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Post-harvest management in Africa: A review of innovative technologies and multidisciplinary approaches for reducing food losses

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Abstract
Food and nutritional security are pressing global challenges, exacerbated by the increasing population. An integrated and innovative approach is needed to guarantee sustainable food production and consumption in the African community. This study outlines post-harvest losses, their impact, innovative technologies to reduce losses, and multidisciplinary approaches to address this issue. An estimated 60% of the total crop harvested is lost due to post-harvest losses in many African countries, leading to high rates of hunger, decreased edible food mass, reduced nutritional value, low income for farmers, and compromised food security as well as livelihoods. Successful technologies for managing food losses include proper storage, handling, and transportation, suitable packaging materials and design, and adequate monitoring and sensing technologies. Moreover, other approaches can be integrated, such as extension services, combining agronomy and material science, and policy frameworks supporting post-harvest management. Successful post-harvest management initiatives in Africa have identified other promising and cost-effective technologies, including establishing post-harvest working groups at the national level that link researchers and other food value chain actors concerned about lowering post-harvest losses, as well as providing farmers with practical training and capacity building. A post-harvest loss reduction strategy should be integrated into agricultural programs in Africa to offer farmers practical guidance and reasonably priced solutions.

Keywords: Food security, Post-harvest management, Post-harvest loss, Sustainable, Technology

Introduction
Postharvest management is crucial for global efforts to end hunger, increase income, and enhance food security. It plays a key role in preserving the quality of fresh produce by maintaining microbiological safety, nutritional value, and sensory attributes. Essential practices include extending shelf life, managing diseases, and improving packing, coating, sorting, cleaning, and storage to reduce crop deterioration and prevent food loss (El-Ramady et al. 2015; Siddiqui et al. 2016). Food loss refers to declining food quality, which reduces safety, economic value, nutritional content, and customer satisfaction (FAO, 2014). This loss occurs at various supply chain stages, including production, storage, processing, distribution, and

consumption. Globally, 24% of food is lost during production, 24% during postharvest, and 35% during consumption, totaling over 80% of food lost across these stages (Xue et al. 2017). This represents a significant waste of resources such as water and energy and reduces economic value (Blakeney, 2019). Food losses particularly impact low-income families, compromise food quality and safety, hinder economic growth, and have negative environmental effects. Reducing food loss can increase the availability of food for human consumption and improve global food security. Factors contributing to food loss include insufficient skills and knowledge among supply chain actors, logistical challenges, inadequate technology, poor infrastructure, and delayed market access (Kitinoja and Gorny, 1999; Parfitt et al. 2010). Addressing food loss and waste requires collaboration among farmers, government bodies, managers, and the public (Cakar et al. 2020).

Postharvest losses in Africa and their impact

Significant emphasis is currently placed on increasing food production by 50–70% to meet the rising demand for safe food for the projected global population of 9.1 billion by 2050. Equally important is addressing the issue of food loss and waste, which is often overlooked but crucial. Despite over 870 million people suffering from hunger, roughly one-third of global food production is lost or wasted annually, totaling 1.3 billion tons (Affogno et al. 2015). In Sub-Saharan Africa, postharvest food loss represents 20–30% of annual production, valued at approximately USD 1.6 billion (Kansanga et al. 2023). In some regions, losses can reach up to 80% of total production, resulting in decreased seed viability, reduced quality, and spoilage, which contribute to revenue loss (Kumar and Kalita, 2017; Minten et al. 2021). These postharvest losses significantly impact development, economic stability, and food security in Sub-Saharan Africa (Abbas, 2018; FAO, 2019). Additionally, the resources invested in producing lost food, such as land, water, and energy, are wasted, and decomposing food in landfills generates methane, a potent greenhouse gas that exacerbates global warming (Sawicka, 2019). This situation has severe ethical, social, and environmental implications (Iordăchescu et al. 2019).

