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PLANTAIN STORAGE TECHNIQUES IN NIGERIA: A REVIEW TO DRIVE INNOVATION OPPORTUNITIES THROUGH POST-HARVEST TECHNOLOGIES.

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ABSTRACT

This comprehensive review examined advancements in storage techniques of plantain in Nigeria to minimize post-harvest losses and ensure food security. It examined factors impacting shelf life, proposed storage solutions, and evaluated their socio-economic influence. The implications of research innovations such as the absorption of ethylene and solar-powered storage are discussed in-depth for their potential to provide affordable and clean energy. This review emphasized the importance of sustainable industry, innovation, and infrastructure in guiding future impacts and opportunities for research in post-harvest storage techniques of plantain in Nigeria. Thus, a compilation of studies in this area provides practical insights that highlight these key findings valuable for agricultural development and economic growth. Addressing critical issues in the plantain storage techniques in Nigeria, this article serves as an important resource for researchers, stakeholders, and policymakers, in addition to responsible consumption, and production of plantain for improved economic stability, food security, and well-being of Nigeria as well as globally. Thus, contributing to good health, the well-being of people, and poverty reduction.

Keywords: *Food security, Innovation, Plantain, Post-harvest Losses, Storage technology, Sustainable development.*

INTRODUCTION

Plantains sometimes called cooking bananas belong to the *Musaceae* family and the *Musa*, genus. Plantain is classified into AAB chromosome group based on its genetic characteristics contributed by a cross of *Musa acuminate* and *Musa balbisiana* as parental source De Langhe *et al.*, (2009). It is between 2-9 m in height, arboreal and perennial (Fig. 1). Tropical regions, including Africa, the Caribbean, Latin America, Asia, and the Pacific, grow it as a staple meal (Tchango *et al.*, 1999). It serves as an essential source of carbohydrates, minerals like calcium, potassium, dietary fibre, and antioxidants such as phenols as well as a cash crop for millions of the population in these regions (IITA, 2011). It is established as a rhizome or corn beneath the soil (Ayanwale *et al.*, 2016). The major species of plantain are *Musa corniculata* (Horn plantain), *M. acuminate* (Gross, Michel, and Cavendish), and *M. paradisciaea* (French plantain/hybrid) Chabi *et al.* (2018). Based on bunch characteristics there are four principal commercial plantain types in Nigeria, the horn type 'Ishitim', French type ‘Obino l'Ewai', false type 'Mbang Okon', and false horn type 'Agbagba' and 'Orishele’. Due to tolerance to poor soil conditions, the false horn type is the most widely cultivated in Nigeria as well as the most widely distributed. Major plantain-producing regions (Figure 2) are Abia, Osun, Oyo, Cross-river, Ondo, Imo, and Ogun State (Akinyemi *et al.*, 2008). Plantain fruit is characterized physically by a slightly curved length with a thick greenish or yellowish color outer covering pod depending on the ripening state and the inner fruit is a pale, white flesh, while ripe plantains exhibit a yellow to light brown color (Robinson *et al.*, 1996).

Figure 1: Fruit of Plantain Tree in a Courtyard in Nigeria.

Figure 2: A map indication of plantain production regions in Nigeria.

In Nigeria, plantains are rarely eaten raw. Instead, they are prepared in various ways, such as allowing them to ripen or cook, roasting, frying (known locally as *"dodo"*), or baking them, depending on how they are to be consumed.

Figure 3: Plantain plantation at Ilawe, Ekiti State.

In Nigeria, consumer demand for plantain persists throughout the year while the production of good quality plantain primarily occurs annually from October to February (Adewunmi *et al.*, 2009). The diameter(size) of the plantain at its mid-point is one of the parameters that can be used to determine maturity using calipers (Ogazi, 1996) as well as other parameters such as color, firmness, presence of dark spots, and flavor. Plantains exhibit a typical climacteric pattern, transitioning from an unripe phase with low basal respiration and minimal ethylene production to a ripe phase marked by increased respiratory rate, ethylene evolution, chlorophyll breakdown, and tissue softening (Marriot and Lancaster, 1983; Ogazi, 1996). Various external and internal fruit characteristics, such as fruit diameter, bunch age, angularity, length, and peel color, aid in assessing plantain maturity (Johnson *et al.,* 1998). The stage of maturity harvest is dependent on the target market; locally sold plantains may be harvested at a more advanced stage than those intended for export (Johnson *et al.*, 1998; Ogazi, 1996). The optimal quality of export-bound plantains is ensured by the harvest before shipment (Ogazi, 1996). Plantains ripen in days after being picked at a mature but unripe stage, making them extremely perishable, particularly when overripe (Robinson, 1996). Post-harvest losses of plantains vary among countries due to differences in market chains and consumption practices, with factors like inadequate transportation, harvest timing, and storage conditions contributing to losses FAO (1987). In Nigeria, significant post-harvest losses occur at the level of production, particularly in isolated areas during the season of rainfall, which should ideally be kept below 35% in developing countries (FAO, 1987).

Plantain serves as a versatile food source and raw material for various delicacies and snacks, contributing significantly to carbohydrate intake in humid tropical Africa (Aina *et al.*, 2012; IITA, 2009). With its substantial annual production of 130 million metric tons globally, and Nigeria's position as one of the top plantain producers globally (FAOSTAT, 2019; FAO, 2012; FAO, 2013). Understanding the present post-harvest storage techniques being employed in the plantain value chain is essential for maximizing its economic and food security benefits (Adejoro *et al.,* 2010). Most of the research conducted on plantain in Nigeria has focused on various aspects such as processing, production, agronomy, marketing, and post-harvest losses. For instance, Kainga and Seiyabo (2012) and Baruwa *et al.* (2011) have delved into production, while studies by Echezona *et al.* (2011) and Shaibu *et al.* (2012) have explored agronomy. Additionally, Oladejo and Sanusi (2008) have examined marketing strategies, while Folayan and Bifarin (2011) and Ladapo and Oladele (2011) have investigated processing techniques and post-harvest losses. These studies have provided insights into the economics of plantain production, processing methods, marketing dynamics, and post-harvest loss management, particularly at the levels of farmers and wholesalers. Another study conducted by Iyabo *et al.* (2013) took place in Southwestern Nigeria, comprising six states, namely Ogun, Oyo, Lagos, Osun, Ekiti, and Ondo (Fig. 2). As a key region for plantain cultivation in the country the area witnesses significant trade volumes of plantain in its urban centers (NPAFS, 2009) and holds promise for value addition with the emergence of processing industries. These zones offer a rich landscape for studying various aspects of plantain production and trade dynamics. These studies also identified the significant constraints encountered by the plantain value chain as inadequate credit accessibility, transportation, storage, and marketing militating against increased plantain production in southwestern Nigeria. Post-harvest storage was also cited by Ladapo and Oladele (2011) as one of the major challenges in the plantain value chain. A lot of research has been carried out on the plantain value chain's upstream, which includes input supplies and production; midstream, which includes assemblers, wholesalers, processors, and exporters; and downstream, which includes retailers and consumers (Adewole, 2017; Olajide and Olonibua 2019; Ayanwale *et al.*, 2018.) not so much research has been carried out into innovative technologies in post-harvest loss occurring due to storage of plantain in Nigeria.

