



Development of Waste-derived, Nutrient-enriched Biodegradable Coatings for Extending Shelf Life of Tropical Fruits in Sub-Saharan Africa

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10.18805/ag.RF-420

ABSTRACT

Postharvest losses of fruits and vegetables in Sub-Saharan Africa (SSA) represent a critical challenge to food security and economic stability, with losses estimated at 30-50%. This review critically examines the development and application of waste-derived, nutrient-enriched biodegradable coatings as a sustainable and transformative solution to this issue. It analyses the multifaceted postharvest challenges in SSA, including infrastructural gaps, crop diversity and weak market dynamics, which conventional preservation methods fail to address. The article details the principles of biodegradable coatings, highlighting their mechanisms of action as barriers to moisture, gases and microbes and surveys conventional biopolymers like starch, chitosan and alginate. Moving beyond current practices, the review identifies emerging research frontiers tailored for SSA, such as the valorisation of local agro-wastes (e.g., cassava peels, mango kernels), smart responsive coatings, nanostructured biopolymers, nutrient fortification and microbiome-aware design. These innovations position coatings not merely as passive barriers but as active, multifunctional preservation systems. Commodity-specific case studies underscore the potential of these coatings to extend the shelf life of key tropical fruits and vegetables. However, significant barriers to adoption persist, including a scarcity of field trials under real SSA conditions, high costs, low consumer awareness and underdeveloped regulatory frameworks. The review concludes that for biodegradable coatings to achieve their full potential, a systems approach is essential, integrating technological innovation with supportive policies, farmer training, consumer education and digital tools for supply chain management. This holistic strategy can position biodegradable coatings as a cornerstone of sustainable, resilient and nutrition-sensitive food systems in SSA.

Key words: Biodegradable coatings, Postharvest losses, Shelf-life extension, Waste-derived biopolymers.

Postharvest losses of fruits and vegetables in Sub-Saharan Africa (SSA) represent a significant challenge to food security, with losses estimated to range from 30% to 50% before consumption. These losses have far-reaching implications, not only for the region's food supply but also for economic stability and the livelihoods of smallholder farmers. The causes of postharvest losses are multifaceted, involving a combination of biological, technical and infrastructural factors. Biological factors, such as perishability and susceptibility to diseases and pests, exacerbate the situation, especially when combined with inadequate harvesting, handling and storage practices. Furthermore, technical and infrastructural challenges, such as the lack of cold chain infrastructure, limited access to efficient packaging and unreliable transportation systems, significantly contribute to the high rates of spoilage. These issues are compounded by socioeconomic factors, such as limited access to technology and market constraints, which affect smallholder farmers' ability to mitigate losses (Makule *et al.*, 2022; Etefa *et al.*, 2022).

A particularly promising solution to reducing postharvest losses in SSA is the use of biodegradable and edible coatings for fruits and vegetables. These coatings offer a low-energy, cost-effective and scalable alternative to traditional plastic-based packaging. The benefits of

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How to cite this article: Tingan, F., Mensah, F.P., Konyannik, B.Y., Fadavi, C., Mahama, I.A., Norku, B., Sayibu, S. and Seidu, M. (2026). Development of Waste-derived, Nutrient-enriched Biodegradable Coatings for Extending Shelf Life of Tropical Fruits in Sub-Saharan Africa. *Agricultural Reviews*. 47(5): 691-703. doi: 10.18805/ag.RF-420.

Submitted: 15-12-2025 **Accepted:** 13-03-2026 **Online:** 01-04-2026

coatings extend beyond preservation, as they can extend the shelf life of perishable produce, reduce spoilage and enhance food safety without relying on harmful synthetic

materials. Given the growing environmental concerns associated with plastic waste, the shift towards biodegradable coatings represents a critical opportunity for both environmental sustainability and economic resilience in SSA. Notably, biodegradable coatings can be derived from natural, renewable sources, such as starch, chitosan and proteins, which are abundant in the region's agricultural sector. This makes their adoption particularly relevant to the unique agricultural and economic context of SSA (Jahangiri *et al.*, 2024; Pirzada *et al.*, 2020).

This review aims to critically analyse the development and application of biodegradable and edible coatings in SSA, focusing on their potential to address the pressing issue of postharvest losses. The article will examine the latest advances in coating technologies, explore novel directions for future research and highlight existing gaps in knowledge and practice. By investigating the interplay between coating materials, the regional agricultural context and technological innovations, this review seeks to provide a comprehensive overview of the potential for biodegradable coatings to transform postharvest management in SSA. The ultimate goal is to chart a path forward for integrating these innovative technologies into practical, scalable solutions for the region's agricultural challenges.

Postharvest challenges specific to SSA

Limited cold storage and unreliable electricity

Among the most pressing post-harvest challenges in SSA is the lack of cold storage infrastructure together with the unavailability of electricity. The use of cold storage infrastructure is vital in retaining the quality of perishable fruits and vegetables; yet in many areas across SSA, this issue persists. For example, in rural areas where most small farm owners are based, the absence of cold storage infrastructure causes food deterioration and losses of 30%-50% of harvested food products (Makule *et al.*, 2022). The lack of sufficient cooling infrastructure further exacerbates the sensitivity of food products to deterioration, especially tropical fruits like mangoes and bananas that are best stored in cooled and infrastructurally enabled surroundings in order to extend the life span of the products. Further absence of electricity in many areas of SSA makes food preservation through retaining the cold chain difficult for

farmers in attempting to protect food products or access cooling infrastructure or technologies (Rutta, 2022).

