selecting appropriate treatments for optimal storage conditions. The study highlights the potential of these treatments to mitigate thermal fluctuations, which is crucial for cocoyam storage[45,46].

The relative humidity of the pit presented in Fig. 8 showed that it is affected by the ambient condition because the pit is open at the top though covered by a net. Within the October period, the ambient relative humidity of the area is high which reflected on the high relative humidity but start to decrease from November towards December as shown. However, occasional rainfall during the November periods affected the pit humidity condition leading to uptick in the relative humidity. This kind of environmental condition has also been reported by Kebede et al.[47], to influence storage conditions relative humidity. General at the initial stage the relative humidity of the pits were higher than the ambient probably due to respiratory activities from the stored product.

Effects of plant Ash on Cocoyam storage weight loss

The effect of different treatments on cocoyam weight loss is presented in Fig. 5. After three months of storage, weight loss ranged from 28 to 60% across all treatments, including ambient storage, with a consistent increase in weight loss observed over time. This trend is common in dry stored agricultural products due to respiratory activities that results in moisture losses, actions of microbial and insect infestations etc[48]. However, the severity of this weight loss is a function of the storage environment. There was no weight loss from the pit treated with Iroko tree bark (IR), feathery Pennisetum grass (G2), and palm kernel ash (PN) in the first three weeks of storage while a weight loss of about 5–10% was recorded in the 4th week as shown in Fig. 5. The weight loss arose due to decayed cocoyam and not from rodent attack. However, the weight loss profile indicates significant

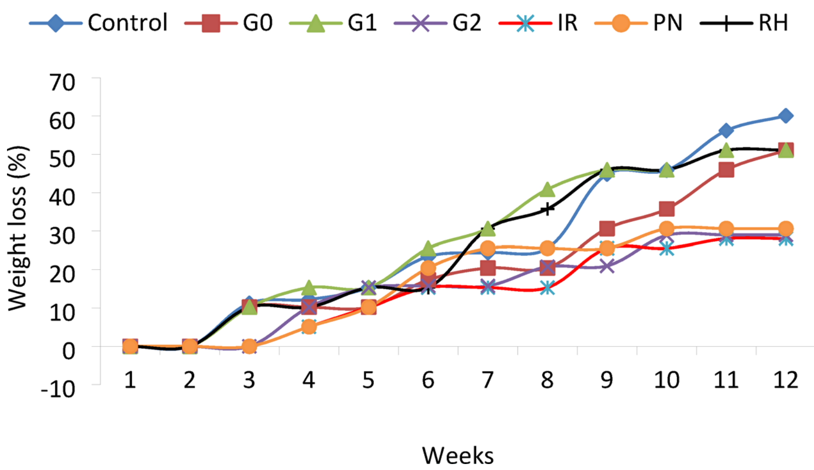

Fig. 5. Percentage mass loss variation of stored cocoyam for (PN) Palm nut shell ash-clay walled storage pit, (G1) Groose Grass (elousine indica) ash-clay walled storage pit, (G2) Feathery Pennisetum Grass ash-clay walled storage pit, (RH) Rice husk ash-clay walled storage pit, (IR) Iroko tree back ash-clay walled treated pit (G0) non ash clay walled storage pit, (control) Ambient condition. IR ash-clay treated pit exhibited the lowest mass loss of cocoyam.

differences between treatments, with the control (above-ground storage) having the highest average percentage mass decrease (60%) and the IR ash treated pits having the least average percentage weight loss 28%f followed by G2 with 28.98%. With IR treated pits providing lower temperature and lower weight loss which indicates less decayed cocoyam, it buttresses the assertion that temperature management is crucial in managing the storage of agricultural products[49]. Over all this value is far lower than 94.9% recorded for corms after 4 months of storage in an un-treated pit[50]. This is consistent with previous research by Opata and Ogbonna[44], who found that certain plant-based treatments can significantly reduce post-harvest losses in stored crops. The coefficient of variation (CV) for weight loss was 20% among treatments, indicating high variability. This was buttressed by the statistical analysis using ANOVA that showed significant differences in percentage mass loss between the pits ($p < 0.05$). The rate of weight loss between the pits with IR, G2, and PN treated ash was more consistent throughout the storage period. Their values are lower than the 36.7% recorded for cormels by Anaele and Nwauisi[23] and 30–40% recorded by Eze et al.[22], for botanical leave-covered cocoyam inside underground pits. This suggests that Iroko tree bark and feathery Pennisetum Grass ash are particularly effective in reducing weight loss during storage. The study demonstrates that different plant ash treatments can significantly impact the environmental dynamics and mass loss in underground pits used for cocoyam storage. Treatments like Iroko tree bark and feathery Pennisetum Grass ash are particularly effective in maintaining lower temperatures and reducing weight loss, making them suitable for extending the storage life of cocoyam compared to untreated pits. These findings are consistent with existing literature, highlighting the importance of temperature control and appropriate treatment selection for optimal cocoyam storage[41,42].

Effects of plant Ash pit treatments on proximate composition

The average proximate composition of cocoyam stored in various treated pits after three months is presented in Table 1. The proximate composition determined includes moisture content (MC), dry mater (DM), ash content (ASH), crude protein (CP), crude fiber (CP) crude fat (FAT) and carbohydrates (CHO). The initial values of these proximate compositions were 51.89% (wb), 89.237%, 3.44%, 7.56%, 1.44%, 1.39% and 75.4% respectively. However, theses contents showed variation during the storage periods for different treatments as shown in Table 2. The moisture content was presented in dry basis. At the initial storage of the cocoyam, the initial moisture content (MC) was 51.89% (wb). After 12 weeks of storage, the moisture content of the cocoyam stored in various pits varied significantly ($P < 0.05$) among each other as shown in Table 2 except for the G1 and RH treated pits that showed no difference between each other. The average MC values ranged from 49.32 to 51.62% (wb), with the control having the highest value (51.62% wb) and IR having the lowest (49.32% wb). Generally, the moisture content variation during the storage decreased for IR, PN and G2 treated pits in the first month except for the control kept outside and G1 treated pits as shown in Fig. 6. There is also a little uptick in moisture content for all treatment in the second month. According to Kebede et al.[47],, agricultural products respond to fluctuations in ambient conditions leading to increase or decrease in moisture content as they try to equilibrate with the environment. Therefore because of agricultural products are hygroscopic in nature they tend to absorb or release moisture based on the moisture content of the ambient air. When the air is dry the crop releases moisture while the surrounding is high it absorbs moisture. This shows the dynamics of different pit treatments in terms of buffering external moisture content. The results are similar with other researchers that have found decrease and subsequent increase in the moisture content of stored agricultural products[51]. The coefficient of variation (CV) value for MC was 1.84%, indicating moderate variability. In comparison, G2 showed a consistent decrease in MC values, from 51.89% db at Month 0 to 49.70% wb at Month 3, indicating a stable drying effect.

Storage Time	MC (% wb)	DM (%)	ASH (%)	CP (%)	CF (%)	FAT (%)	CHO (%)
At initial loading	51.89 ± 0.26	89.23 ± 0.47	2.98 ± 0.19	7.56 ± 0.53	1.44 ± 0.09	1.59 ± 0.10	75.4 ± 0.86
12th week of storage							
Control	51.61 ± 0.04a	89.33 ± 0.16f	3.59 ± 0.01a	7.37 ± 0.19a	1.33 ± 0.00	1.36 ± 0.02d	75.68 ± 0.36e
G0	50.89 ± 0.07d	89.64 ± 0.21c	3.47 ± 0.03b	6.25 ± 0.11f	1.45 ± 0.01b	1.39 ± 0.00c	77.01 ± 0.44c
G1	51.27 ± 0.11b	89.48 ± 0.11e	2.91 ± 0.01c	6.54 ± 0.19d	1.39 ± 0.01d	1.38 ± 0.04c	77.22 ± 0.41b
G2	49.62 ± 0.21e	90.15 ± 0.11b	3.25 ± 0.03b	6.66 ± 0.15c	1.34 ± 0.01e	1.42 ± 0.00b	77.62 ± 0.40a
IR	49.32 ± 0.09f	90.23 ± 0.14a	3.59 ± 0.00a	7.16 ± 0.11b	1.42 ± 0.00c	1.36 ± 0.00d	76.73 ± 0.12d
PN	51.37 ± 0.14c	89.45 ± 0.13d	3.23 ± 0.01b	5.80 ± 0.12 g	1.33 ± 0.00e	1.55 ± 0.01a	77.48 ± 0.33a
RH	51.42 ± 0.11b	89.42 ± 0.12e	3.41 ± 0.02a	6.48 ± 0.12e	1.46 ± 0.01a	1.26 ± 0.02e	76.71 ± 0.18d
CV (%)	1.84	0.541	5.281	8.211	6.413	6.699	0.989

Table 2. Proximate composition of Cocoyam stored in different storage pits. (PN) Palm nut shell ash-clay walled storage pit, (G1) Groose Grass (elousine indica) ash-clay walled storage pit, (G2) Feathery Pennisetum Grass ash-clay walled storage pit, (RH) Rice husk ash-clay walled storage pit, (IR) Iroko tree back ash-clay walled treated pit (G0) non ash clay walled storage pit, (Ambient) Ambient condition. Column with different letters are significantly different ($p < 0.05$) at 12th weeks of storage.

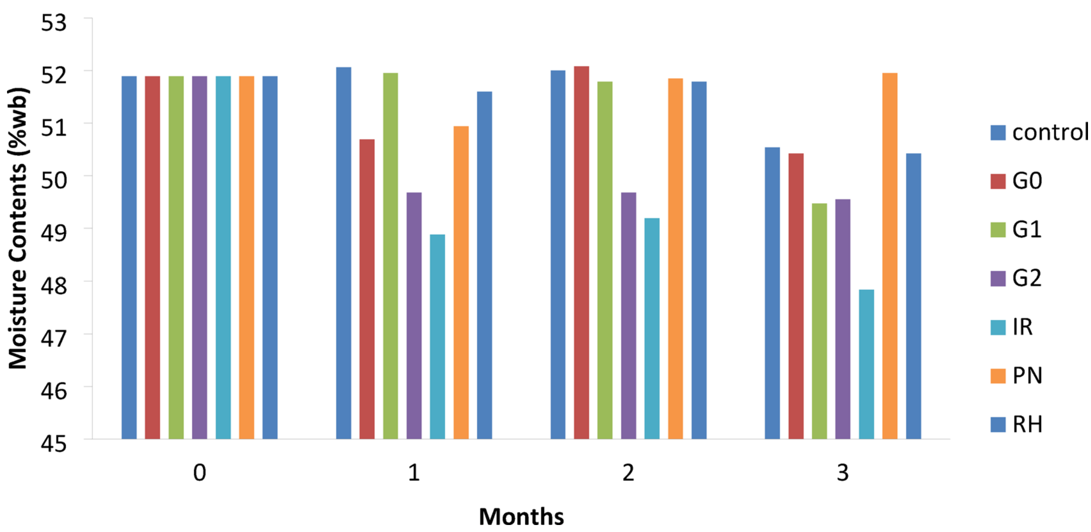

Fig. 6. comparison of monthly moisture (%) variations in the cocoyam storage pits for (PN) Palm nut shell ash-clay walled storage pit, (G1) Groose Grass (elousine indica) ash-clay walled storage pit, (G2) Feathery Pennisetum Grass ash-clay walled storage pit, (RH) Rice husk ash-clay walled storage pit, (IR) Iroko tree back ash-clay walled treated pit (G0) non ash clay walled storage pit, (control) Ambient condition.

This is consistent with the study of Dubale et al.[52] that also indicated a consistent reduction of moisture content during storage of agricultural product.

The average values of DM values ranged from 89.33 to 90.23%, with IR having the highest value (90.23%) and the control having the lowest (89.33%) as shown in Table 2. The dry matter contents increased from the initial value at the end of the storage periods. Statistical analysis revealed significant differences among treatments ($p < 0.05$), with IR and G2 having similar DM values (90.23% and 90.15%, respectively) and differing from the control. Compared to the control, IR and G2 showed an increase in DM by 1.00% and 0.91%, respectively. The CV value for DM was 0.541%, indicating low variability. In comparison, IR treatment may be more effective in enhancing dry matter content.

The average ash content values ranged from 2.91 to 3.59%, with the control having the highest value (3.59%) and G1 has the lowest (2.91%). The ash contents increased from the initial values after the 12 weeks of storage. Statistical analysis revealed significant differences among groups ($p < 0.05$), with G1 and G2 having similar ash content values (2.91% and 3.25%, respectively) and differing from the control as shown in Table 2. Compared to the control, G1 and G2 showed a decrease in ash content by 18.94% and 9.47%, respectively. The CV value for ash content was 5.281%, indicating moderate variability. The Ash content results reveal the control group had the highest ash content (3.59%), while G1 had the lowest (2.91%). Significant reduction in ash content in G1 and G2 treatments suggests these treatments help retain mineral content[53].

The crude protein content showed reduction for all the treatments. According to researchers, decrease in protein content during storage of agricultural products can be attributed to several factors that include protein

Variable	PC1	PC2	PC3
MC (%)	0.956	0.142	0.131
DM (%)	0.944	0.166	0.155
ASH (%)	0.651	0.517	0.281
CP (%)	0.711	−0 0.454	0.242
CF (%)	0.567	0.601	−0.329
FAT (%)	0.459	−0.743	0.191
CHO (%)	−0.768	0.541	0.148

Table 3. PCA results (Component Loadings).

Component	Eigenvalue	Explained Variance (%)	Cumulative Variance (%)
PC1	4.549	57.11	57.11
PC2	1.931	24.14	81.25
PC3	0.813	10.16	91.41

Table 4. PCA results (Explained Variance).

denaturation, respiration and aging[47]. This also agrees with the work of Olorunfemi and Kayode[54],, which also indicated protein losses during storage of agricultural products. The average CP values ranged from 5.80 to 7.37%, with the control having the highest value (7.37%) and PN having the lowest (5.80%) after twelve weeks of storage. Statistical analysis revealed significant differences among groups ($p < 0.05$), with PN and G1 having similar CP values (5.80% and 6.54%, respectively) and differing from the control as shown in Table 2 after twelve weeks of storage. Compared to the control, PN and G1 showed a decrease in CP by 21.29% and 11.14%, respectively. The CV value for CP was 8.211%, indicating high variability.

The crude fat content (FAT) reduced generally for all treated pits. Reduction in crude fats might be attributed to oxidation of fatty acids due to exposure to oxygen or pest attack[55]. Similarly, the alkalinity or acidity of ash content of the pit treatment can lead to saponification or hydrolyze the fats leading to decrease in fat contents. The average fat content values ranged from 1.26 to 1.55%, with P having the highest value (1.55%) and RH having the lowest (1.26%). Statistical analysis revealed significant differences among groups ($p < 0.05$), with P and G1 having similar fat content values (1.55% and 1.39%, respectively) and differing from RH. Compared to RH, PN and G1 showed an increase in fat content by 22.58% and 10.32%, respectively. The CV value for fat content was 6.699%, indicating moderate variability.

The average crude fibre (CF) also decreased in values ranged from 1.33 to 1.46%, with RH having the highest value (1.46%) and the control having the lowest (1.33%) after twelve weeks of storage. Kebele et al. (2024) also reported the same effect on crude fiber during storage agricultural product. Statistical analysis revealed significant differences among groups ($p < 0.05$), with RI and G2 having similar CF values (1.56% and 1.34%, respectively) and differing from the control as shown in Table 2 compared to the control, RH and G2 showed an increase in CF by 17.29% and 1.50%, respectively. The average carbohydrate content values ranged from 75.68 to 77.62%, indicating a slight increase for all treatments with G2 having the highest value (77.62%) and the control has the lowest (75.68%) as shown in Table 2 at the end of storage. increase in carbohydrates can be attributed to the decrease in other nutritional content since it depends on the value of these nutritional contents[47]. Statistical analysis revealed significant differences among groups ($p < 0.05$), with G2 and G1 having similar carbohydrate content values (77.62% and 77.22%, respectively) and differing from the control. Compared to the control, G2 and G1 showed an increase in carbohydrate content by 2.55% and 2.03%, respectively. The CV value for carbohydrate content was 0.989%, indicating low variability.

Principal components analysis (PCA) for proximate composition

Further principal components analysis (PCA) results in Tables 3, 4 and 5 reveal valuable insights into the relationships between various treatments and nutrient compositions, with PC1 (57.11% explained variance) primarily associated with moisture content (MC), dry matter (DM), and crude protein (CP), and PC2 (24.14% explained variance) linked to ash content (ASH), crude fiber (CF), and fat content (FAT). The component scores show that Control (above-ground storage) and G1, exhibit high PC1 scores, indicating elevated MC, DM, and CP levels, while G0 and IR, display negative PC1 scores, suggesting lower MC, DM, and CP levels. A high moisture uptick might indicate moisture absorption leading to decay. PN and RH have distinct profiles with high PC2 scores, indicating increased ASH and CF levels, and G2 shows moderate PC1 and PC2 scores, indicating balanced nutrient compositions. The relationships between treatments can be inferred, with Control and G1 being similar, G0 and IR resulting in decreased MC, DM, and CP levels, PN and RH enhancing ASH and CF levels, and M_0, M_1, and M_3 exhibiting varying nutrient composition changes as expected.

From the above results, G2 is the best treatment in terms of nutritional retention for cocoyam storage due to its consistently low moisture content (9.85%), high dry matter levels (90.15%), and balanced nutrient composition. It maintains stable crude protein levels, minimizes protein breakdown, and preserves starch, resulting in high carbohydrate content (77.62%). Additionally, G2 exhibits low variability in most parameters, indicating stable

Sample	PC1	PC2	PC3
Control	0.321	−0.541	0.191
G0	−0.185	0.236	−0.313
G1	0.052	0.183	0.269
G2	0.281	−0.217	0.044
IR	−0.412	0.361	−0.141
PN	0.231	−0.492	0.221
RH	0.191	0.281	−0.361
M0	0.143	−0.215	0.269
M1	0.269	0.183	−0.044
M2	0.044	−0.361	0.313
M3	−0.217	0.236	−0.191

Table 5. PCA results (Component Scores).

Ash type	B_1 (Mg/100 g)	B_2 (Mg/100 g)	B_3(Mg/100 g)	C (Mg/100 g)
At initial loading	0.34 ± 0.04	0.67 ± 0.09	1.35 ± 0.19	3.69 ± 0.33
12th week of storage				
Control	0.35 ± 0.02a	0.69 ± 0.06a	1.50 ± 0.03a	3.81 ± 0.12b
G0	0.28 ± 0.01d	0.62 ± 0.02b	1.35 ± 0.01d	3.44 ± 0.08e
G1	0.30 ± 0.00c	0.63 ± 0.03b	1.28 ± 0.01e	3.49 ± 0.04d
G2	0.31 ± 0.02c	0.67 ± 0.02a	1.41 ± 0.04c	3.30 ± 0.06f
IR	0.33 ± 0.00b	0.69 ± 0.04a	1.47 ± 0.01b	3.63 ± 0.12c
PN	0.24 ± 0.02e	0.42 ± 0.01c	0.91 ± 0.04f	3.17 ± 0.11 g
RH	0.30 ± 0.01c	0.62 ± 0.01b	1.28 ± 0.11e	3.90 ± 0.03a
CV (%)	3.237	1.870	1.013	0.563
HSD	0.015	0.018	0.021	0.032

Table 6. Average vitamin value of stored Cocoyam in different pits. (PN) Palm nut shell ash-clay walled storage pit, (G1) Groose Grass (elousine indica) ash-clay walled storage pit, (G2) Feathery Pennisetum Grass ash-clay walled storage pit, (RH) Rice husk ash-clay walled storage pit, (IR) Iroko tree back ash-clay walled treated pit (G0) non ash clay walled storage pit, (Ambient) Ambient condition. Column with different letters are significantly different ($p^< 0.05$) at 12th weeks of storage.

storage conditions. Principal Component Analysis (PCA) supports this, with G2 showing moderate PC1 (0.281) and PC2 (−0.217) scores, indicating balanced nutrient composition and minimal moisture uptake. G2's balanced profile makes it the optimal treatment, effectively controlling moisture uptake, reducing decay risk, and demonstrating minimal nutrient loss, outperforming other treatments.

Effect of vitamin analysis

The effectiveness of the treatments on the vitamin content of the cocoyam varied across different treatments as presented in Table 6. The average vitamin B_1 values ranged from 0.22 to 0.38, with IR having the highest value (0.38) and PN having the lowest (0.22). Statistical analysis revealed significant differences among groups ($p < 0.05$), with IR and G2 having similar B_1 values (0.38 and 0.36, respectively) and differing from PN. Compared to PN, IR and G2 showed an increase in B_1 by 36.36% and 31.82%, respectively. The CV value for B1 was 10.53%, indicating moderate variability. The average B_2 values ranged from 0.33 to 0.76, with control having the highest value (0.76) and PN having the lowest (0.33). Statistical analysis revealed significant differences among groups ($p < 0.05$), with control and IR having similar B_2 values (0.76 and 0.76, respectively) and differing from PN. Compared to PN, control, and IR showed an increase in B_2 by 136.36% and 136.36%, respectively. The CV value for B2 was 12.17%, indicating moderate variability. The average B_3 values ranged from 0.84 to 1.58, with control having the highest value (1.58) and PN having the lowest (0.84). Statistical analysis revealed significant differences among groups ($p < 0.05$), with control and IR having similar vitamin B_3 values (1.58 and 1.53, respectively) and differing from PN. Compared to PN, control and IR showed an increase in B_3 by 87.5% and 80%, respectively. The CV value for B_3 was 9.49%, indicating moderate variability. The average vitamin C values ranged from 3.12 to 4.22, with control having the highest value (4.22) and PN having the lowest (3.12). Statistical analysis revealed significant differences among groups ($p < 0.05$), with control and IR having similar C values (4.22 and 3.84, respectively) and differing from PN. Compared to PN, control and IR showed an increase in C by 35.48% and 22.92%, respectively. The CV value for vitamin C was 6.33%, indicating moderate variability.

Ash Type	Ca (Mg/kg)	Fe (Mg/kg)	Zn (Mg/kg)	*P* (Mg/kg)
At initial loading	3071.4 ± 178.3	66.9 ± 3.9	34.7 ± 1.9	219.7 ± 27.9
12th week of storage				
Control	3293.8 ± 114.6 b	72.1 ± 2.6a	109.1 ± 5.6a	274.3 ± 1.46a
G0	3248.5 ± 161.1 d	62.8 ± 2.2 g	102.2 ± 0.45c	235.6 ± 18.7c
G1	3267.3 ± 214.6 c	65.9 ± 1.9e	98.2 ± 3.9d	229.3 ± 12.2d
G2	3352.7 ± 203.6 a	68.1 ± 1.3d	94.9 ± 2.2e	229.9 ± 14.5d
IR	3242.9 ± 180.4 e	65 ± 1.1f	103.3 ± 6.7b	254.8 ± 12.2b
PN	3104.6 ± 171.1 g	69.3 ± 0.9c	89.3 ± 4.8f	203.4 ± 11.7f
RH	3162.6 ± 175.6 f	69.9 ± 1.0b	87.7 ± 4.5 g	206.6 ± 19.1e
CV (%)	2.54	5.08	8.36	10.68
HSD	0.131	0.047	0.095	0.118

Table 7. Average mineral content value of stored Cocoyam in different pits. (PN) Palm nut shell ash-clay walled storage pit, (G1) Groose Grass (elousine indica) ash-clay walled storage pit, (G2) Feathery Pennisetum Grass ash-clay walled storage pit, (RH) Rice husk ash-clay walled storage pit, (IR) Iroko tree back ash-clay walled treated pit (G0) non ash clay walled storage pit, (Ambient) Ambient condition. Column with different letters are significantly different ($p < 0.05$) at 12th weeks of storage.

Mineral analysis

The Ca content values in Table 7 ranged from 3104.6 mg/kg (P) to 3352.7 mg/kg (G2). G2 had the highest Ca content, followed by control, which had a value of 329.38 mg/100 g. G0, G1, and IR had lower Ca content values, ranging from 3242.9 mg/kg to 3267.3 mg/kg. PN had the lowest Ca content value, which may indicate a potential deficiency in this treatment. The statistical analysis revealed significant differences in Ca content between treatments ($p < 0.05$), with G2 and control being significantly higher than PN. Based on these results, G2 and control treatments appear to be the most effective in maintaining Ca content. Therefore, these treatments may be the best choice for ensuring adequate Ca levels. The iron (Fe) content values in Table 5 ranged from 62.8 mg/kg (G0) to 72.1 mg/kg (control). The Control had the highest Fe content, followed closely by RH, which had a value of 69.9 mg/kg. G2, G1, and IR had lower Fe content values, ranging from 63.5 mg/kg to 68.1 mg/kg. G0 had the lowest Fe content value, which may indicate a potential deficiency in this treatment.

Conclusion

This study highlights the potential of using specific plant ashes in underground pits for enhancing cocoyam storage, with notable improvements in temperature control, mass loss reduction, and nutrient preservation. Iroko tree bark (IR) ash treatment stood out for its ability to maintain the lowest average temperature (27.28 °C) and thermal gradient (0.7958 °C/m), resulting in significantly reduced mass loss (28% after three months) compared to the control samples (60%). Additionally, Pennisetum Grass (G2) ash treatment demonstrated stable nutrient retention, characterized by low moisture content, high dry matter levels (90.15%), and a balanced nutrient composition, including a high carbohydrate content (77.62%). The effectiveness of these treatments in controlling moisture uptake and minimizing nutrient loss makes them optimal solutions for cocoyam storage. To further leverage these findings, future research should prioritize scaling up the application of these ash treatments, exploring their potential for storing other root and tuber crops, and conducting comprehensive assessments of their long-term environmental impacts, economic viability, and social acceptability among small-scale farmers. By addressing these areas, the full potential of plant ash treatments in improving post-harvest management of cocoyam and other staple crops in sub-Saharan Africa can be realized.

Data availability

The datasets used and/or analyses during the current study are available from the corresponding author on reasonable request.

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Author contributions

LO: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Writing – Original draft. CNT: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Writing – Original draftIE: Conceptualization, Methodology, Investigation, Validation, Writing – Orig¬inal draft. LA: Conceptualization, Methodology, Investigation, Writing – Original draft.MFU: Conceptualization, Methodology, Supervision, Formal analysis, Visualization, Writing – Original draft.EI: Conceptualization, Methodology, Investigation, Software, Validation, Writing – Orig¬inal draft.GUA: Methodology, Supervision, Investigation, Software, Visualization, Writing – Original draft.EJ: Methodology, Formal analysis, Visualization, Writing – Original draft.UE: Investigation, Formal analysis, Validation, Writing – Original draft. NMC: Conceptualization, Methodology, Supervision, Formal analysis, Visualization, Writing – Original draft.

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Competing interests

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Science4Impact statement

By developing and validating a novel, low-cost composite underground storage technology incorporating plant-derived ash, this research aims to reduce food losses and improve food security for smallholder farmers in tropical African regions, promoting sustainable post-harvest management practices and enhancing the storage life of cocoyam, a staple crop,

Additional information

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