This review serves to explore both the most advanced techniques and their possible application in Nigeria; as well as the available and affordable resources in Nigeria to encourage strategic and sustainable research into storage techniques that can mitigate post-harvest losses of plantain in Nigeria thereby encouraging innovation and thus enhancing food security.

PLANTAIN STORAGE CHALLENGES IN NIGERIA

Plantains have the potential to be exported and to drive economic growth in Nigeria while contributing to bolstering food security. However, the perishable nature of plantain fruits, coupled with deficient post-harvest systems, has curtailed the industry's advancement, resulting in quality degradation and notable Post-Harvest Losses (Adeoye *et al.*, 2013; CBN, 2003; Ebiowei, 2013). Positioned geographically in West Africa, Nigeria is classed among the world's top plantain-producing countries, because of its excellent production conditions, which include a favorable climate and fertile lands, especially in the southern region of the nation (Akinyemi et al., 2010). The South-West (Oyo state) and South-South (Bayelsa, Rivers State, Akwa Ibom) states include the majority of the primary production regions. Nigeria's plantain output doubled over the previous 20 years, estimated at 2.8 million tons in 2012 and valued at USD1,850 million (FAOSTAT, 2012). Nevertheless, the industry's economic growth has lagged (Fig. 4) in other African countries like Ghana (Kainga and Seiyabo, 2012; Olayerni *et al.*, 2012), which leads to lower profitability for farmers and limits their potential for income generation.

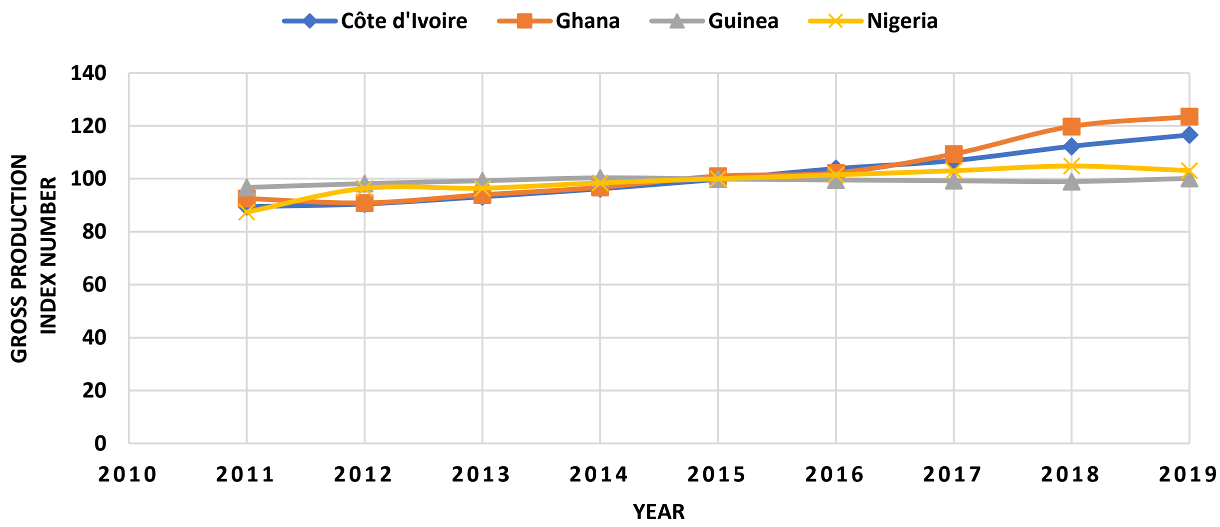

Figure 4: Plantain Production in West Africa (2010 – 2019)
Source: Data retrieved from FAOSTAT 2019

Persistent challenges include insufficient production to meet domestic demands and inadequate yields, reliance on traditional farming methods by smallholder farmers, who are the major producers of this crop, and limited extension services accessibility (Olayerni *et al.*, 2012; Kainga and Seiyabo, 2012). Moreover, substandard harvest quality and ineffective post-harvest handling. These exacerbate the situation, leading to rapid deterioration of product quality and economic value along the supply chain that contributes to economic losses for farmers. Despite numerous studies on food supply chains (FSCs) in Nigeria, including post-harvest loss estimations for various commodities, data often conflict, particularly for plantain (Olorunda and Aworth, 1996).

Plantain post-harvest losses vary widely, ranging from 17-40%, with variations observed across different regions within Nigeria (Akalumbe *et al.*, 1996; Olorunda and Aworth, 1996). These losses reduce farmers' revenues, and overall profitability, and reduce the availability of plantains in the market, potentially driving up prices and affecting consumers' purchasing power. These discrepancies may stem from differences in post-harvest technologies and practices among production areas Ajayi and Mbah (2007). Most research on plantain post-harvest losses in Nigeria has concentrated primarily on supply chain segments, which may have resulted in an under or overestimation of losses (Parfitt *et al.,* 2010). Establishing accurate estimation procedures for post-harvest losses and documenting the causes of losses are crucial steps toward improving post-harvest management and enhancing the efficiency of plantain FSCs in Nigeria (Parfitt *et al.*, 2010; Hodges *et al.,* 2010). Additionally, identifying the contributions of every causative component on the overall post-harvest losses throughout the entire supply chain is essential for developing effective solutions and ensuring a more robust plantain post-harvest system nationwide.

Figure 5: A cross-section of handling practices of plantain in Nigeria.
Source: Punch Newspaper 28th December 2018.

Bayeri and Nwachukwu, (2003) cited high post-harvest losses pose a significant challenge in ensuring an adequate supply of plantains in the country. Poor storage and handling practices (Fig. 5) contribute to the prevalence of post-harvest diseases in domestically sold fruits. Most huge farms are situated deep within forests, lacking easy road access, resulting in prolonged periods of produce waiting on the roadside. Although rail transportation of crops was prevalent in the late 1980s, effective distribution and marketing to non-producing areas are currently hampered by the lack of a current rail system for plantain transportation from the producing areas and sufficient road networks.

The shelf life of plantain is affected by environmental conditions such as temperature, humidity, and air composition; combined with limited storage facilities, distribution networks, and ripening procedures (Chukwu, 1997; Olorunda *et al.*, 1978; Ajayi and Mbah, 2003). Furthermore, an inefficient marketing system characterized by disorganized small enterprises has led to sub-optimal grading, packaging, and presentation. The absence of an organized marketing system for plantain products exacerbates the situation, stemming from a lack of information exchange between buyers and sellers (Akinwolemiwa, 1975; Ngeze, 1994).

Harvesting fruits at the wrong time further compounded issues of poor product quality within the plantain industry (Akalumbe *et al.,* 1990). Particularly at the retail level, post-harvest losses have been known as a challenge to the marketing system (Akalumbe *et al.,* 1990). This translates to financial losses for farmers and other stakeholders along the supply chain. Transportation delays due to inadequate road networks further contribute to post-harvest losses and impact farmers' ability to deliver their produce to market centers on time. Inadequate research investment represents another significant challenge in plantain production in Nigeria. Research in various aspects of plantain production has historically been overlooked compared to other cash crops, with low or absent government funding exacerbating the situation (Ngeze, 1994). This lack of emphasis on research hindered the industry's growth and development. Without adequate funding for research and development, farmers are unable to access modern farming techniques, post-harvest technologies, and improved plantain varieties. This limits their productivity and competitiveness in the market, ultimately affecting their economic well-being.

Traditionally, plantains in Nigeria are stored simply by stacking them on the ground (Fig. 5). This practice, while simple, leaves the fruit vulnerable to damage and spoilage. Certain precautions are sometimes taken to mitigate these risks, such as storing bananas in the shade or covering the piles with banana leaves or moistened bags (Tchango *et al.,* 1999). In the producing regions of Nigeria, plantains are often combined with other agricultural products in baskets and pans for transportation. They are then carried on top of a person's head or loaded onto bicycles or motorbikes for transport to markets or selling points. This method, traditional, can result in mechanical damage to the plantains due to their fragile nature (Dadzie, 1994; Marchal, 1990; Wainwright and Burdon, 1991; N'da Adopo *et al.,* 1996). Furthermore, plantains sold domestically are typically transported as intact bunches without any packaging. While this method may be suitable for short distances, it can lead to bruising and spoilage during transportation Tchango *et al.* (1999).

An evaluation of the effectiveness of current storage practices reveals both strengths and weaknesses. Traditional methods, while ingrained in the culture and practices of local communities, may not be suitable for long-distance transportation or export markets. These methods often result in mechanical damage and spoilage, leading to a loss of revenue for producers and traders. On the other hand, modern storage methods offer potential solutions to these challenges.

FACTORS AFFECTING THE SHELF LIFE OF PLANTAIN

Various factors impact the shelf life of plantains. The respiration rate of harvested plantains plays a crucial role in their metabolic processes, elevated temperatures can accelerate respiration and CO_2 production, affecting the quality of stored plantains. Additionally, in climacteric produce like plantains, CO_2 production can stimulate ethylene synthesis, influenced by factors such as exposure time, O_2 or CO_2 levels, and ripening stage (Kader, 1982).

PHYSIOLOGICAL FACTORS

Respiration

Fluctuating environmental conditions in Nigeria pose serious challenges for managing the post-harvest physiology of plantains. Respiration is the metabolic process in which complex organic substances, such as carbohydrates, proteins, and lipids, turn into simpler components, resulting in the release of energy. Under normal atmospheric conditions, aerobic respiration occurs in plantain, leading to a depletion of stored food reserves, hastening senescence, and compromising flavor quality, especially sweetness. The rate of deterioration is typically correlated with the respiration rate (Irtwange, 2006).

In Nigeria's market areas, where plantains are harvested green and undergo ripening. Since plantains are shipped green, the pre-climacteric time following harvest is essential for importers and ripeners. In this phase, mature green plantains demonstrated a low basal respiration rate, with ethylene production nearly undetectable, a phenomenon referred to as the "green life". Prolonging this period is desirable, achievable by lowering temperatures to 14 °C and storing under low O_2 (≤ 8%) and high CO_2 (≥ 2%) conditions (Marriott and Lancaster, 1983). Being climacteric, plantains experience a respiratory peak during ripening post-harvest at 20 °C. Within days, the respiration rate may increase drastically, followed by a decline as ripening progresses, accompanied by substantial water loss through transpiration (Kadam and Salunkhe, 1995).

Substrate loss from stored plantain products results in decreased tissue energy reserves, shortening their effective shelf life. Respiration also reduces overall food mass, affecting marketing systems based on weight (Kays, 1991). Oxygen removal from the storage environment due to respiration is critical, as excessive depletion can lead to anaerobic conditions, accelerating spoilage. Controlling respiration rates is essential for determining ventilation requirements and suitable packaging design. Also, manipulating oxygen concentration can extend the storage life of plantains. Elevated CO_2 levels resulting from respiration can inhibit the process, potentially extending storage life (Kays, 1991). The primary respiratory substrates in plantains consist of sugars and organic acids, which have a vital role in determining the flavor. The interplay of these elements affects the overall flavor of plantains, which is generated from the assimilation of sunlight by the plant. Plantains exhibit variations in their assimilation and accumulation processes during their growth and ripening stages, which in turn affect the optimal timing for harvest and shelf-life management (Iglesias *et al.,* 2007). However, achieving these optimal conditions in Nigeria's fluctuating environment can be challenging, requiring careful monitoring and management.

Overall, the fluctuating environmental conditions in Nigeria present ongoing challenges for managing the post-harvest physiology of plantains. The respiration rate significantly influences the deterioration and weight loss of plantains, impacting their value in the market (Morris *et al.,* 2019). Plantain fruits, harvested green and predominantly ripened in markets, undergo a respiratory peak during ripening, influenced by storage conditions and gas composition Hailu *et al.* (2013). The pre-climacteric phase post-harvest is crucial for importers, during which maintaining a low respiration rate is vital for extending shelf life (Hailu *et al.*, 2013). Manipulating storage conditions, such as temperature and gas composition, can effectively extend the green life of plantains, preserving their quality during transit and storage (Brat *et al.,* 2020; Dias *et al.,* 2021).

Ethylene influence on plantain ripening

The natural product of plant metabolism, ethylene, has a major impact on plantain physiology. Among the several elements influencing its production are fruit ripeness, post-harvest length, ethylene exposure period, disease presence, mechanical damage, and storage temperature, Hailu *et al*. (2013). For instance, lower O_2 levels, rising CO_2 levels, and storage temperatures tend to raise ethylene levels around fresh food; colder storage temperatures can therefore help to limit ethylene generation near plantains, Izumi *et al*, (2016). Plantain ethylene biosynthesis is intricately linked with ripening and senescence. Multiple steps are involved in this process: methionine is first converted to S-adenosyl methionine (SAM), which ACC synthase (ACS) then changes into 1-aminocyclopropane 1-carboxylic acid (ACC). ACC oxidase (ACO) then turns ACC into ethylene. Ethylene receptors perceive ethylene, instigating a signaling cascade involving various transcription factors and genes associated with fruit ripening (Watkins, 2017; Pech *et al.,* 2012).

The increase in ethylene levels triggers many physiological changes in plantains, including the transformation of starch into sugars, breakdown of chlorophyll, production of fragrance, buildup of carotenoids, and breakdown of cell wall components (Ge *et al.,* 2017). Exposure to ethylene accelerates the ripening process by increasing the respiration rate of climacteric fruits such as plantains. The production of ethylene in unripe plantains remains constant until the beginning of ripening, at which point there is a simultaneous increase in ethylene production and respiration rate. When the generation of ethylene decreases, the rate of respiration reaches its highest point (Hailu *et al.,* 2013). Different packing techniques can delay the start of climacteric ripening, therefore extending the shelf life of plantains by reducing ethylene production and sensitivity Hailu *et al.* (2013). The storage conditions have a notable impact on the rates at which ethylene is produced in plantains. For instance (Opara *et al.,* 2013) demonstrated that storage temperature and relative humidity can impact ethylene production, potentially altering metabolic processes during ripening.

Factors such as fruit maturity, mechanical damage, disease incidence, and temperature fluctuations govern ethylene production rates in plantains. Conversely, low temperatures and controlled atmospheric conditions can suppress ethylene production, impacting the quality attributes of plantains, including color, texture, sweetness, aroma, volatile production, and nutritional value (Irtwange, 2006). Considering these challenges, understanding the intricate interplay between environmental conditions and ethylene physiology is essential for optimizing post-harvest practices and ensuring the quality and marketability of plantains in Nigeria's fluctuating climate.

Transpiration

Transpiration is the evaporation of water from plant tissues and is a significant contributor to producing deterioration in plantain (Irtwange, 2006). Initially, water loss results in decreased marketable weight and adverse changes in appearance, such as wilting and shriveling. Furthermore, it impacts textural quality through enhanced softening, loss of crispness and juiciness, and a reduction in nutritional quality. The epidermal system, morphological and anatomical traits, surface-to-volume ratio, surface injuries, and growth stage of plantain all play a role in how much water is lost. Environmental factors such as the amount of air flow, relative humidity, and atmospheric pressure, also play a part in transpiration. Several things can be done to control transpiration, such as using waxes and plastic films as obstacles and changing the temperature, relative humidity, and air flow (Hailu *et al.,* 2013).

In the case of plantains, transpiration continues even after harvesting, with the intensity influenced by temperature and relative humidity. Notably, during ripening, there is an initial decline in transpiration rate followed by stabilization at a level determined by temperature and humidity. As ripening progresses, there is a sharp increase in transpiration rate, culminating in a new steady state (Lufu *et al.*, 2020). Additionally, a final rise in water loss occurs due to degenerative changes in the skin caused by fungal attack, though this may not strictly be considered transpiration. The ripening process of plantain bunches conceals individual finger transpiration peaks, resulting in a steadily rising curve of water loss during ripening (Montanaro *et al.,* 2012). After harvesting and cutting, green plantain fruit may experience an initial reduction in transpiration rate before stabilizing at a level primarily dependent on humidity and temperature. A significant peak in transpiration rate accompanies plantain fruit ripening Hailu *et al.* (2013). Addressing these challenges requires a multifaceted approach that considers the interplay of environmental conditions, fruit physiology, and post-harvest handling practices to optimize storage and prolong the shelf life of plantains in Nigeria's fluctuating climate.

ENVIRONMENTAL FACTORS

Temperature

The duration of the pre-climacteric stage can be altered, and the metabolism during maturation can be influenced by temperatures that exceed 25°C. The development of the peel and pulp becomes desynchronized at temperatures exceeding 35°C, as the pulp's softening exceeds the peel's coloration. This results in fruits that have a soft pulp but a green exterior, which are referred to as "cooked" or "boiled" green fruit. Ripening is effectively halted when temperatures exceed 48°C, which prevents the climacteric phase. It is important to mention that the storage of plantains in refrigerators can result in their blackening and should be avoided (Hailu et al. 2013). Green plantains are typically stored and transported at temperatures between 13 and 14°C to postpone the maturation process. Nevertheless, chilling injury, which is characterized by symptoms such as dull, grey skin color, poor ripening, and insufficient conversion of starch to sugars, can result from exposure to lower temperatures. This can result in substandard flavor development and an increased susceptibility to decay. The severity of symptoms is contingent upon both the duration and temperature of exposure, with susceptibility primarily determined by the cultivar. (Aziz *et al.,* 2020).

A study revealed that higher temperatures, particularly at 25°C and 30°C, resulted in significant weight loss and faster ripening in climacteric like bananas. Conversely, fruit stored at lower temperatures (15°C) took significantly longer to ripen. This variation in ripening time is attributed to the emission of ethylene during the ripening process, thus plantains have the possibility of exhibiting low sensitivity to ethylene within a certain range but becoming more sensitive as temperatures increase. Additionally, plantains stored at higher temperatures exhibited shorter finger lengths and showed trends of reduced fruit volume, weight, peel weight, and pulp weight compared to those stored at lower temperatures (Kadam and Salunkhe, 1995). The impact of temperature on fruit ripening, as demonstrated by Ahmad *et al.* (2001), aligns with these findings. Temperature plays a crucial role in controlling the respiration rate, with every 5-10°C rise in temperature resulting in a doubling or tripling of the respiration rate, consequently shortening the shelf life (Bhande *et al.*, 2008). Thus, maintaining an optimal temperature is essential for extending shelf life, with refrigeration serving to delay ripening, although caution must be exercised to prevent temperature abuse during transportation and storage of plantains.

Just as storage temperatures below 10°C can induce chilling injury in plantains, characterized by the development of brown spots on the peel (Broughton and Wu, 1979), attributed to dopamine oxidation (Mohapatra *et al.*, 2010). Conversely, tropical temperatures around 30°C inhibit ethylene production, which hinders chlorophyll degradation, resulting in uneven de-greening (Yang *et al.,* 2009). The recommended storage temperature for optimal ripening control is approximately 13-14°C (Robinson, 1996), with bananas ripened at 20°C under ethylene treatment exhibiting better flavor, reduced astringency, and enhanced sweetness (Ahmad *et al.*, 2001). Thus, for transportation purposes, it is advised to store plantains at around 13-14°C while employing ethylene treatment to enhance quality characteristics. Hence, maintaining appropriate storage temperatures around 13-14°C and employing ethylene treatment during transportation are advised to preserve plantain quality during transit and storage in Nigeria's fluctuating environmental conditions.

Relative humidity

Relative humidity (RH) is a measure of the amount of moisture present in the atmosphere, stated as a percentage of the maximum amount of moisture that the atmosphere can contain at a given temperature (Kader, 2013). This parameter plays a crucial role in the shelf-life and quality maintenance of fresh fruit like plantains (Kusumaningrum *et al.*, 2015), impacting factors such as transpiration rate and fruit weight. Ideally, plantains thrive in an RH range of 90-95 % (Opara *et al.*, 2013). Maintaining high humidity levels, around 95%, is beneficial during the ripening process as it prevents browning spots on the peels. However, it can lead to the dropping off the fingers due to peel rupture at the pedicel, caused by pectin degradation (Finger *et al.*, 1995). Conversely, storing plantains under conditions of lower humidity may shorten the shelf life by enhancing ethylene production and respiration during the pre-climacteric stage. The recommended relative humidity for storage is approximately 80% at a temperature of 20°C Broughton and Wu (1979). Lower relative humidity levels result in increased water loss and a shorter pre-climacteric duration. This, in turn, accelerates ethylene production and respiratory rise, although the intensity of ethylene production may vary depending on the plantain variety (Gowen, 1995).

Storage gas composition

The gas composition within storage atmospheres is pivotal in determining the longevity of horticultural products, including plantains, a significant crop in Nigeria. Fluctuations in the levels of respiratory gases, notably oxygen and carbon dioxide, can affect storage duration. While often utilized alongside low-temperature storage methods, modifications to the storage atmosphere offer a viable alternative to refrigeration, particularly for commodities like plantains (Wills *et al.,* 1998). Specifically, reducing oxygen and increasing carbon dioxide levels have been observed to minimize respiratory activity and delayed ripening processes in plantains (Ahmad *et al.*, 2006). Rapid equilibration of oxygen and carbon dioxide upon transitioning from reduced oxygen to normal air environments has been noted in studies focusing on plantain and other fruits (Paul and Pandey, 2014). This underscored the importance of gas dynamics in the storage environments of *Musaceae* (Ahmad *et al.,* 2006; Knee, 1980). Moreover, research conducted by Shorter *et al.* (1987) highlights that employing plastic film with controlled gas content, including 2% oxygen and 5% carbon dioxide, can prolong the storage life of bananas, particularly when supplemented with an ethylene scrubber. However, improper gas permeability in packaging, as observed with polythene film, can elevate carbon dioxide levels to potentially harmful concentrations, leading to symptoms of CO_2 injury such as skin darkening and outer pulp softening in plantains (Shorter *et al.,* (1987).

Furthermore, gas composition emerges as a critical determinant of fresh produce longevity in storage atmospheres, particularly in the context of Nigeria's plantain production. Variations in oxygen and carbon dioxide concentrations play a pivotal role in extending the storage duration of plantains (Kusumaningrum *et al.,* 2015). Controlled atmosphere storage (CAS) techniques, exemplified by the regulation of oxygen and carbon dioxide proportions, offer a means to preserve the quality of plantains in Nigeria by mitigating respiratory activity and ripening processes during storage (Sugianti *et al.,* 2022). While definitive recommendations for ideal carbon dioxide and oxygen levels remain elusive, researchers generally advocate for a balanced approach, with a combination of 6%–8% carbon dioxide and 2% oxygen at temperatures ranging from 11°C to 15°C considered optimal for storage of plantains in Nigeria (Brat *et al.,* 2020).

Challenges posed by fluctuating environmental conditions in Nigeria, such as varying temperatures and humidity levels, add complexity to the storage of plantains. These conditions can disrupt the delicate balance of gas composition within storage atmospheres, potentially accelerating ripening and decay processes. Additionally, unreliable access to electricity for maintaining controlled storage environments presents logistical challenges for producers and exporters. Strategies for overcoming these challenges may involve investing in alternative energy sources or implementing innovative storage technologies that can operate effectively in Nigeria's variable environmental conditions. Addressing these challenges is essential for ensuring the quality and longevity of plantains throughout the supply chain, from harvest to consumption.

STORAGE TECHNOLOGIES

COLD STORAGE TECHNIQUES

The study conducted by KA *et al.* (2017) examines the effectiveness of traditional cold storage, specifically using a "desert fridge," in preserving plantains in the region of Man, Côte d'Ivoire. According to their findings, the traditional cooling pot method prolonged the green lifespan of plantains for both Corne 1 and Agnrin cultivars, with lifespans ranging from 15 to 22 days (KA *et al.,* 2017). During storage, observable changes in physical and biochemical characteristics such as mass loss, firmness, starch content, dietary fiber, and color transformation from green to yellow were noted (KA *et al.,* 2017).

Figure 6: Cooling pot a traditional method of plantain storage.
Source: KA *et al.* (2017).

The effectiveness of traditional preservation methods in reducing post-harvest losses has also been supported by research in other agricultural contexts. For instance, a study by Stathers *et al*. (2019) investigated the use of traditional storage structures, such as underground pits, in preserving fruits and vegetables in sub-Saharan Africa and South Asia. Their findings demonstrated that these methods were not only cost-effective but also contributed to prolonging the shelf life of perishable produce, thereby enhancing food security and economic viability for small-scale farmers.