Various solutions have been proposed over the years because of the gaps in the current infrastructure; however, most of these solutions are yet to be utilized due to the prevailing high costs and lack of awareness regarding the products being promoted in preference over those requiring refrigeration (Sibanda and Workneh, 2020). Despite the challenges in investing in cold chains or other forms of renewable solutions, there are opportunities in meeting this challenge (Mayanja and Oluk, 2023) (Fig 1).

Crop diversity and postharvest losses

The diversity of products in SSA's agriculture sector also remains quite high and includes tropical fruits like mangoes, papayas, avocados and bananas, in addition to indigenous veggies like amaranth, African nightshade and spider plant. The post-harvest factors these products encounter is quite different from others due to the perishable nature of the products and unavailability of proper storage and processing infrastructure. For tropical fruits, diseases like fungal infections, *Colletotrichum* and *Fusarium* have been significant factors in the loss of post-harvest yield of fruits in SSA due to unfavorable climatic factors (Kouadia *et al.*, 2019). Damage from bruises due to mechanical damage, inappropriate handling and storage in addition to the warmer climate have also resulted in increased disposal of spoil fruits (Sharma *et al.*, 2024).

The local veggies also have challenges of their own such as a low market demand and poor post-harvest handling. Despite the nutritional and local significance of the veggies, they often suffer from poor post-harvest handling and hence incur high losses (Strecker *et al.*, 2022). The varieties of the veggies, each handled in different ways based on distinct features of the veggies, highlight the need for different approaches in post-harvest handling.

Smallholder-dominated, informal markets and weak logistics

The post-harvest losses in SSA are further hampered by the nature of markets in agriculture that are mostly smallholder-dominated and involve informal markets. The smallholder farmers do not have access to advanced post-harvest technologies and infrastructure and the

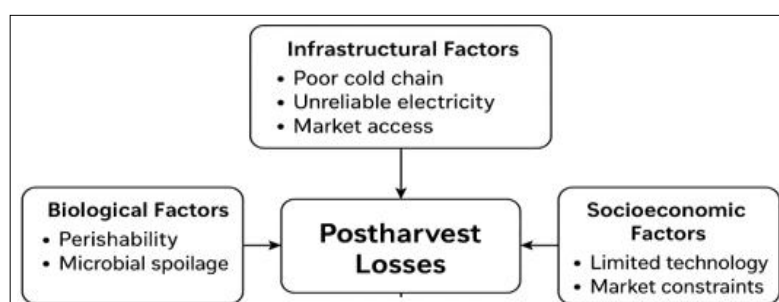


Fig 1: Conceptual framework of postharvest losses in Sub-Saharan Africa.

involvement in informal markets hinders the standardization of post-harvest management approaches (Kansanga *et al.*, 2023). The informal markets are characterized by poor logistics infrastructure, no access to cold storage infrastructure and inefficient transport networks.

All this further hampers the reduction of post-harvest losses in SSA. It has also been observed that in most cases, the vegetables and fruits are distributed over long distances through unideal approaches, further leading to the wastage of products owing to their deterioration (Gelaye, 2024). Absence of synchronization among farmers, suppliers and consumers further hampers this process through lack of standard approaches in post-harvest management.

Low awareness of coatings and limited food safety frameworks

The consumer landscape in SSA also poses challenges for the adoption of innovative postharvest solutions, such as biodegradable coatings for fruits and vegetables. Consumer awareness of the potential benefits of coatings remains low and there is limited understanding of their role in enhancing shelf life and improving food safety (Ahlawat and Kumari, 2025). Notably, there is a lack of regulatory frameworks to standardise the use of such technologies, which hinders their widespread adoption (Picot-Allain *et al.*, 2022). The absence of robust food safety frameworks further exacerbates the situation, as consumers are often unaware of the risks associated with improperly stored or handled produce. Without adequate regulation and consumer education, the potential for widespread adoption of innovative postharvest technologies like edible coatings remains limited.

The socio-economic barriers, such as income levels and education, can influence consumer behaviour, with those in higher income brackets more likely to accept biofortified or coated foods (Etumnu, 2016) (Table 1). Addressing gaps in consumer awareness and regulatory frameworks is essential for promoting the acceptance and scalability of new postharvest technologies. Enhancing consumer education on the benefits of coatings and improving food safety standards would support reducing postharvest losses and improving food security in SSA.

Principles and current practices of biodegradable and edible coatings

Barriers to moisture, gases and microbes

The effectiveness of edible coatings is rooted in their ability to act as barriers against moisture, gases and microbial contamination. Polysaccharides and lipids form hydrophilic and hydrophobic matrices, respectively, which reduce water loss and maintain firmness in perishable produce (Buṭu *et al.*, 2024; Matche and Singh, 2023). In addition, coatings regulate the exchange of gases such as oxygen and carbon dioxide, thereby slowing respiration and delaying ripening, a mechanism that mimics modified atmosphere storage (Tapia-Blácido *et al.*, 2018; Dhall, 2013). Beyond passive

Table 1: Major causes of postharvest losses in Sub-Saharan Africa and their implications for tropical fruits.

Cause/driver	Description	Affected commodities	Estimated loss range (%)	Implications
High ambient temperature and humidity	Accelerates respiration, ethylene production and microbial growth.	Mango, papaya, tomato, leafy greens	30-50	Rapid ripening and decay; fungal proliferation.
Inadequate cold storage and poor electricity access	Limited cold chain facilities; intermittent power supply.	Avocado, banana, mango	25-40	Reduced shelf life; softening and spoilage.
Mechanical damage during harvest and transport	Rough handling, overpacking and lack of cushioning.	Banana, avocado, tomato	20-35	Bruising, tissue breakdown, accelerated spoilage.
Microbial infection	Fungal and bacterial contamination (e.g., <i>Colletotrichum</i> , <i>Fusarium</i>).	Mango, papaya, leafy vegetables	15-30	Postharvest rot; loss of marketable quality.
Extended, informal supply chains	Multiple intermediaries, poor transport conditions.	Banana, tomato, leafy greens	20-40	Quality deterioration and market rejection.
Limited packaging and preservation technologies	Lack of affordable alternatives to plastics.	Fruits and vegetables (general)	25-50	Accelerated moisture loss; poor appearance.

Source: (Gelaye, 2024; Picot-Allain *et al.*, 2022).

barriers, coatings can be enriched with antimicrobial and antioxidant compounds such as essential oils, phenolics, or herbal extracts, providing active defence against microbial growth and oxidative degradation (Rajial *et al.*, 2024; Zaritzky, 2010). Collectively, these mechanisms protect perishable produce from both physical and biochemical deterioration, making coatings a critical tool for reducing losses in perishable supply chains.

Conventional biopolymers for edible coatings

The most widely studied edible coatings rely on biopolymers derived from renewable resources such as starch, alginate, chitosan and gums. Starch is abundant, inexpensive and valued for its film-forming capacity, though its poor water resistance necessitates chemical or physical modification (Rostamabadi *et al.*, 2024; Veiga-Santos and dos Ouros, 2024). Alginate, extracted from brown seaweed, offers strong gel-forming properties in the presence of calcium ions and can be combined with other polymers to improve mechanical stability (Wardejn *et al.*, 2024). Chitosan, derived from chitin, is notable for its inherent antimicrobial and antifungal properties, which have been exploited in composite coatings enriched with essential oils (Elgadir *et al.*, 2024; Díaz-Montes and Castro-Muñoz, 2021) (Fig 2). Gums such as gum Arabic and xanthan gum serve as hydrocolloids that enhance texture and barrier properties, especially when blended with starch or alginate (Marasinghe *et al.*, 2024; Ravindran *et al.*, 2024). While these biopolymers are promising, limitations in mechanical strength, transparency and water vapour resistance remain critical challenges, requiring further innovation and adaptation for SSA's climatic conditions.

Feasible low-tech application methods

The practical deployment of edible coatings depends heavily on the method of application, with dipping, brushing and spraying being the most common. Dipping ensures uniform coverage but can lead to excess use of coating material, making it inefficient for large-scale operations. Brushing allows for precise, targeted application but is labour-intensive and best suited for small-scale or artisanal

production (Xiao, 2021). Spraying, by contrast, provides consistent coverage and is scalable, making it the most efficient option for industrial applications, though it requires initial investment in atomising equipment (Andrade *et al.*, 2012). From a sustainability perspective, spraying also minimises material waste and energy inputs compared to dipping and brushing (Buṭu *et al.*, 2024; Jurić *et al.*, 2024; Avramescu *et al.*, 2020) (Table 2). For SSA, where low-cost, adaptable solutions are critical, dipping and brushing remain feasible for smallholder farmers, while spraying holds promise for cooperative packhouses and larger-scale value chains.

Emerging directions in biodegradable coating research for SSA

The development of biodegradable coatings tailored for Sub-Saharan Africa (SSA) is moving beyond conventional biopolymers toward advanced, multifunctional materials. These innovations draw on locally available resources, frontier material science and nutrition-sensitive agriculture frameworks (Fig 3).

Waste-derived biopolymers

Agro-waste valorisation presents a sustainable pathway for generating biopolymers such as cellulose, starch and chitosan from materials like cassava peels, banana pseudo-stems and mango kernels. These raw materials are abundant in SSA and offer dual benefits: reducing agro-waste while producing low-cost, biodegradable packaging alternatives (Nath, 2024; García-Mahecha *et al.*, 2023). Their biodegradability and biocompatibility make them suitable for edible coatings, with demonstrated applications in packaging, mulching films and fruit surface treatments (Garg *et al.*, 2024; Ashitha *et al.*, 2020) (Table 3). Importantly, local production of these coatings aligns with circular economy principles, promoting value addition within rural communities and reducing dependence on imported synthetic polymers (Valle *et al.*, 2024; Ni and Friedman, 2024). Despite this potential, challenges persist around standardisation, scalability and cost competitiveness compared to plastics, highlighting the need for region-specific techno-economic evaluations.

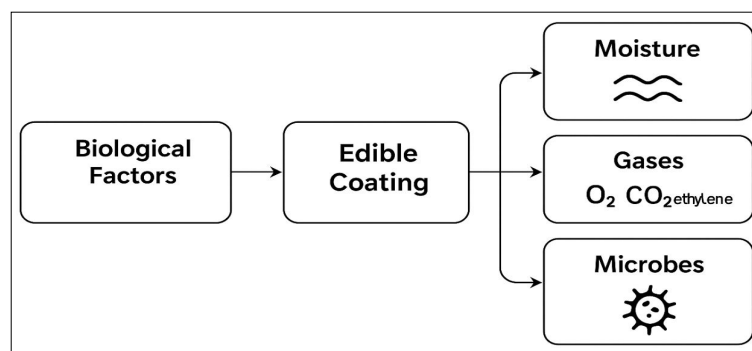


Fig 2: Mechanism of action of biodegradable and edible coatings.

Table 2: Common biopolymers used in edible coatings and their functional properties.

Biopolymer	Natural source	Key functional properties	Advantages	Limitations	Example applications
Starch	Cassava, maize, potato, rice	Excellent film-forming ability; transparent and tasteless; biodegradable	Abundant and inexpensive; compatible with food systems	Poor water vapor resistance; brittle without plasticizers	Mango and tomato coatings blended with gums or lipids
Alginate	Brown seaweed	Forms strong gels in presence of Ca ²⁺ ; good oxygen barrier	Edible, biocompatible, low toxicity	Poor moisture barrier in high humidity	Apple and banana coatings with calcium chloride crosslinking
Chitosan	Shellfish waste, fungal biomass	Cationic polymer; antimicrobial and antifungal; good gas barrier	Natural antimicrobial; enhances shelf life	Solubility limited to acidic conditions	Antimicrobial coatings for avocado, papaya
Pectin	Citrus peels, apple pomace	High hydrophilicity; forms cohesive films	Renewable, biodegradable	Sensitive to moisture; weak mechanical strength	Used in fruit surface films combined with lipids
Gum arabic	Acacia tree exudates	Excellent emulsifier and film-forming properties	Enhances surface gloss; biodegradable	Weak mechanical stability when used alone	Mango coatings with starch-gum blends
Pullulan	Microbial fermentation (<i>Aureobasidium pullulans</i>)	Highly transparent and oxygen-impermeable	Excellent gloss and flexibility	Costly and limited regional availability	Coatings for high-value fruits (berries, grapes)
Gelatin	Animal by-products	Protein-based; forms flexible, transparent films	Good elasticity; compatible with edible lipids	Non-vegan; moisture sensitive	

Source: (Ravindran *et al.*, 2024; Díaz-Montes and Castro-Muñoz, 2021).**Table 3:** Agro-waste sources and derived biopolymers for coating development in SSA.

Agro-waste source	Derived biopolymer/ component	Extraction or conversion method	Functional properties	Potential coating applications	Regional availability in SSA
Cassava peels	Starch, cellulose	Washing → drying → milling → starch extraction (aqueous)	Good film-forming ability; biodegradable; hydrophilic	Base polymer for edible films; blending with lipids/gums for moisture resistance	Widely available (Nigeria, Ghana, Tanzania)
Banana pseudo-stems	Cellulose, hemicellulose, lignin	Alkaline treatment → bleaching → microfibrillation	High tensile strength; good gas barrier; biodegradable	Reinforcement for starch-based coatings or nanocellulose composites	High availability (Uganda, Kenya, Rwanda)
Mango kernels	Starch, oil, polyphenols	Solvent extraction → starch isolation → drying	Film-forming; antioxidant and antimicrobial properties	Active coatings for high-value tropical fruits	Seasonal abundance in West and East Africa
Pineapple leaves	Nanocellulose	Acid hydrolysis → mechanical homogenisation	High crystallinity; reinforces mechanical and barrier strength	Nanocomposite coatings for moisture and gas control	Abundant in Ghana, Côte d'Ivoire, Kenya
Sisal fibers	Cellulose, lignin	Mechanical extraction → alkali delignification	Good tensile strength; biodegradable	Structural reinforcement for biodegradable films	Widely grown in Tanzania and Kenya
Cereal bran and husks (e.g., maize, rice)	Polysaccharides, proteins	Milling → enzymatic hydrolysis → drying	Good oxygen barrier; low water permeability	Composite coatings with starch or chitosan	Common in most SSA countries

Source: (Rozas *et al.*, 2025; Chandrababu *et al.*, 2024; Phillip *et al.*, 2024).

Smart and responsive coatings

Smart coatings represent a next-generation approach, integrating materials that respond to ethylene accumulation, microbial activity, or pH fluctuations. Ethylene scavenging coatings incorporating agents like potassium carbonate can delay fruit ripening, while antimicrobial polymer films with embedded nanoparticles inhibit microbial growth (Gaikwad *et al.*, 2025; El Guerraf *et al.*, 2024). Similarly, pH-responsive films provide visual indicators of spoilage, enabling real-time quality monitoring (Zhang *et al.*, 2025; Pawar and Rana, 2019). Globally, such technologies remain in the early adoption phase due to high production costs and concerns over the overuse of active agents (Bhattacharya *et al.*, 2023). For SSA, the relevance of these coatings lies in their potential integration once basic biodegradable coating use is established. Their application could bridge postharvest technology gaps by reducing losses in long, informal supply chains while supporting consumer trust through visible freshness indicators (Singh *et al.*, 2025; Yogita *et al.*, 2024).

Nanostructured biopolymers

Nanocellulose derived from agro-residues such as pineapple leaves and sisal fibres offer superior mechanical strength, barrier performance and antimicrobial potential for coating formulations (Vanaraj *et al.*, 2024). Incorporating nanostructures enhances gas and moisture barrier properties, crucial for tropical environments with high humidity (Zhao *et al.*, 2025). Nanocomposite films also exhibit antioxidant activity, further extending fruit shelf life (Türker, 2024). The nanostructures used in these formulations have unique properties that make them useful for food packaging. For example, nanocellulose reinforcement features rod-like cellulose nanocrystals (5-20 nm diameter, 100-500 nm length) embedded in a polymer matrix, showcasing its crystalline structure and hydrogen bonding networks. Chitosan nanoparticles (50-200 nm diameter) have a positively charged shell that encapsulates antimicrobial cargo, demonstrating a membrane disruption mechanism against bacterial cells.

Notably, nanoemulsion structures feature lipophilic droplets (50-200 nm) dispersed in a hydrophilic continuous phase, stabilized by a surfactant layer. Nanoencapsulation

systems include unilamellar and multilamellar liposomes (100-500 nm) with bilayer phospholipid membranes that compartmentalize hydrophobic and hydrophilic bioactive compounds (Fig 4). However, debates persist around nanoparticle migration, food safety and regulatory oversight, particularly in SSA, where regulatory frameworks for nanomaterials are underdeveloped (Mishra *et al.*, 2024; Ghanbarzadeh *et al.*, 2015). Addressing these concerns requires collaborative policy development and consumer education to balance performance benefits with health and safety assurance.

Microbiome-aware coating design

In SSA, spoilage is often driven by polymicrobial consortia thriving under hot and humid conditions. Conventional coatings with broad-spectrum antimicrobials may be insufficient in these contexts. A novel direction involves metagenomics-guided coating design, which tailor antimicrobial activity against dominant spoilage organisms while minimising disruption of beneficial microbiota (Anupama *et al.*, 2025). Such precision approaches could extend shelf life more effectively than generic formulations and reduce the risk of fostering antimicrobial resistance (Mäki *et al.*, 2023; Schmidt *et al.*, 2017, 2018). However, the integration of genomics into coating design is still experimental, requiring interdisciplinary collaboration between microbiologists, material scientists and agronomists.

Commodity-specific case studies in SSA

The perishable crop commodity groups in SSA include high-value export fruits like mangoes, papayas and avocados, as well as staple crops like bananas, plantains, tomatoes and leafy vegetables (Mohanapriya *et al.*, 2024). These crops are crucial for food security and export earnings. However, they face substantial postharvest losses due to factors like inadequate infrastructure, poor handling and lack of cold storage.

Mangoes, papayas and avocados are valuable export products, but face losses due to premature harvesting, fungal diseases and high temperatures (Geremu *et al.*, 2022; Rimpika *et al.*, 2021). Inexpensive materials can help reduce respiration rates and disease incidence, opening up export opportunities. Bananas and plantains

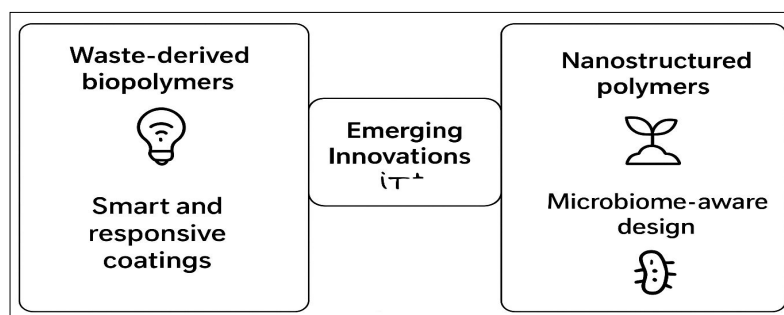


Fig 3: Emerging innovations in biodegradable coatings for SSA.

are widely consumed in SSA, but suffer significant losses due to poor handling, high moisture and warm climates (Kikulwe *et al.*, 2018). Social factors, like resource constraints in female-headed households, exacerbate these losses. The lack of cold storage infrastructure and poor logistics networks further worsen this aspect of food preservation (Mensah *et al.*, 2025).

Tomatoes and leafy vegetables are essential in SSA's daily diet, but face substantial losses due to inadequate packaging, lack of pre-cooling and poor storage capacity (Amissah *et al.*, 2025). The particular category of veggies referred to includes amaranth and nightshade veggies that are more fragile compared to other veggies like tomatoes (Tschirley *et al.*, 2010). Antimicrobial or antioxidant coatings could be a cost-effective preservation solution, but research is still in its early stages. Lab research shows promise, but field studies involving SSA value chains are needed to develop applicable solutions.

Physiological and microbiological outcomes

Edible coatings contribute to postharvest quality by delaying physiological ripening processes and suppressing microbial growth. By modulating gas exchange and reducing respiration rates, coatings extend the shelf life of perishable produce such as mangoes, tomatoes and leafy greens (Zdulski *et al.*, 2024). Antimicrobial agents incorporated into coatings such as essential oils, phenolics and chitosan effectively inhibit microbial colonisation and decay during storage (Muñoz-Tebar *et al.*, 2023; Aguilar-Veloz *et al.*, 2020). Studies also demonstrate that coatings can lower ethylene production and delay enzymatic browning, further preserving quality under tropical conditions. These physiological and microbiological

benefits make coatings a valuable tool for mitigating losses in SSA's hot and humid environments, where pathogens thrive and supply chains are prolonged.

Environmental and economic perspectives in SSA

Plastic alternatives and recycling limitations

Plastic remains the dominant packaging material in SSA, yet the region faces acute challenges in managing plastic waste due to weak recycling infrastructure. Urban centres generate increasing volumes of single-use plastics, but less than 10% is recycled, with most ending up in landfills, waterways, or open dumps (Ziani *et al.*, 2023). Biodegradable coatings offer a compelling alternative by eliminating the need for synthetic plastic films while maintaining protective functions for perishable produce. Their biodegradability and renewable origin reduce environmental pollution and align with global sustainability goals. For SSA, where waste management systems are underdeveloped, coatings present an attractive option for reducing reliance on plastics while simultaneously addressing postharvest losses.

Cost considerations and local sourcing

Affordability is critical in SSA, where smallholder farmers and informal traders dominate the fresh produce sector. For coatings to be viable, they must be produced at low cost and preferably from locally available raw materials such as cassava peels, mango kernels, or banana pseudo-stems (Gupta *et al.*, 2022). Locally sourced production not only reduces dependency on imports but also stimulates rural bioeconomies and creates employment opportunities (Sørensen *et al.*, 2022). However, cost constraints remain a significant challenge: commercial biopolymers like alginate or chitosan are often expensive and inaccessible

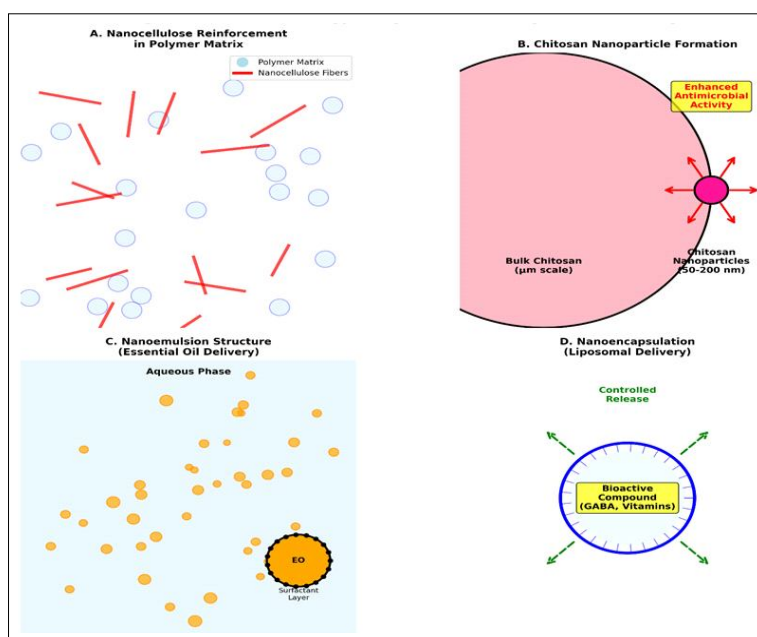


Fig 4: Nanotechnology integration in coatings.

in SSA markets. Developing low-cost extraction and processing methods tailored to regional agro-wastes is therefore essential to ensure competitiveness with both plastics and traditional packaging.

Competing with traditional packaging

A critical debate concerns whether biodegradable coatings can realistically outcompete traditional, low-cost packaging methods such as banana leaves, jute sacks and woven baskets. These materials are widely used in informal markets and are deeply embedded in local food systems (Samanta *et al.*, 2015). While coatings offer superior preservation by delaying ripening and suppressing microbial growth, traditional packaging has cultural acceptance, availability and near-zero cost on its side (Jahangiri *et al.*, 2024). Thus, coatings may be most viable as complementary technologies, enhancing the performance of traditional packaging rather than replacing it outright. For example, applying coatings to tomatoes transported in woven baskets could reduce spoilage while maintaining existing distribution practices. The environmental and economic dimensions of edible coatings in SSA underscore both opportunities and constraints. Coatings provide a promising plastic alternative, particularly in regions with poor recycling infrastructure and offer potential economic benefits through local production from agro-wastes (Soni *et al.*, 2023). However, cost competitiveness and the need for SSA-specific LCA evidence remain unresolved challenges. Moreover, the cultural entrenchment of traditional packaging suggests that coatings may succeed best when positioned as complementary innovations rather than direct substitutes.

Integration into SSA food systems

Smallholder adoption barriers

Adoption of coatings by smallholder farmers, the backbone of SSA's food production, faces several challenges, including limited awareness, lack of technical training and high input costs. Education levels and access to extension services directly influence farmers' capacity to understand and implement new technologies (Mabe *et al.*, 2021). Where extension systems are weak, farmers rely on informal knowledge networks, which may not disseminate accurate information about coating benefits. Financial barriers are equally critical: most smallholders operate with minimal access to credit and are hesitant to invest in untested technologies (Kamau *et al.*, 2022) (Fig 5). The absence of cooperative financing models and local processing units for coating materials further limits accessibility. To promote adoption, initiatives should emphasize farmer training, demonstration plots and inclusive financing schemes that lower entry costs and build confidence in coating technologies.

Synergies with other interventions

Integrating coatings with complementary technologies such as evaporative cooling and improved packaging offers a powerful pathway to strengthen SSA's postharvest systems.

Evaporative cooling using simple, locally available materials such as charcoal, clay, or sand provides an affordable, low-energy method to maintain humidity and reduce temperature during storage (Palumbo *et al.*, 2022). When combined with coatings, this method can double shelf life by reducing both physiological and microbial spoilage. Likewise, advanced biodegradable packaging enhanced with nanoparticles or antimicrobial compounds (e.g., silver, zinc oxide) can reinforce the protective function of coatings (Lei *et al.*, 2024). Together, these interventions offer synergistic benefits: coatings act as primary preservation barriers, while evaporative cooling and packaging maintain the external microenvironment. However, widespread adoption depends on developing context-specific combinations suited to local climate and market dynamics, supported by training and supply chain integration.

Policy and regulatory harmonization

The absence of harmonised regional food safety regulations remains a key barrier to scaling coatings in SSA. Fragmented national frameworks, outdated legislation and limited regulatory capacity restrict the commercial rollout of novel postharvest technologies (Morse *et al.*, 2018). In countries like Malawi and Ethiopia, inconsistent food safety enforcement limits market confidence, particularly for export commodities. Regional harmonisation through organisations such as the African Continental Free Trade Area (AfCFTA) and the East African Community (EAC) could streamline standards, enhance traceability and facilitate trade (Union *et al.*, 2014). International collaboration guided by WHO and FAO frameworks can further ensure that coatings meet global benchmarks for food contact materials (Das *et al.*, 2024). Strengthening capacity in testing laboratories, certification systems and risk communication is therefore essential to ensure safe and equitable implementation.

Linking coatings with ICT and sensor-based shelf-life prediction

The integration of ICT and sensor-based systems represents a novel frontier for optimizing the application

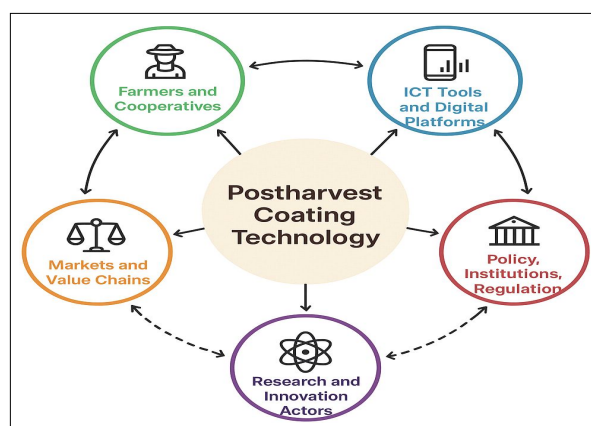


Fig 5: Integrated system model for coating adoption in SSA.

and distribution of coated produce in SSA. IoT-enabled sensors and wireless monitoring platforms such as FreshSense allow for real-time tracking of temperature, humidity and ethylene levels throughout the supply chain (Kumar and Sharma, 2024). Machine learning algorithms can analyse this data to predict remaining shelf life, enabling dynamic routing of produce to markets before spoilage occurs. Intelligent packaging with visual indicators such as pH-sensitive films can also inform traders and consumers about freshness status (Kansal *et al.*, 2024; Qiao *et al.*, 2024).

Integrating coatings with these digital systems would not only reduce waste but also enhance market efficiency and traceability. However, technological disparities, high setup costs and limited digital literacy among farmers pose challenges. Addressing these gaps through public-private partnerships and digital extension platforms could accelerate adoption while ensuring inclusivity. Integrating biodegradable coatings into SSA's food systems requires an ecosystem approach that bridges technology, policy and socio-economics. Overcoming smallholder adoption barriers, aligning coatings with other low-cost preservation strategies and harmonising regulatory frameworks are immediate priorities. The emerging convergence between coatings and ICT-driven shelf-life monitoring offers a transformative opportunity to modernise SSA's postharvest chains. If effectively implemented, these integrated systems could reduce food waste, enhance trade competitiveness and foster resilient, sustainable food systems across the region.

CONCLUSION

Biodegradable and edible coatings present a transformative opportunity for reducing postharvest losses and promoting food system sustainability in Sub-Saharan Africa (SSA). They offer environmentally sound alternatives to plastics and contribute to food security, nutrition and circular economy goals. Coatings derived from locally available waste streams could underpin a cost-effective bioeconomy. Frontier innovations like smart coatings, nanostructured polymers and nutrient-fortified films offer novel scientific directions if adapted to SSA's realities.

A systems approach is imperative, coupling material innovation with policy frameworks, farmer training and consumer engagement. Integration with digital tools can enable predictive shelf-life management and traceability. Harmonized regulations and investment in safety assessments are essential for public trust.

Edible coatings represent a convergence of sustainability science, food security and innovation in SSA. By aligning technical efficacy with socio-economic inclusion and environmental responsibility, they can catalyze resilient, equitable and resource-efficient food systems. Progress depends on multidisciplinary collaboration among researchers, policymakers and private sector actors,

turning the promise of biodegradable coatings into practical solutions for Africa's postharvest challenges.

ACKNOWLEDGEMENT

The authors would like to extend their appreciation to colleagues and experts in the field of study.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

Not applicable.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

REFERENCES

- Aguilar, V.L.M., Calderón, S.M., Vazquez, G.Y. and Ragazzo, S.J.A. (2020). Application of essential oils and polyphenols as natural antimicrobial agents in postharvest treatments: Advances and challenges. *Food Science and Nutrition*. **8(6)**: 2555-2568. doi: 10.1002/fsn3.1437.
- Ahlawat, P. and Kumari, A. (2025). Physicochemical alterations in fruits caused by edible coatings during storage: A review. *Agricultural Reviews*. **46(5)**: 693-702. doi: 10.18805/ag.R-2641.
- Amissah, J.G.N., Adjei, M.Y.B., Amissah, J.N., Asem, F.E. and Kolog, J.D. (2025). Processing, preservation and value addition of indigenous food crops in West Africa. *Frontiers in Sustainable Food Systems*. **9**: 1657056. <https://doi.org/10.3389/fsufs.2025.1657056>.
- Andrade, R.D., Skurtys, O. and Osorio, F.A. (2012). Atomizing spray systems for application of edible coatings. *Comprehensive Reviews in Food Science and Food Safety*. **11(3)**: 323-337. <https://doi.org/10.1111/j.1541-4337.2012.00186.x>.
- Anupama, A., Pattapulavar, V. and Christopher, J.G. (2025). The past, present, future of listeria monocytogenes: Understanding the molecular pathways, antibiotic resistance and public health implications. *Medicine in Microecology*. pp. 100127. <https://doi.org/10.1016/j.medmic.2025.100127>.
- Ashitha, G.N., Sunny, A.C. and Nisha, R. (2020). Effect of pre-harvest and post-harvest hexanal treatments on fruits and vegetables: A review. *Agricultural Reviews*. **41(2)**: 124-131. doi: 10.18805/ag.R-1928.
- Avramescu, S.M., Butean, C., Popa, C.V., Ortan, A., Moraru, I. and Temocico, G. (2020). Edible and functionalized films/coatings-performances and perspectives. *Coatings*. **10(7)**: 687. <https://doi.org/10.3390/coatings10070687>.

- Bhattacharya, B., Roy, P., Bhattacharya, S., Prasad, B. and Mandal, A.K. (2023). Nanotechnology and Sustainable Development: Overcoming the Obstacles by Adopting Ethical Practices for Future Farming. In: Engineered Nanomaterials for Sustainable Agricultural Production, Soil Improvement and Stress Management. Academic Press. pp. 431-445. <https://doi.org/10.1016/B978-0-323-91933-3.00020-9>.
- Buṭu, A., Arion, I., Buṭu, M. and Rodino, S. (2024). Bio-based edible films and coatings with applications in fruit storage life extension. *Fruit Growing Research*. **40**: 207-213. <https://doi.org/10.33045/fgr.v40.2024.29>.
- Chandrababu, V., Parameswaranpillai, J., Gopi, J.A., Pathak, C., Dominic, C.M., Feng, N.L. and Ganguly, S. (2024). Progress in food packaging applications of biopolymer-nanometal composites-A comprehensive review. *Biomaterials Advances*. **162**: 213921. <https://doi.org/10.1016/j.bioadv.2024.213921>.
- Das, S.K., Biswas, O. and Biswas, B.K. (2024). Policies and Social Issues of Food Safety. In: Climate Change and Food Security. GB: CABI. pp. 194-214. <https://doi.org/10.1079/9781800625037.0011>.
- Dhall, R.K. (2013). Advances in edible coatings for fresh fruits and vegetables: A review. *Critical Reviews in Food Science and Nutrition*. **53(5)**: 435-450. <https://doi.org/10.1080/10408398.2010.541568>.
- Díaz-Montes, E. and Castro-Muñoz, R. (2021). Trends in chitosan as a primary biopolymer for functional films and coatings manufacture for food and natural products. *Polymers*. **13(5)**: 767. <https://doi.org/10.3390/polym13050767>.
- El Guerraf, A., Ziani, I., