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Strategies for enhancing post-harvest quality and shelf life of tuber crops: Insights from physiological perspectives

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Abstract

This comprehensive review explores various strategies aimed at improving the quality and extending the shelf life of tubers such as potato, cassava, sweet potato and yams after they are harvested. It focuses on the physiological aspects involved in post-harvest storage. The review delves into the changes that occur within the tuber crops during storage, such as metabolic and biochemical transformations, shifts in respiration rates and ethylene production, and modifications in the composition and texture of cell walls. Additionally, the review addresses common physiological disorders that can arise during the storage of tuber crops, discussing their causes and the impact of storage conditions on their development. The review further provides insights into pre-harvest considerations, optimized harvesting techniques, post-harvest treatments for disease and pest control, and the optimization of storage conditions to maximize the shelf life of tuber crops. It emphasizes the significance of physiological markers and indicators in assessing tuber quality and their role in making informed decisions during the post-harvest phase. The review also explores advancements in post-harvest technologies, including modified atmosphere storage, cold storage, and innovative approaches for maintaining quality and inhibiting sprouting and discusses emerging trends in post-harvest physiology research, the challenges and opportunities for enhancing tuber crop quality, and potential areas for future investigation.

Keywords: Tuber crops, Post harvest management, shelf life, physiological properties, dormancy

Introduction

Background and significance

Tuber crops, including potatoes, sweet potatoes, yams, cassava, and aroids have a significant impact on global food security and livelihoods, acting as essential staple foods for millions of people worldwide. These crops provide vital nutrients and contribute to dietary diversity. Fresh tubers are highly perishable and prone to post-harvest losses, resulting in considerable economic ramifications and diminished food availability. Post-harvest losses in perishable crops, encompassing fruits, vegetables, and tubers present formidable challenges to both food security and economic sustainability. In developing countries, post-harvest losses after harvest can reach as high as 40% for fruits, vegetables, and root crops (Atanda et al., 2011; Kiaya, 2014). Multiple factors contribute to these losses such as inefficient harvesting, packaging, and handling practices, as well as fluctuations in temperature and humidity, pathogenic infections, and damage caused by insects and rodents (Atanda et al., 2011; Kiaya, 2014). Several strategies can be implemented to mitigate

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these challenges. Enhancing harvesting, packaging, and handling practices is paramount to minimize mechanical damage and exposure to extreme conditions (Atanda et al., 2011; Kiaya, 2014). Furthermore, establishing appropriate storage conditions, including maintaining optimal temperature and humidity levels, can effectively prevent spoilage (Atanda et al., 2011; Kiaya, 2014). Effective pest control methods are also crucial in safeguarding crops against pests and pathogens (Atanda et al., 2011). Additionally, the utilization of improved varieties and rootstocks plays a pivotal role in reducing post-harvest losses by bolstering resistance to pests, diseases, and environmental stresses while simultaneously prolonging the shelf life of tuber crops (Atanda et al., 2011; Kiaya, 2014; Kader and Rolle, 2004). Proper post-harvest management practices assume vital significance in ensuring the quality, safety, and market value of horticultural produce, particularly for root, tuber, and bulb crops (Kader and Rolle, 2004).

The post-harvest phase is crucial in determining tuber crop quality and shelf life. This phase encompasses physiological and biochemical changes impacting sensory attributes, nutritional composition, and market value. These changes include weight loss, sprouting, enzymatic browning, softening, and the accumulation of toxic compounds. Researchers and stakeholders have been actively involved in developing strategies to improve post-harvest quality and prolong the shelf life of tuber crops. Tuber crops possess underground storage organs that store significant amounts of starch, minerals, vitamins, and other valuable components. However, the inherent physiological characteristics render them susceptible to rapid deterioration after harvest. Post-harvest losses in tuber crops can be attributed to enzymatic reactions, microbial growth, mechanical damage, and unfavourable storage conditions. These factors interact and accelerate the degradation processes, leading to a decline in quality and nutritional value.

Enhancing post-harvest quality and extending the shelf life of tuber crops hold immense importance for multiple reasons. Firstly, minimizing post-harvest losses contributes to global food security by ensuring a consistent supply of nutritious tuber crops throughout the year, particularly in regions where they serve as staple foods and provide primary calorie sources. Secondly, improving post-harvest characteristics reduces economic losses for farmers, traders, and other stakeholders involved in the supply chain. By extending the shelf life, farmers gain access to distant markets and can obtain higher prices for their produce. Lastly, enhancing the post-harvest quality of tuber crops aligns with sustainable development goals by reducing food waste and promoting efficient resource utilization.

In recent years, considerable research efforts have been devoted to understanding the physiological processes involved in the post-harvest deterioration of tuber crops. These studies have contributed valuable insights into the factors that influence tuber quality and shelf life, leading to the development of innovative strategies to mitigate post-harvest losses. This review aims to provide a comprehensive understanding of the physiological aspects related to enhancing post-harvest quality in tuber crops while discussing promising strategies for preserving their freshness, nutritional value, and marketability. The objectives of this review are multifaceted. Firstly, it seeks to offer a comprehensive overview of the physiological processes that impact the post-harvest quality and shelf life of tuber crops. Researchers and stakeholders can identify critical intervention points and develop targeted strategies for preserving quality by gaining insights into the underlying mechanisms. Secondly, the review highlights recent advancements in post-harvest technologies, encompassing innovative storage techniques, packaging materials, and treatments that have demonstrated potential in enhancing post-harvest attributes. By examining scientific evidence and practical applications, this review aims to provide valuable insights for researchers, policymakers, and industry professionals engaged in the production, storage, and distribution of tuber crops.