Furthermore, a study by Tortoe *et al*. (2021) highlighted the importance of post-harvest management practices in extending the shelf life of plantains. They emphasized the role of proper handling, packaging, and storage conditions in minimizing losses and maintaining fruit quality. This aligned with the findings of KA *et al*. (2017), indicating that effective cold storage methods can contribute immensely to reducing post-harvest losses. In discussing the feasibility of implementing cold storage facilities in Nigeria, insights from studies on agricultural infrastructure and technology adoption become relevant. Research by Kuka *et al*. (2020) examined the challenges and opportunities associated with enhancing post-harvest management practices in Nigeria's agricultural sector. They identified issues such as inadequate storage facilities, poor transportation networks, and limited access to markets as key barriers to reducing post-harvest losses. Addressing these challenges would require comprehensive strategies that integrate technological innovation, policy support, and community engagement to promote sustainable agricultural practices and enhance food security in the region. While the study by KA *et al*. (2017) provides valuable insights into the effectiveness of traditional cold storage methods for preserving plantains, incorporating findings from other research studies enriches the discussion on post-harvest management practices and agricultural development strategies. Collaborative efforts involving researchers, policymakers, and stakeholders are essential for addressing the multifaceted challenges associated with reducing post-harvest losses and improving food security in Nigeria and similar agricultural contexts.

MODIFIED ATMOSPHERE PACKAGING (MAP):

Considering the intricate nature of handling plantain, including factors such as varying respiration rates dependent on product type and temperature, diverse optimal storage temperatures for each item, water absorption, and the production of by-products, selecting suitable packaging technology involves several considerations. One promising area of study is modified atmosphere packaging (MAP), as highlighted by Farber *et al*. (2003). This method entails actively or passively adjusting the atmosphere surrounding the product within a package made of various film types. MAP involves altering the normal air composition to create an optimal atmosphere for extending the storage life and quality of produce. Active MAP involves displacing gases in the package with a desired mixture, while passive MAP relies on the product's respiration and gas diffusion through the film. A study by Basel *et al*. (2002) suggests that MAP treatments can extend the shelf life of plantains by inhibiting ripening. Furthermore, Hassan (2004) demonstrated that combining modified atmosphere technology with refrigeration can extend plantain storage for over eight weeks. Modifying the storage atmosphere can also benefit post-harvest disease control by suppressing pathogen growth and maintaining host resistance, as discussed by Irtwange (2006). Different packaging methods affect plantain ripening and physiological characteristics. For instance, Salunkhe and Kadam (1995) observed delayed ripening in plantains stored in polyethylene bags compared to those stored without packaging.

Packaging materials play a crucial role in maintaining desired atmospheric conditions. MAP systems utilizing specific film materials can prolong plantain shelf life, as evidenced by studies using low-density polyethylene (LDPE), silicone membranes, and diffusion channel systems (Leelaphiwat and Chonhenchob, 2020). However, challenges persist, such as the occurrence of spoilage leading to food toxicity in MAP environments. Developing appropriate packaging materials to prevent anoxic conditions during storage is crucial. Despite these challenges, maintaining proper storage conditions, particularly temperature (11–15°C) and humidity (95–98%), remains essential for preserving plantain quality (Tajeddin *et al.,* 2018).

Exploring the potential of modified atmosphere packaging (MAP) in extending shelf life and assessing its adaptability to the Nigerian agricultural landscape could offer valuable insights for enhancing plantain storage and distribution practices in the region. Researching MAP's efficacy in extending shelf life specifically for plantains within the Nigerian context could provide actionable data for farmers, distributors, and policymakers. This research could involve studying various factors such as local climatic conditions, transportation infrastructure, and market demands to tailor MAP techniques effectively. By understanding how MAP influences plantain shelf life in Nigerian conditions, stakeholders can make informed decisions regarding packaging, storage, and distribution strategies (Ayanwale *et al.,* 2016).

Assessing the adaptability of MAP to the Nigerian agricultural landscape involves evaluating its feasibility and practicality within existing agricultural systems. This assessment would consider factors like the availability and affordability of packaging materials, the infrastructure for implementing MAP technologies, and the training needed for farmers and distributors. By understanding the challenges and opportunities associated with integrating MAP into Nigerian agricultural practices, stakeholders can develop tailored solutions to improve plantain storage and distribution efficiency (Adeoye *et al.,* 2013).

Moreover, conducting research and assessments on MAP in Nigeria can lead to the development of best practices and guidelines for its implementation. This would involve identifying optimal packaging materials, storage conditions, and distribution methods to maximize the benefits of MAP while minimizing costs and logistical challenges. By establishing standardized protocols for MAP usage in the Nigerian context, stakeholders can ensure consistent quality and safety standards for plantain products throughout the supply chain. Additionally, exploring MAP's potential in Nigeria could foster innovation and collaboration within the agricultural sector. Researchers, entrepreneurs, and policymakers may collaborate to develop new packaging technologies, storage facilities, and distribution networks optimized for plantains. This interdisciplinary approach could lead to the creation of sustainable solutions that address the unique challenges faced by Nigerian plantain producers and distributors (Faturoti *et al.,* 2007). Overall, by investigating the potential of MAP and assessing its adaptability to the Nigerian agricultural landscape, stakeholders can unlock opportunities to improve plantain storage and distribution practices, enhance food security, and promote economic development in the region.

INNOVATIONS AND EMERGING TECHNOLOGIES

SOLAR-POWERED STORAGE:

In Nigeria, the absence of adequate cold storage facilities has led to huge losses of fresh fruits and vegetables. However, a promising initiative called ColdHubs (Ikegwuonu, 2020) was introduced in 2016 to address this issue. ColdHubs are modular, solar-powered cold rooms installed in farms and marketplaces. They offer uninterrupted storage for fresh produce, extending its shelf life from 2 to 21 days. Additionally, ColdHubs creates employment opportunities for women, with two women managing each unit. Operational customers pay approximately $0.5 per crate per day for cold storage. Since its inception, ColdHubs has saved nearly 5800 tonnes of fruits and vegetables from spoilage and have substantially increased the monthly incomes of over 300 farmers and traders. Given its success, this model could potentially be replicated in other Sub-Saharan African countries.

Figure 7: ColdHubs: A solar-powered, walk-in, modular unit for storing fresh produce in Nigeria.
Source: Ikegwuonu (2020).

Figure 8: Several people sorting vegetables which are to be stacked inside the cold room in plastic crates an initiative of ColdHubs refrigeration in Nigeria.
Source: Ikegwuonu (2020).

Figure 9: Stacking of vegetables which are to be stacked inside the cold room.
Source: Ikegwuonu (2020).

ETHYLENE ABSORPTION TECHNOLOGY

Ethylene (C_2H_4) gas is commonly utilized for the artificial ripening of bananas, a technique typically conducted in ripening rooms equipped with ventilation and exhaust systems. These rooms maintain optimum temperature and relative humidity levels while introducing controlled concentrations of C_2H_4 gas. Bananas are typically fumigated with C_2H_4 at concentrations ranging from 10 to 150 parts per million (ppm) for 2 to 3 days (Saltveit, 1999). However, the practical application of C_2H_4 fumigation in small ripening houses can be hindered by high costs. This is because ethylene is required for the ripening of climacteric fruits like plantain and banana so a regulation of its presence would also promote the shelf life of the fruit.

Research has explored various methods for reducing ethylene production or inhibiting its action to preserve the quality and shelf life of produce. One avenue of investigation involves active and intelligent food packaging innovation, where industries aim to use fewer ingredients in response to consumer demand (Janjarasskul and Suppakul, 2018). Active packaging systems, incorporating ethylene scavenging attributes, can effectively mitigate the adverse effects of ethylene by modifying the environment within the packaged food during storage, thus maintaining food safety and quality (Vilela *et al.,* 2018; Ahvenainen, 2003). Alternative materials for ethylene elimination, such as silica gel, activated alumina metal oxides, layer silicates, clays, zeolite, and activated carbon, are now commercially available. These materials can be packaged in sachets or incorporated into packaging materials to remove ethylene from the atmosphere (Álvarez-Hernández *et al.,* 2018; Vilela *et al.,* 2018; Tas *et al.,* 2017; Kumar *et al.,* 2021). For instance, the impregnation of ethylene scavenging agents inside the packaging matrix has shown promising results in reducing the required quantity of scavenging agents while meeting customer demands for safe and healthy food (Álvarez-Hernández *et al.*, 2018; Vilela *et al.*, 2018; Kumar *et al.*, 2021).

The demand for environmentally friendly packaging materials has led to research on incorporating ethylene scavenging agents into packaging made from waste materials, such as pine needles, which have demonstrated remarkable ethylene scavenging properties (Kumar *et al.,* 2021). Incorporating ethylene removal systems into packaging materials has been shown to delay ethylene-induced deterioration effects during storage (Amit *et al.,* 2017; Sivakumar and Bautista-Baños 2014). Given the close relationship between bananas and plantains as related crops, the application of ethylene scavenging technologies developed for bananas can potentially be adapted for use with plantains. Studies have shown that treatments with ethylene scavengers, such as potassium permanganate ($KMnO_4$), can effectively delay senescence and maintain fruit quality in bananas (Aguirre-Joya *et al.*, 2017; Yin *et al.*, 2020). By leveraging similar ethylene scavenging techniques, it may be possible to extend the shelf life and maintain the quality of plantains during storage. Although primarily applied in banana ripening, these technologies could potentially be adapted for use with plantains, given their similar ripening characteristics. Advancements in ethylene scavenging technologies and innovative packaging solutions developed for bananas can offer valuable insights and potential applications for preserving the quality and extending the shelf life of plantains, contributing to improved storage and distribution practices for this related crop.

SOCIO-ECONOMIC IMPLICATIONS

ECONOMIC BENEFITS:

Adopting effective storage methods for plantains in Nigeria can yield economic benefits for farmers and enhance market access, leading to potential income growth. Research indicated that implementing efficient storage methods, whether traditional or modern, can help minimize post-harvest losses of plantains (Elum and Tigiri, 2018). Currently, a considerable portion of harvested plantains in Nigeria is lost due to inadequate storage facilities and poor handling practices. By reducing these losses, farmers can capitalize on more of their produce, thereby increasing their overall marketable product leading to higher revenue. With effective storage methods, farmers can prolong the shelf life of plantains (Hernandez, 1973). This will allow farmers to better manage their inventory and market supply. With extended shelf life, farmers have greater flexibility in marketing their produce, targeting distant markets without worrying about rapid spoilage during transportation. This expanded market reach can result in increased demand and better prices for their products. Certain storage techniques, such as cold storage and controlled atmosphere storage, help preserve the quality and freshness of plantains for longer periods (Hernandez, 1973). This enhanced quality can command premium prices in the market, especially for export-oriented markets where consumers prioritize freshness and appearance. By adding value to their produce through improved storage methods, farmers can capture higher returns on their investments.

Furthermore, effective storage methods enable farmers to access new markets, both domestically and internationally (Hernandez, 1973). With improved preservation capabilities, farmers can participate in off-season markets, supplying plantains when local production is low. By meeting quality standards required for export markets, farmers can tap into lucrative international markets, diversifying their revenue streams and reducing dependency on volatile local markets. The combination of reduced post-harvest losses, extended shelf life, value addition, and enhanced market access contributes to income growth for plantain farmers (Adeoye, 2015). By optimizing storage practices, farmers can realize higher profits per unit of produce sold, leading to overall income growth. This additional income can be reinvested in farm infrastructure, technology adoption, or livelihood improvements, further strengthening the agricultural sector's resilience and sustainability. As the plantain value chain expands due to improved storage practices and increased market demand, it creates employment opportunities along the entire supply chain, from production and harvesting to processing, packaging, and distribution (Adeoye, 2015). This job creation contributes to economic development in rural areas, where agriculture is a primary source of livelihood for many communities. Adopting effective storage methods for plantains in Nigeria not only reduces post-harvest losses but also unlocks economic opportunities for farmers, leading to income growth, market expansion, and employment generation. It is essential for stakeholders, including government agencies, agricultural organizations, and private sector actors, to collaborate in promoting and supporting initiatives aimed at enhancing storage infrastructure and practices to realize these economic benefits fully.

CHALLENGES AND SOLUTIONS:

The implementation of cold storage facilities in Nigeria faces various challenges. Traditional refrigeration technologies are often unsuitable for rural areas due to their inability to withstand harsh conditions. Moreover, unreliable power grids and the high cost of equipment further hinder widespread adoption. To overcome these obstacles, Cold-Hubs provides a localized solution by utilizing solar power and employing a pay-per-use system (Ikegwuonu, 2020). Educating farmers, retailers, and wholesalers about the benefits of cold storage remains a significant challenge. Cold-Hubs employ a two-pronged approach, offering free trials and providing educational materials in local languages to promote post-harvest best practices. Additionally, operational challenges such as equipment security and managing cash transactions require innovative solutions, including partnerships with local market unions and government bodies. Despite these challenges, initiatives like Cold-Hubs demonstrate the potential of social entrepreneurship to address critical gaps in the food supply chain. With continued innovation and collaboration, the implementation of cold storage facilities could greatly benefit agricultural practices in Nigeria and beyond (Morris *et al.*, 2019).

By leveraging innovative solutions like Cold-Hubs and addressing these challenges, Nigeria can enhance the preservation and distribution of plantains, thereby bolstering agricultural productivity, improving food security, and fostering economic growth in rural communities.