Sub-Saharan Africa is among the most impoverished and food-insecure regions globally, facing challenges like low productivity, unpredictable weather, limited financial resources, heavy reliance on food aid, and substantial postharvest losses (Ndaka et al. 2012). For example, Nigeria incurs about $9 billion in annual losses due to postharvest issues in agriculture (Mayanja and Oluk, 2023). Postharvest loss, defined as the reduction in quantity and quality of food from harvest to consumption, impacts acceptability, edibility, and nutritional value (Kiaya, 2014). In Africa, losses are substantial, ranging from 30% to 50% of total food production, depending on the crop and region. Sub-Saharan Africa, for instance, loses grains worth approximately US $4 billion per year (Sawicka, 2019). Inadequate infrastructure and poor management practices can lead to up to 50% loss of harvested crops (Kumar et al. 2017). Postharvest losses vary by region: about 50% in East Africa (e.g., Ethiopia), 30–80% in West and Central Africa (e.g., Ghana, Rwanda), and 20–50% in Southern Africa (e.g., Swaziland) depending on the product (Sibanda and Workneh, 2020).

Food cereals in some African countries can experience up to 25% loss of the total harvest (Kiaya, 2014). The dairy industry in East Africa and the Near East could incur annual losses averaging US $90 million due to spoilage and waste (FAO, 2004; Kiaya, 2014). Specific losses include approximately 95 million liters of milk annually in Kenya, valued at about US $22.4 million; 59.5 million liters in Tanzania, representing over 16% of dairy production in the dry season and 25% in the wet season; and 27% of milk production, or US $23 million, in Uganda (FAO, 2004; Kiaya, 2014). These losses impact the livelihoods of millions of small-scale farmers and affect food availability and commercial value (Sawicka, 2019).

Impact on Food Security

High postharvest losses exacerbate food insecurity by reducing food availability, leading to higher prices and diminished access to essential nutrients for vulnerable populations. This situation increases the risk of malnutrition among these groups (Jin et al. 2021; World Bank, 2022). The economic impact of postharvest losses is substantial. The FAO (2021) estimates that up to 50% of harvested crops in Sub-Saharan Africa are lost due to inadequate storage, poor infrastructure, and ineffective processing techniques. These losses not only waste labor and inputs but also result in lost income for farmers, affect national economies, and increase food system costs. According to FAO (2019), postharvest losses cost African farmers billions of dollars annually, leading to lost potential revenue and slower economic growth.

Innovative Technologies for Postharvest Management

Postharvest losses due to inadequate storage alone range from 10% to 60%, depending on the type of food (Igbeka, 2013). Improper drying has caused high aflatoxin levels in crops such as grains, nuts, cereals, and pulses, posing health risks to consumers and challenges for farmers (Odijo et al. 2024). A 2022 United Nations study indicates that food loss in Sub-Saharan Africa remains steady, highlighting the need for effective storage technologies (Olorunfemi et al. 2021). Technologies such as Purdue Improved Cowpea Storage (PICS) bags and metal silos are making significant impacts. PICS bags create an airtight seal that reduces oxygen levels quickly, effectively controlling insect and fungal activity and extending storage life (Jones et al. 2019). These bags, initially developed for cowpea farmers in West and Central Africa, also effectively store maize, rice, and other cereals (William et al. 2017). Metal silos, similarly hermetically sealed, offer a durable long-term solution, helping to mitigate losses from pests and allowing for extended storage periods. In Kenya, metal silos have reduced losses and increased profits from grain sales (Baral and Hoffmann, 2018).

The Zero Energy Cooling Chamber (ZECC) is another innovative technology that improves the shelf life and quality of fruits and vegetables by maintaining a cool temperature and appropriate humidity without electricity (Gustavsson et al. 2011; Baral et al. 2018). This is especially beneficial for farmers in areas with unreliable power. Ethylene management during postharvest storage is critical for maintaining the freshness and quality of fruits and vegetables (Mabusela et al. 2021). Ethylene accelerates the ripening process of ethylene-sensitive produce, which can lead to rapid deterioration and waste (Mahajan et al. 2014). Understanding and regulating ethylene pathways and biochemical processes are essential for extending produce shelf life (Brasil et al. 2018). Recent research trends emphasize the shift from traditional chemical controls to alternative methods, including technology-assisted breeding and gene editing. These advancements aim to produce crops that are better suited to supply chain constraints and ensure peak quality (Ninama et al. 2024; Ramos-Parra et al. 2019).

Integrating agronomy, engineering, materials science, extension services, farmer training, and economic and policy frameworks is crucial for enhancing postharvest management. A multifaceted approach that leverages advancements across these disciplines is essential for effectively addressing postharvest losses and improving food security.

Roles of Agronomy in postharvest management

Agronomy, the science and practice of crop production and soil management, plays a vital role in addressing challenges and providing sustainable solutions for food security (Kumar et al. 2023). It is crucial in postharvest management by influencing factors that affect the quality, safety, and shelf life of harvested crops.

Crop Selection and Breeding: Agronomists enhance postharvest qualities by eliminating plants with undesirable traits and selecting crop varieties with improved traits such as longer shelf life, disease resistance, and reduced susceptibility to mechanical damage. The genetic characteristics linked to these desirable traits are conserved and become more prevalent in the progeny genome through successive breeding cycles (Glenn et al. 2017).

Soil and Nutrient Management: Proper soil and nutrient management during the growing season can improve the postharvest quality of crops. For example, balanced fertilization enhances the structural integrity and nutritional content of fruits and vegetables (Rathod and VijayKumar, 2024). Agronomic practices, including reduced-tillage techniques and optimized planting populations, help maximize crop growth while minimizing soil disturbance (Verma et al. 2006).

Water Management: Adequate irrigation practices are essential for maintaining optimal moisture levels in crops, which reduces the risk of postharvest diseases and physiological disorders (Cassandra and Swett, 2020).

Pest and Disease Control: Effective pest and disease management during the growing season minimizes the incidence of postharvest losses caused by microbial infections and infestations (Kumar and Kalita, 2017).

Harvest Timing and Techniques: Agronomists determine the optimal harvest time and techniques to ensure crops are harvested at the right maturity stage, minimizing damage and maximizing quality (Erkan and Dogan, 2019).

Postharvest Handling Practices: Research in agronomy informs best practices for handling, sorting, grading, and packaging crops to reduce mechanical damage and spoilage during transportation and storage (Iorliam and Richard, 2022).

Storage and Preservation: Agronomists recommend storage conditions and preservation methods, such as controlled atmosphere storage and natural preservatives, to extend the shelf life of crops (Ogunnupebi et al. 2020; Kaur and Watson, 2024).

Agronomy is crucial for optimizing crop production and quality, which directly impacts postharvest outcomes. By implementing best practices in crop management—including pest and disease control, soil fertility, and irrigation—agronomists ensure that produce reaches its full potential before harvest. This foundation is essential for minimizing losses in subsequent stages of the supply chain. Integrating these agronomic practices into postharvest management can significantly reduce losses, improve food quality, and enhance food security.

Roles of Engineering in Postharvest Management

Engineering significantly contributes to postharvest management through the development of innovative technologies and systems for harvesting, processing, storage, and transportation. For example, efficient cold storage facilities and transportation systems can greatly extend the shelf life of edible food and prevent spoilage (Bai et al. 2023). Engineering also encompasses the mechanization of harvesting and processing, which enhances efficiency and reduces labor costs (Pargi et al. 2024).

Development of Storage Systems: Engineers design and optimize storage facilities to control temperature, humidity, and atmospheric composition, which are crucial for maintaining produce quality (Jayas, 2002). Advanced storage technologies such as modified atmosphere packaging and controlled atmosphere storage can significantly extend produce shelf life (Fang and Wakisaka, 2021).

Design of Packaging Solutions: Innovative packaging solutions, including biodegradable and bioactive materials, are developed to protect produce from physical damage, microbial contamination, and spoilage. These packaging materials also help to enhance the shelf life and safety of the produce (Yuvaraj et al. 2021; Ramesh et al. 2020).

Postharvest Handling Equipment: Engineering contributes to the design and development of equipment for sorting, grading, washing, and drying produce. These machines reduce manual labor, improve efficiency, and maintain produce quality (Awulachew, 2024).

Transportation and Logistics: Engineers create systems for efficient transportation and logistics to minimize postharvest losses. This includes designing refrigerated transport systems and optimizing supply chain logistics to ensure timely delivery of fresh produce (Schudel et al. 2023).

Processing Technologies: Postharvest engineering involves developing processing technologies that convert raw produce into value-added products. Techniques such as canning, freezing, drying, and juicing help reduce waste and increase marketability (Parmar et al. 2024).

Use of Biotechnology and Genetic Engineering: Biotechnology and genetic engineering are employed to develop crop varieties with improved postharvest qualities, such as extended shelf life, resistance to pests and diseases, and enhanced nutritional value (Datta, 2013).

Automation and Robotics: Automation and robotics are increasingly used in postharvest operations to improve efficiency, reduce labor costs, and minimize human error. This includes automated sorting and grading systems, robotic harvesters, and drones for monitoring crop conditions (Subeesh and Mehta, 2021).

Roles of Material science in postharvest management

Materials science plays a crucial role in postharvest management by advancing packaging and preservation technologies. The development of biodegradable and smart packaging materials helps preserve the quality and safety of products during transportation and storage. These materials can also provide real-time information about the state of the crop, enabling timely interventions to prevent spoilage (Sani et al. 2021).

Packaging Materials: Advanced materials such as biodegradable plastics, nanomaterials, and intelligent packaging extend the product's shelf life by managing moisture, gas exchange, and microbial growth (Imahori and Bai, 2024).

Coatings and Films: Edible coatings and films made from natural polymers can reduce water loss and delay ripening, thereby maintaining the freshness of fruits and vegetables (Priya et al. 2023).

Sensors and Monitoring Devices: Materials used in sensors can detect changes in temperature, humidity, and gas composition within storage environments. These sensors facilitate real-time monitoring and help maintain optimal conditions (Sunny et al. 2020).

Controlled Atmosphere Storage: Materials that absorb or release gases such as ethylene are employed to control the atmosphere around stored produce, slowing down the ripening process and reducing spoilage (El-Ramady et al. 2015).

Postharvest Treatments: Materials science also contributes to the development of treatments to reduce microbial load and prevent decay. This includes antimicrobial coatings and UV-absorbing materials (Pal, 2023).

These advancements in materials science are essential for reducing postharvest losses and ensuring that produce reaches consumers in the best possible condition.

Roles of Extension Services in postharvest Management

Programs for agricultural extension are essential for advancing agricultural development, empowering farmers, and disseminating knowledge (Xu et al. 2023). Agricultural extension services encompass a range of initiatives designed to provide farmers and rural actors with the knowledge and assistance needed to develop their technical, organizational, and management skills, thereby improving their standard of living (Živković et al. 2009).

Extension services and farmer training are critical for spreading knowledge and best practices. Effective extension programs bridge the gap between research and practice, ensuring that farmers have access to the latest techniques and technologies (Bellout et al. 2020). Training programs may cover various topics, including post-harvest handling, storage, market access, and business management. To support food security, it is crucial for developing nations to prioritize the introduction of appropriate research technologies and teach farmers how to use them effectively.

The ultimate goal of extension services is to enhance farmers' practices, increase productivity, and promote sustainable development (Mwangi and Kariuki, 2015).

Two notable extension models include:

Training and Visit (T&V) System: This approach involves periodic visits by extension agents to train farmers on new techniques and technologies (Knickel et al. 2009).

Field School (FFS): Developed by the Food and Agriculture Organization (FAO), this model emphasizes experiential learning and farmer participation. It has been particularly effective in transferring integrated pest management techniques (Shiferaw et al. 2009; Minh et al. 2010).

Roles of Economic and Policy Frameworks in Postharvest Management

Economic and policy frameworks are crucial for supporting and incentivizing the adoption of improved post-harvest practices. Policies that promote investment in infrastructure, research, and development, as well as those facilitating access to markets and credit, are essential for sustainable post-harvest management. Economic incentives, such as subsidies and grants, encourage farmers and businesses to invest in better technologies and practices (Bisheko and Rejikumar, 2023; Djihad et al. 2020).

Case Studies of Successful Postharvest Management Initiatives in Africa

Africa, rich in plant diversity, faces significant postharvest losses of key crops like cereals, legumes, and tuber crops, primarily due to pest infestations and phytopathogenic microorganisms (Enyiukwu et al. 2020). These losses are exacerbated by inadequate storage facilities, outdated wooden cribs, uncontrolled chemical use, excessive moisture, and fluctuating temperatures (Hell et al. 2000; Hell et al. 2008). According to the African Postharvest Loss System, average grain weight losses for millets, rice, sorghum, and maize over five years (2007–2012) were 18.0%, 13.9%, 12.4%, and 9.6%, respectively (Hodges et al. 2014).

However, successful post-harvest management strategies have been implemented across Africa, improving storage practices and reducing losses. These strategies include building metal silos, optimizing harvest timing, and employing various packaging and preservation methods (Mvumi and Stathers, 2020). Such measures have proven effective in diverse agroecological zones and value chain levels, helping farmers store produce safely and enhance food security.

Historically, Africa has faced food supply and access crises due to post-harvest losses, which restrict farmers' income, jeopardize food security, and exacerbate rural poverty (Ibrahim et al. 2022; Okoruwa et al. 2009). Approximately 5-25% of perishable produce, including fruits and vegetables, is lost post-harvest (Okoruwa et al. 2009; Mbuk et al. 2011). Nevertheless, comprehensive studies and successful initiatives have demonstrated the effectiveness of various post-harvest management techniques across more than 16 African nations. These include building metal silos, improving harvesting techniques, and applying technologies for drying, salting, fermenting, and pickling (Kimatu et al. 2012; Stathers et al. 2020).

In countries like Nigeria, the Nigeria Stored Products Research Institute has developed various technologies to address post-harvest loss in the country. These include the Evaporative Cooling System (ECS) for fruit and vegetable storage, Experimental Silos for grain storage, a Fish Smoking Kiln, fruit dryer, hybrid dryer, Inert Atmosphere Silo, NSPRI Dust for insect control in stored products, Parabolic Solar Dryer, and more. These technologies are part of the institute's efforts to find sustainable solutions to post-harvest loss in the country.t Furthermore, the use of clean, well-ventilated vehicles for transportation, careful handling to prevent damage, and avoiding contact with water have also been effective in reducing losses in the country (Atanda et al. 2011). Eastern African countries, such as Uganda, Kenya, Tanzania, Rwanda, and Burundi, have reported lower food losses due to effective postharvest management practices (Nanyunja, 2015).

Processing and packaging also play crucial roles in reducing postharvest losses. Processing activities, like peeling, washing, grating, and fermentation, stabilize and diversify food supplies, improving their shelf life and market value (Noort et al. 2022). For example, processing technologies in Nigeria for crops like tomatoes, potatoes, and onions have been applied effectively (Belitz et al. 2004). Ghana and Burkina Faso have also reduced their reliance on imported perishable foods through local processing facilities (Sugri et al. 2021). In terms of packaging, natural and synthetic fiber sacks, bags, and molded plastic boxes are commonly used in Africa. Despite erratic weather conditions, these packaging methods have proven effective for tubers and grain crops (Kiaya, 2014).

Conclusion

Postharvest losses, reaching up to 50% for some crops in Sub-Saharan Africa, significantly impact food security, economic stability, and environmental sustainability. Addressing this challenge requires a comprehensive strategy combining technological innovations, improved infrastructure, and enhanced management practices. Solutions such as PICS bags, metal silos, and Zero Energy Cool Chambers have proven effective in reducing losses and improving farmers' incomes. Integrating advanced agronomic practices, including better crop selection and precise harvesting, further enhances crop quality and resilience. Innovations in ethylene management, gene editing, and smart packaging offer long-term benefits for crop preservation and quality maintenance. Robust extension services are crucial for knowledge dissemination and technology adoption, while supportive economic policies promote necessary investments in infrastructure. Successful case studies from Africa demonstrate that this integrated approach, combining technological advancements, improved practices, and supportive policies, can create a more resilient and efficient food system. By addressing postharvest losses comprehensively, we can improve food availability, enhance livelihoods, and contribute to the overall socio-economic development of Sub-Saharan Africa and other regions facing similar challenges.

Conflict of interest

No conflict of interest concerning the study.

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