Physiological changes during post-harvest storage of tuber crops

Tuber crops, including potatoes, sweet potatoes, taro, tannia, elephant foot yam, and yams, are globally recognized for their significant contribution to food security and nutrition. However, once harvested, the tubers and rhizomes undergo various physiological and biochemical changes that can impact their quality, nutritional composition, and shelf life. A comprehensive understanding of the metabolic and biochemical transformations occurring during post-harvest storage is essential for implementing adequate storage and preservation strategies. These transformations involve intricate interactions between enzymes, substrates, and environmental factors, resulting in alterations in carbohydrate, lipid, and protein metabolism, as well as the presence of phytochemicals. The primary objective of this review is to delve into the metabolic and biochemical transformations that occur during the post-harvest storage of tuber crops and explore their implications for the quality and preservation of these invaluable food resources.

Metabolic and biochemical transformations

Metabolic and biochemical transformations occur during the post-harvest storage of tuber crops, influencing their quality and shelf life (Uritani, 1999). These transformations encompass a range of metabolic processes and biochemical reactions that impact the tubers' composition, texture, and overall state. Notably, carbohydrate metabolism assumes a significant role in tuber crops, as the enzymatic breakdown of starch, the primary carbohydrate reserve, results in the formation of soluble sugars, which contribute to sweetness, flavour, and texture (Ngadze et al., 2018). Lipid metabolism also experiences changes during storage, with the potential for lipid degradation and oxidation, leading to undesirable flavors, rancidity, and alterations in nutritional profile (Kader, 2002). Furthermore, protein degradation occurs, leading to the breakdown of proteins into amino acids, thereby influencing texture, nutritional value, and sensory attributes (Ngadze et al., 2018). Enzymatic activities, including those of amylase, glucanase, and other enzymes, play a role in starch conversion, protein breakdown, and lipid degradation, thereby impacting the overall quality of tubers. Moreover, the levels of phytochemicals, such as phenolics and antioxidants, can change storage, influenced by factors such as temperature, light exposure, and oxygen availability. Managing storage conditions, encompassing temperature, humidity, and handling practices, is critical in controlling these metabolic and biochemical transformations and preserving tuber crops' quality and nutritional value.

Changes in respiration rates and ethylene production

Apart from metabolic and biochemical changes, ethylene and oxidative damages play significant roles in the post-harvest storage of tuber crops. Ethylene, a plant hormone, can be induced during post-harvest stages and affects various physiological processes, including cell wall changes and tissue softening (Yahia and Carrillo-Lopez, 2018; Dong et al., 2020). Ethylene exposure can lead to alterations in cell wall components, contributing to texture changes in tubers (Dong et al., 2020; Reilly et al., 2007). Furthermore, oxidative damages caused by increased susceptibility to pathogens (Yahia and Carrillo-Lopez, 2018; Martinez-Romero et al., 2007). Proper management of storage conditions, including temperature, humidity, and handling practices, assumes a crucial role in controlling these transformations, ethylene effects, and oxidative damages, thereby preserving the quality and nutritional value of tuber crops (Ravi and Aked, 1996; Uritani, 1999; Yahia and Carrillo-Lopez, 2018).

Changes in respiration rates and ethylene production are observed in tuber crops during post-harvest storage (Hirose et al., 1984). Respiration, a metabolic process involving carbohydrate breakdown and energy release, can increase in tuber crops due to factors like injury or biochemical changes (Hirose et al., 1984; Hajirezaei et al., 2003). Increased respiration rates can deplete stored nutrients and contribute to metabolic activity and tuber deterioration (Hajirezaei et al., 2003). Ethylene, a natural plant hormone, regulates physiological processes, including ripening and senescence. Tubers produce ethylene during storage, impacting their quality and shelf life (Martinez-Romero et al., 2007). Ethylene accelerates ripening, tissue softening, and the formation of aroma and flavor compounds in tubers (Martinez-Romero et al., 2007; Yahia and Carrillo-Lopez, 2018). Reactive oxygen species (ROS) cause oxidative damage during tuber crop storage (Yahia and Carrillo-Lopez, 2018). ROS induces oxidative stress, leading to cellular damage, membrane deterioration, and decreased tuber quality (Yahia and Carrillo-Lopez, 2018). Antioxidant systems in tuber tissues mitigate ROS and maintain tuber quality (Mu et al*.,* 2021). Various strategies can be employed to minimize the adverse effects of ethylene and oxidative damage during post-harvest storage. These include using ethylene inhibitors or scavengers to control ethylene levels and applying antioxidants or modified atmosphere packaging to reduce oxidative stress (Yahia and Carrillo-Lopez, 2018).

Dormancy regulation in tuber crops

Definition and types of dormancy

Dormancy is a critical physiological process in tubers that enables them to endure unfavourable conditions and maintain long-term viability. It involves suspended growth and metabolic activity until suitable conditions for sprouting and growth are present.

Two primary types of dormancies are observed in tubers:

Endodormancy: Endodormancy is an internal form of dormancy regulated by physiological factors within the tuber itself. During this period, tuber growth and metabolic processes are inhibited, and the tuber becomes unresponsive to external triggers for sprouting. Hormones such as abscisic acid (ABA) and ethylene suppress tuber sprouting and maintain dormancy (Gong et al., 2021; Mani et al., 2014).

Eco-dormancy: Eco-dormancy, also known as exodormancy, is influenced by external environmental factors. It occurs when external conditions, such as temperature, moisture, or photoperiod, are unfavourable for tuber growth and sprouting. Eco-dormancy prevents tubers from sprouting under unfavourable conditions, allowing them to conserve resources until more favourable conditions arise (Suttle, 2007).

Physiological and molecular mechanisms underlying tuber dormancy

The physiological age and genotype of tubers influence tuber dormancy. It initiates during tuberization and is determined by genetic factors, environmental conditions, and tuber age (Haider et al., 2021). Gaining insights into the molecular mechanisms that govern dormancy and sprouting is vital for devising strategies to manipulate dormancy in tuber crops.

The regulation of potato tuber dormancy and sprouting is a multifaceted process involving genetic, physiological, and environmental factors. Phytohormones play a pivotal role in controlling various stages of tuber development, including tuberization, initiation, growth, dormancy, and sprouting. Among these hormones, abscisic acid (ABA) and ethylene are crucial for regulating tuber dormancy and suppressing sprouting (Gong et al., 2021; Mani et al., 2014; Aksenova et al., 2013; Sonnewald and Sonnewald, 2014). These hormones act as inhibitors of sprouting, maintaining tuber dormancy during storage or unfavourable conditions. Although the exact mechanisms are still being investigated, molecular changes occur within the tuber during dormancy (Sonnewald and Sonnewald, 2014). The transition from dormancy to sprouting involves gene expression and hormonal metabolism, activating specific genes and biochemical processes (Agrimonti and Marmiroli, 2008). Additionally, non-structural sugar metabolism has been found to regulate tuber dormancy in certain yam species. Furthermore, environmental factors such as temperature, light, and humidity impact tuber dormancy and sprouting (Gong et al., 2021).

Factors influencing dormancy release and sprouting

Dormancy and sprouting in tuber and storage root crops are complex processes influenced by various factors. Phytohormones, including abscisic acid (ABA) and ethylene, play a crucial role in regulating dormancy and suppressing sprouting. Additionally, factors such as genetic manipulation, environmental conditions, sugar metabolism, and chemical treatments contribute to the control of dormancy and sprouting. Understanding these factors is essential for developing effective strategies to optimize storage conditions and manage the dormancy of tuber crops, ensuring their quality and viability.

Several factors have been identified as significant contributors:

Phytohormones: ABA and ethylene are involved in dormancy regulation and sprouting control in tuber crops.

Methyl jasmonate: Methyl jasmonate influences sprouting incidence in stored sweet potatoes and helps preserve overall quality (Véras et al., 2021).

Sugars: Sugar content in tubers affects dormancy, sprouting, and growth. Changes in sugar metabolism contribute to the transition from dormancy to sprouting.

Genetic factors: Genetic factors have a significant impact on tuber dormancy. Understanding the physiological and molecular basis of dormancy in tubers, such as yams, provides insights for genetic manipulation to control dormancy and sprouting.

Environmental factors: Temperature and photoperiod influence dormancy release and sprouting in tubers (Cheema, 2010). Favourable conditions trigger sprouting, while unfavourable conditions can prolong dormancy.

Chemical treatments: Triadimefon and ethylene inhibitors are among the chemical treatments explored to inhibit sprouting and maintain tuber quality during storage (Lima et al., 2021).

Understanding these factors and their interactions is crucial for developing strategies to control dormancy release and optimize storage conditions in tuber and storage root crops.

Physiological Disorders in Stored Tuber Crops

Common physiological disorders and their causes

Physiological disorders in stored tuber crops are common occurrences that can significantly impact their quality and market value (Véras et al., 2021). Factors such as temperature, humidity, tuber age, and improper storage conditions contribute to the development of these disorders. One prevalent physiological disorder is sprouting, where shoots emerge from tubers during storage. Excessive sprouting leads to weight loss, firmness loss, and reduced tuber marketability (Véras et al., 2021). Physiological weight loss is another common disorder caused by the natural metabolic processes of tubers during storage. Respiration and transpiration of stored tubers contribute to weight loss, impacting overall tuber weight and quality (Lima et al., 2019). Environmental factors such as temperature and humidity can exacerbate weight loss in tubers. Internal discoloration or necrosis is a manifestation of physiological disorders in tuber crops. The accumulation of reducing sugars triggers Maillard reactions(Zhu et al., 2014), resulting in browning or darkening of tuber tissues. Improper storage conditions, high temperatures, and tuber injury contribute to internal discoloration and necrosis. In the case of cassava, post-harvest deterioration is a significant concern (Saravanan et al., 2015; Saravanan et al., 2016). Enzymatic and biochemical changes after harvest lead to quality degradation, loss of nutritional value, enzymatic browning, cyanogenic glucoside degradation, microbial spoilage, and textural changes. Chilling injury is another common physiological disorder observed in tuber crops stored at low temperatures. It causes tubers to become soft, develop surface pitting, and experience tissue breakdown (Cheema, 2010). Exposure to temperatures below the optimal range results in chilling injury and significant post-harvest losses.

Impact of storage conditions on disorder development

The impact of storage conditions on disorder development in tuber crops, including cassava, has been extensively studied and documented in the literature (Yan et al., 2016; Lalel et al., 2003; Bartz et al., 2009;

Mwitondi et al., 2021). Factors such as temperature, humidity, and ventilation are crucial in determining the extent of disorder development during storage.High temperatures during storage have been associated with an increased risk of physiological disorders in tuber crops. For instance, temperatures above 30°C have been found to promote the development of disorders such as vascular discoloration and internal necrosis in cassava (Yan et al., 2016). Curing is a postharvest treatment that can help to extend the storage life of root, tuber. This process plays a significant role in extending the shelf life of crops by promoting wound healing, strengthening the outer layers, and enhancing their overall quality (More et al., 2019). During curing, factors like temperature and humidity are carefully controlled to create an optimal environment for the crops. This promotes the sealing of wounds, reduces the risk of rot and spoilage, and helps retain moisture content, preventing excessive dehydration. Conversely, storing tubers at low temperatures can induce chilling injury, characterized by symptoms such as tissue softening, discoloration, and increased susceptibility to decay (Lalel et al., 2003). Humidity levels also influence disorder development in stored tubers. Excessive humidity can lead to increased water loss, promoting desiccation and shrivelling of tubers. Conversely, high moisture levels create a favourable environment for the growth of microorganisms, increasing the risk of rot and decay (Bartz et al., 2009).

Ventilation is another critical factor in tuber storage. Insufficient ventilation can result in the buildup of ethylene, carbon dioxide, and other metabolically produced gases, leading to accelerated deterioration and the development of disorders such as sprouting and internal browning (Mwitondi et al., 2021). By implementing appropriate storage conditions, including maintaining optimal temperature and humidity levels and providing adequate ventilation, the incidence, and severity of physiological disorders in stored tubers, including sweet potato and yams can be minimized. This

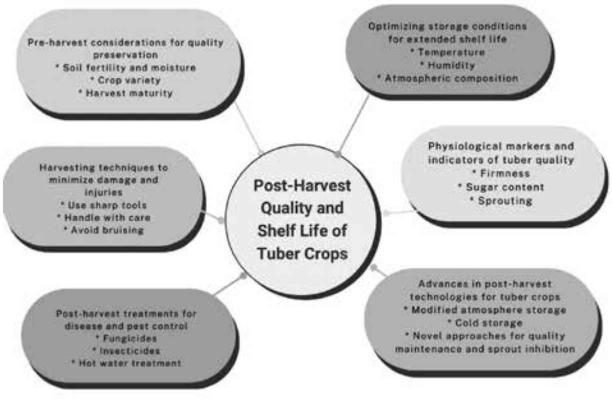

Fig. 1. Schematic diagram of physiological strategies for post-harvest quality and shelf-life of tuber crops

preservation of quality and nutritional value is essential in ensuring the marketability and usability of stored tuber crops.

Physiological approaches to mitigate disorders

Various physiological approaches can be utilized to mitigate physiological disorders in stored tubers and preserve their quality. These approaches encompass a range of techniques and treatments that specifically address underlying physiological processes and factors associated with disorder development. Some commonly employed physiological approaches are discussed below.

Temperature management: Proper temperature control is crucial for minimizing disorder development. Adjusting storage temperatures within optimal ranges for specific tuber crops can help reduce the incidence of disorders such as vascular discoloration, internal necrosis, and chilling injury (Kays, 1997). Specific temperature and humidity conditions for the curing of tubers can vary depending on the type of tuber and specific environmental factors. However, in general, optimal curing conditions for tropical tubers often involve temperatures ranging from 25°C to 35°C (77°F to 95°F) and relative humidity levels between 85% and 95%. For instance, sweet potatoes are commonly cured at temperatures around 30°C (86°F) with relative humidity maintained at approximately 90%. Cassava tubers, on the other hand, may require slightly higher temperatures, ranging from 32°C to 35°C (89.6°F to 95°F), while maintaining a relative humidity of 85% to 90% (Ravi and Aked, 1996; FAO, 1986)

Modified atmosphere storage (MAS): Creating a controlled atmosphere within storage facilities can help mitigate disorders. By regulating oxygen, carbon dioxide, and ethylene levels, MAS can effectively slow down physiological processes and delay the onset of disorders such as sprouting, decay, and internal browning (Valero et al., 2004).

Controlled humidity: Maintaining optimal humidity levels during storage is essential. Controlling humidity helps prevent excessive moisture loss, which can lead to tuber shrinkage, desiccation, and skin cracking. On the other hand, it also prevents excessive moisture buildup, which can contribute to rot and fungal growth (GraBmann et al., 2015).

Preharvest and post-harvest treatments: Various preharvest and post-harvest treatments can be applied to tubers to enhance their resistance to disorders. These treatments may include the application of protective coatings, antioxidants, fungicides, and growth regulators, which can help reduce oxidative stress, delay senescence, and inhibit microbial growth (Nguyen et al., 2021).

Hormonal regulation: Hormones play a significant role in tuber physiology and can be manipulated to mitigate disorders. For instance, applying plant growth regulators, such as ethylene inhibitors, can delay sprouting and senescence processes, reducing the risk of sprouting-related disorders.

Implementing these physiological approaches in tuber storage practices can significantly reduce the occurrence and severity of physiological disorders, improve the shelf life, and maintain the overall quality of stored tubers. These strategies are essential for ensuring the marketability and usability of tuber crops in various agricultural and commercial contexts.

Strategies for post-harvest management of tuber crops

Pre-harvest considerations for quality preservation

Pre-harvest considerations are essential for preserving the quality of tuber crops. Various factors and techniques can be employed to improve post-harvest outcomes. Research shows that pre-harvest pruning can reduce the occurrence of rotten roots in sweet potatoes during storage (Tomlins et al., 2002). The application of foliar phosphonates has been found to suppress tuber infections of potato late blight (Mayton et al., 2008). When applied as a pre-harvest foliar treatment, Glyphosate shows the potential for suppressing sprout growth in stored potato tubers (Paul et al., 2014). Pre-harvest curing of sweet potato roots under tropical conditions can enhance skin adhesion, chemical composition, and shelf life (Parmar et al., 2017). Effective biocontrol treatments before harvest can reduce aflatoxin accumulation during drying (Kinyungu, 2019). Additionally, considering pre-harvest practices and storage conditions is crucial for maintaining quality and preventing losses in nectarines and potatoes during storage (Foukaraki et al., 2014). These pre-harvest considerations contribute to preserving tuber crop quality and storage outcomes.

Implementing appropriate strategies before harvest can help minimize the risk of physiological disorders and maximize the shelf life of tubers. Here are some critical strategies for pre-harvest quality preservation:

- Optimal Harvest Time: Harvesting tubers at the right stage of maturity is essential to maintain their quality during storage. Delaying harvest beyond the optimal stage can increase the risk of physiological disorders and reduce the storage life of tubers.
- Proper Field Management: Good field management practices, such as appropriate irrigation, fertilization, and pest control, are essential to promote healthy tuber growth and minimize the occurrence of diseases and pests that can impact post-harvest quality.
- Integrated Pest Management (IPM): Implementing IPM strategies helps control pests and diseases sustainably. This approach combines various pest management techniques, including cultural practices, biological control, and judicious use of pesticides, to minimize chemical inputs while effectively managing pests and diseases.
- Tubers that are in good health generally exhibit an extended duration of storage as opposed to those that are damaged.
- Disease and Pest Monitoring: Monitoring tuber crops for diseases and pests allows for early detection and timely intervention. This can involve scouting the fields, inspecting plants for signs of diseases or pests, and taking appropriate measures, such as applying targeted treatments or removing infected plants to prevent the spread of pathogens or pests.
- Proper Handling and Storage Practices: Adequate care should be taken during harvesting, handling, and storage to prevent physical damage, bruising, and contamination of tubers. Gentle handling, using appropriate tools, and providing suitable storage conditions, such as optimal temperature and humidity levels, help maintain the quality and extend the shelf life of tubers.

Harvesting techniques to minimize damage and injuries

Harvesting techniques are crucial in minimizing damage and injuries to tuber crops. Research has shown that the choice of harvesting technique significantly affects tuber damage. Using new technology and avoiding mechanical injuries are essential in reducing tuber damage (Peters, 1996). In the case of potato tubers, mechanical injury during harvesting can be a significant concern, and factors such as the height of the drop and careful loading practices can impact the extent of injury (Zahara et al., 1961). For cassava roots, water loss from wounds caused during harvesting can lead to vascular discoloration and decreased quality (Marriott et al., 1978; Saravanan et al., 2015; Saravanan et al., 2016). Pre-harvest curing and preventing cuts, breaks, and skinning injuries can contribute to maintaining sweet potatoes' quality and shelf life (Tomlins et al., 2002). Similarly, mechanical damage during post-harvest handling of fruits and tubers is influenced by factors such as soil humidity and harvesting conditions (Martinez-Romero et al., 2004). Understanding and implementing proper harvesting techniques are essential for minimizing injuries and preserving the quality of tuber crops (Parmar et al., 2017; Ravi and Aked, 1996; Parmar et al., 2017).

Post-harvest treatments for disease and pest control

Post-harvest treatments for disease and pest control are crucial in preserving the quality of tuber crops. Storage roots of sweet potatoes are prone to various forms of post-harvest losses, including sprouting, diseases, and pests (Ray et al., 2010). Effective post-harvest handling and storage methods significantly minimize these losses (Ray, 2015). The occurrence of post-harvest spoilage in sweet potatoes can be attributed to factors such as diseases, pests, and storage conditions. Among the pests, the sweet potato weevil is a significant concern (Ray and Ravi, 2005). Similarly, yam tubers are susceptible to post-harvest diseases and pests, emphasizing the need for proper handling, storage, and control measures (Okigbo, 2004). The application of foliar phosphite has shown promising results in reducing disease symptoms in post-harvest potato tubers (Lobato et al., 2011). Implementing appropriate storage methods and considering resistance traits in yam genotypes can help control post-harvest microbial rot (Nyadanu et al., 2014). It is vital to integrate genotype selection, storage methods, and biological control measures to minimize post-harvest losses caused by pests and diseases (Kiaya, 2014).

Optimizing storage conditions for extended shelf life

Optimizing storage conditions is crucial for extending the shelf life of tuber crops. Various factors, including curing treatments, storage temperature, humidity control, ventilation, light exposure, disease and pest control, and storage duration, play significant roles in ensuring the quality and longevity of tubers during storage. Curing treatments and storage temperature significantly influence the quality of Chinese yams during storage (Lee and Park, 2013). Proper control of water temperature and contact time is crucial in hot water treatment to inhibit the sprouting and spoilage of cured sweet potatoes without compromising their shelf life (Sheibani et al., 2014). Storage temperature plays a vital role in determining sweet potato tubers' storage stability and quality (Krochmal-Marczak et al., 2020). Changes in storage conditions or treatment can affect Chinese yam tubers' nutrient composition and sensory qualities (Zhang et al., 2014). Optimizing storage procedures, including humidity control, is necessary for the successful storage and sprouting prevention of yam micro tubers (Ovono et al., 2010). Standardization and refinement of storage procedures are essential for conserving and preserving tuber crops (Benson et al., 2011). Maintaining appropriate humidity levels prevents excessive moisture, which can lead to rot, fungal growth, and tuber dehydration. Optimal ventilation and airflow in storage facilities help regulate temperature and humidity, preventing the accumulation of ethylene, carbon dioxide, and moisture that can accelerate tuber deterioration and storage disorders. Tubers should be stored in darkness or under low-light conditions to avoid greening caused by chlorophyll accumulation and synthesize toxic compounds that can affect tuber quality and shelf life. Implementing effective disease and pest control measures during storage is crucial to minimize post-harvest losses. Using appropriate fungicides, insecticides, or biocontrol agents helps prevent the spread of diseases and infestation by pests. Different tuber crops have specific storage durations that optimize their shelf life. Sweet potatoes, for example, have a relatively shorter shelf life and should be consumed within a few months, while certain potato varieties can be stored for several months under appropriate conditions. By carefully managing these factors, tubers can be stored for extended periods while maintaining quality and minimizing post-harvest losses.

Physiological markers and indicators of tuber quality

Non-destructive techniques play a crucial role in the quality assessment of root and tuber crops. Spectroscopic techniques, such as near-infrared reflectance spectroscopy and hyperspectral imaging, offer rapid and non-destructive evaluation of the quality of staple foods (Su et al., 2017). These techniques enable screening cassava storage roots for provitamin A carotenoids and assessing flesh color in sweet potatoes (Su et al., 2017; Sanchez et al., 2020). Other non-destructive methods, including X-ray imaging, laser light backscattering imaging, infrared thermal imaging, and ultrasonic technology, have also been applied for the quality evaluation of agricultural produce (Kotwaliwale et al., 2014; Chen and Sun, 1991; Farokhzad et al., 2020; Mizrach, 2008). X-ray imaging provides insights into internal quality, while laser light backscattering imaging and infrared thermal imaging offer non-destructive identification of fungal infections and quality assessment of foods, respectively (Kotwaliwale et al., 2014; Farokhzad et al., 2020; Sanchez et al., 2020). Ultrasonic technology enables fast and reliable evaluation of fresh fruit and vegetables during pre- and post-harvest processes (Mizrach, 2008). These techniques contribute to the detection of internal damage, identification of fungal infections, evaluation of texture, colour, and chemical composition, and overall quality assessment of tuber crops without causing physical harm to the samples (Farokhzad et al., 2020). They provide valuable tools for ensuring food safety, reducing post-harvest losses, and enhancing quality assurance in the storage and distribution of tuber crops (Sinha et al., 2017).

Role of physiological indicators in post-harvest decision making

Physiological indicators play a significant role in post-harvest decision-making. They provide valuable information about the quality and condition of agricultural produce, aiding in determining storage conditions, shelf life, and post-harvest treatments. Common indicators of post-harvest quality in fruits and vegetables include factors such as visual appearance, firmness, colour, aroma, taste, nutritional content, presence of decay or physical damage, and overall shelf-life (Barbosa-Cánovas et al., 2003). In the context of post-harvest losses in India's fruit and vegetable supply chain, a study identified thirty indicators to evaluate critical causal factors and guide policy decisions (Gardas et al., 2018). In the case of post-harvest processing of Norwegian farmed salmon, measurable indicators were specified to reduce food loss (Abualtaher and Bar, 2020). The choice of post-harvest technology and storage decisions is influenced by multi-criteria methodologies considering different indicators, such as efficiency, cost-effectiveness, and environmental impact (Lenin et al., 2014). For the smallholder farmers' post-harvest decisions, including storage and processing, the risk and time preferences are influencing criteria (Ruhinduka et al., 2020). Understanding the key factors leading to post-harvest losses and waste involves analysing performance criteria and their indicators. For specific crops like potatoes and sugar beets, storage decisions are crucial for minimizing post-harvest losses. Assessing the quality before storage and considering long-term storage effects are essential for making informed decisions (Bachmann and Earles, 2000). Economic and logistics indicators also play a role in assessing post-harvest loss reduction strategies (Gunasekera et al., 2017). The use of physiological indicators in post-harvest decision-making ranges from assessing ripeness and quality to considering efficiency, risk preferences, and environmental impact. By incorporating these indicators, stakeholders can make informed decisions to minimize post-harvest losses and optimize the storage and processing of agricultural produce.

Advances in post-harvest technologies for tuber crops

Modified atmosphere storage and controlled atmosphere storage

Modified atmosphere storage (MAS) and controlled atmosphere storage (CAS) are advanced post-harvest technologies that play a crucial role in extending the shelf life of vegetables, fruits, and tubers. The MAS involves modifying the composition of the surrounding atmosphere, typically by reducing oxygen levels and increasing carbon dioxide levels, to create an optimal storage environment (Rao, 2015). This technique effectively inhibits respiration, slows down metabolic processes, and reduces microbial growth, thereby delaying spoilage. On the other hand, CAS takes the concept of modified atmosphere storage further by precisely controlling the gas composition, temperature, and humidity, creating an ideal storage condition for tuber crops (Aharoni et al., 2007). By customizing and optimizing storage conditions based on specific crop requirements, CAS has shown remarkable success in minimizing weight loss, retarding sprouting, reducing physiological disorders, and preserving overall quality attributes of tuber crops such as potatoes and sweet potatoes (Rao, 2015; Aharoni et al., 2007). These technologies hold immense potential in improving post-harvest management practices and ensuring extended storage life for tuber crops, thus benefiting producers and consumers.

Cold storage and refrigeration technologies

Cold storage and refrigeration are essential for preserving the quality and prolonging the shelf life of tubers. Lower temperatures, such as 4°C, have decreased polyphenol oxidase (PPO) activity in potatoes and sweet potatoes, reducing browning and maintaining overall quality during storage (Sun et al., 2011). Ultrasound treatment has been shown to inhibit browning and improve the antioxidant capacity of fresh-cut sweet potatoes throughout the refrigeration period (Pan et al., 2020). In the case of sweet potato tuberous roots, a combination of low-temperature conditioning and cold storage promotes rapid sweetening while preserving quality (Li et al., 2018). Jerusalem artichoke tubers can benefit from refrigerated storage at zero degrees Celsius with a relative humidity of 90% (El-Awady and Ghoneem, 2011). These studies collectively emphasize the importance of cold storage and refrigeration techniques in preserving the quality and extending the storage life of tubers.

Novel approaches for quality maintenance and sprout inhibition

Advancements in post-harvest technologies for tuber crops have focused on novel approaches for sprout inhibition and quality maintenance. One such approach is the application of essential oils as a natural and alternate method for inhibiting and inducing the sprouting of potato tubers (Shukla et al., 2019). This eco-friendly method offers an alternative to using harmful chemicals and maintaining expensive cold storage conditions. Additionally, nonthermal treatments have shown promise in enhancing the shelf stability of fresh-cut potatoes, with novel nonthermal techniques demonstrating inhibitory effects on potato tuber sprouting (Rashid et al., 2021). Evaluating ecologically acceptable sprout suppressants has also been explored to enhance dormancy and potato storability, providing a wide range of options to prevent sprouting and maintain tuber quality (Gumbo et al., 2021). Furthermore, using microcapsules containing methyl jasmonate has shown preserving effects on post-harvest potato tubers, inhibiting sprouting and maintaining quality attributes. These advancements offer valuable insights into improving tuber crop sprout inhibition and quality maintenance.

Future Directions and Challenges

Emerging trends in post-harvest physiology research

The field of post-harvest physiology research is continuously evolving, and several emerging trends offer exciting prospects for the future. One key direction is the exploration of novel preservation techniques that can extend the shelf life and enhance the quality of harvested produce. Nonthermal technologies, such as high-pressure processing, pulsed electric fields, and ultrasound treatment, have shown promise in maintaining the freshness and nutritional attributes of fruits and vegetables (Sun et al., 2011; Pan et al., 2020). These technologies can potentially replace traditional thermal treatments, offering more energy-efficient and environmentally friendly options. Another area of focus is the development of intelligent packaging systems that incorporate sensors, indicators, and active materials to monitor and regulate the post-harvest environment. These advanced packaging solutions can provide real-time information on the quality and freshness of the produce, detect spoilage factors, and release bioactive compounds to extend shelf life (López-Rubio et al., 2020; Singh et al., 2021). Additionally, integrating nanotechnology in packaging materials promises enhanced barrier properties and controlled release of antimicrobial agents, further contributing to post-harvest preservation (Chaudhry et al., 2018).

There is growing interest in understanding the molecular and genetic mechanisms underlying post-harvest processes. Advances in genomics, transcriptomics, proteomics, and metabolomics have enabled researchers to unravel the complex networks regulating fruit ripening, senescence, and post-harvest responses (Ding et al., 2019; Huang et al., 2021). This knowledge can be leveraged to develop targeted interventions, such as genetic modification or gene editing approaches, to improve post-harvest traits and reduce losses. However, along with these promising avenues, several challenges need to be addressed. Sustainable post-harvest practices that minimize waste, reduce energy consumption, and mitigate environmental impact are of utmost importance. Finding alternative solutions to synthetic chemicals for pest and disease management, such as biocontrol agents and natural compounds, is a critical area for further research (Adu-Gyamfi et al., 2020; Fuentes et al., 2021). Additionally, post-harvest research should consider the specific requirements and constraints of different crop types and geographical regions, ensuring the practical applicability and relevance of the developed technologies.

Challenges and opportunities and potential areas for enhancing tuber crop quality

Tuber crops, such as potatoes, sweet potatoes, yams andtaro play a vital role in global food security. Enhancing tuber crop quality and extending their post-harvest shelf life are important challenges in ensuring food availability and reducing post-harvest losses. Here is some information on the challenges, opportunities, and potential areas for future investigation in these areas:

Challenges for enhancing tuber crop quality:

1. Physiological Changes: Tuber crops undergo various physiological changes during storage, including sprouting, weight loss, starch degradation, and accumulation of reducing sugars. These changes negatively impact quality and shelf life.
2. Post-Harvest Losses: Tuber crops are susceptible to damage during harvesting, handling, transportation, and storage. Mechanical injuries, diseases, and pests can lead to significant losses, reducing their market value.
3. Sprouting and Dormancy: Sprouting is a significant issue during storage, as it affects tuber crops' quality and nutritional value. Managing dormancy and preventing sprouting is crucial for maintaining their quality.
4. Pathogen and Disease Control: Tuber crops are prone to various pathogens and diseases, such as late blight in potatoes. Controlling these diseases is essential for preserving tuber quality and preventing post-harvest losses.

Opportunities for enhancing tuber crop quality:

1. Breeding and Genetic Improvement: Developing improved varieties with enhanced resistance to diseases, pests, and physiological disorders can improve tuber crop quality. Breeding programs can focus on traits like extended shelf life, reduced sprouting, and better storage characteristics.
2. Pre-Harvest Factors: Implementing appropriate pre-harvest practices, such as optimizing irrigation, nutrient management, and crop protection strategies, can positively impact tuber quality and post-harvest performance.
3. Post-Harvest Technologies: Utilizing post-harvest technologies like modified atmosphere storage, controlled atmosphere storage, and low-temperature storage can help extend the shelf life of tuber crops. These technologies slow down physiological processes and inhibit microbial growth.
4. Integrated Pest Management (IPM): Implementing IPM practices can effectively control pests and diseases while minimizing the use of chemical pesticides. IPM strategies include cultural practices, biological control agents, and resistant varieties.

Potential areas for future investigation on strategies for enhancing post-harvest quality and shelf life of tuber crops:

1. Physiological Mechanisms: Understanding the underlying physiological mechanisms involved in tuber crop quality changes during storage can provide insights into developing targeted strategies for maintaining quality and extending shelf life.
2. Post-Harvest Treatments: Investigating the effects of various post-harvest treatments, such as applying antioxidants, ethylene inhibitors, and plant growth regulators, can help identify effective methods for reducing sprouting, weight loss, and decay.
3. Molecular Approaches: Exploring the molecular mechanisms underlying tuber development, dormancy, and sprouting can lead to identifying critical genes and regulatory pathways. This knowledge can be used to develop molecular tools for improving tuber quality and storage life.
4. Sustainable Packaging: Researching sustainable packaging materials and technologies that minimize moisture loss, control gas exchange, and prevent mechanical damage can contribute to maintaining tuber quality during storage and transportation.
5. Consumer Preferences and Market Demand: Studying consumer preferences for tuber crop quality attributes, such as taste, texture, and nutritional value, can help guide breeding programs and post-harvest interventions to meet market demands.

Continued research and innovation in these areas can contribute to enhancing the quality, shelf life, and market value of tuber crops, ensuring their availability and reducing post-harvest losses

Conclusion

In conclusion, insights from physiological perspectives highlight critical strategies for enhancing the post-harvest quality and shelf life of tuber crops. Understanding factors such as respiration rates, ethylene production, and water loss is crucial in improving post-harvest management (Atanda et al., 2011). Implementing modified atmospheric packaging, controlled temperature and humidity conditions, and natural compounds can effectively extend shelf life. Further research and development are needed to optimize these strategies for practical application, reducing losses and increasing the market value of tuber crops.

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