CASE STUDIES AS WELL AS LOW-COST SUCCESS STORIES

To enhance the shelf life of plantains, researchers have proposed packaging strategies involving the use of plastic bags to minimize air circulation, coupled with storage at controlled temperatures typically ranging from 12 to 14 degrees Celsius. This recommendation is grounded in empirical studies conducted on the post-harvest handling of plantains harvested at maturity in Côte d'Ivoire (Gugerty *et al.*, 2013). These studies underscore the critical role of temperature and packaging in extending the shelf life of plantains.

Plantains wrapped in plastic bags, particularly when combined with dry cocoa leaf powder or rice husk, have demonstrated extended shelf lives ranging from 14 to 27 days, depending on the prevailing temperature conditions. This finding underscores the efficacy of modified atmosphere packaging (MAP) techniques in creating an environment conducive to prolonged storage by reducing gas exchange and moisture loss, thereby mitigating spoilage processes (Tchango *et al.,* 1999). Packaging plantains in plastic bags and storing them at specific temperatures can significantly extend their shelf life, reducing spoilage and improving overall quality. Similarly, the use of reusable plastic cages for transportation can minimize mechanical damage during transit, ensuring that the plantains reach their destination in optimal condition (Ikegwuonu, 2020).

Despite the potential benefits of utilizing plastic bags for packaging, traditional plantain producers and traders often refrain from adopting such practices due to cost considerations. The initial investment required for plastic bags and refrigeration equipment, along with ongoing operational expenses, presents a significant barrier to adoption within this demographic (Tchango *et al.,* 1999). The recommendation is to pack plantains in plastic bags and store them within a controlled temperature range aligned with modified atmosphere packaging (MAP) principles. By leveraging these strategies, plantain producers and traders can potentially extend the shelf life of their produce, thereby reducing post-harvest losses and enhancing overall marketability. However, efforts to promote adoption among traditional stakeholders must address economic constraints to ensure widespread implementation.

FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

Improving the storage of plantains in Nigeria is essential for reducing post-harvest losses, ensuring food security, and boosting farmers' income. Several avenues for further research and exploration can address the current shortcomings in plantain storage effectively. Such as the utilization of Modified Atmosphere Packaging (MAP) offers promising potential for extending the shelf life of plantains by regulating the gas composition, including oxygen, carbon dioxide, and ethylene, within the packaging (Mangaraj and Goswami, 2009; Olveira-Bouzas *et al.,* 2021). Exploring Controlled Atmosphere (CA) storage systems, which control temperature, humidity, and gas composition, presents an opportunity for preserving plantains. Research should focus on enhancing the viability of CA storage for both commercial and small-scale plantain storage facilities (Adeyeye, 2017; Bodbodak and Moshfeghifar, 2016).

Additionally, the application of Nanotechnology, particularly the utilization of nanoparticles in plantain coatings, warrants investigation. This approach aims to extend shelf life and minimize postharvest losses by evaluating the concentration of antibacterial and barrier characteristics of nanocoating for plantain preservation (Kuswandi, 2016). Also, exploring eco-friendly preservatives derived from plant extracts, essential oils, or antimicrobial peptides holds promise for preventing microbial growth and prolonging the shelf life of plantains during storage (Khameneh *et al*., 2019). Furthermore, there is a need to develop economically, and user-friendly packaging solutions tailored for small-scale farmers. Research should investigate the incorporation of intelligent sensors and indicators into packaging materials to monitor plantain condition and longevity during storage (Halonen *et al.*, 2020). More research is warranted to examine the effectiveness of postharvest treatments such as immersion in hot water, vapor, or irradiation with Ultraviolet C in preventing decay and extending the shelf life of plantains. Optimizing treatment parameters and evaluating their impact on fruit quality should be a focus of research and development efforts (Pristijono *et al.*, 2019).

Implementing policy changes and interventions to enhance plantain storage in Nigeria requires a diversified approach that addresses various factors contributing to storage challenges. Government collaboration with stakeholders is essential in implementing effective strategies. Key recommendations include investment in storage infrastructure such as cold storage facilities, warehouses, and transportation networks to improve post-harvest handling and storage practices, ultimately reducing losses due to spoilage and damage during transit. Additionally, enhancing market access and value chain development initiatives will create an enabling environment for smallholder farmers by improving storage practices, strengthening market linkages, and empowering farmers to invest in storage infrastructure (Adeoye and Oni, 2014). Establishing supportive policies and incentives for private sector investment in storage infrastructure and value chain development is crucial to stimulate growth in the plantain sector and encourage investment in storage solutions.

Providing training and extension services to farmers on proper post-harvest handling and storage techniques is essential through capacity-building initiatives to improve farmers' knowledge and skills, leading to reduced losses and improved market access. Moreover, promoting research and innovation in post-harvest technologies and storage methods tailored to local conditions is vital to develop effective and affordable solutions for plantain storage challenges (Faturoti *et al.*, 2007). Collaborative efforts between the government, industry stakeholders, and research institutions are necessary to implement these recommendations effectively. By addressing storage challenges comprehensively, Nigeria can strengthen its plantain sector, reduce post-harvest losses, enhance food security, and create economic opportunities for farmers.

CONCLUSION

However, the adoption of these modern methods faces barriers, including resistance from traditional producers and traders, as well as the cost associated with implementing new technologies. Additionally, there is a need for further research to optimize these methods for different contexts and environments. There is a need for continued research and innovation in the field of plantain storage. This includes exploring new technologies and techniques to further extend the shelf life of plantains and reduce post-harvest losses. Additionally, efforts should be made to raise awareness and provide training to local producers and traders on the benefits of modern storage methods and how they can be implemented effectively. Furthermore, collaboration between researchers, government agencies, and industry stakeholders will be essential to drive the adoption of modern storage methods and address the challenges facing the plantain industry. By working together, we can develop sustainable solutions that benefit both producers and consumers while preserving the cultural and economic importance of plantains in Nigeria.

Traditional and modern storage methods for plantains offer diverse approaches to preserving freshness and quality. While traditional methods remain prevalent in many parts of Nigeria, modern techniques hold promise for improving shelf life and reducing post-harvest losses. However, the adoption of these methods faces challenges, and further research and collaboration will be needed to overcome these barriers and ensure the long-term sustainability of the plantain industry.

STATEMENT AND DECLARATION

Author Contributions

Jane Nnamani Akinniyi contributed to conceptualization, review design, data interpretation, and manuscript preparation and editing. Monica Ndidi Ejoh contributed to conceptualization, review design, data interpretation, supervision, and manuscript preparation.

Consent for declaration.

All authors have provided their consent for the publication of this work.

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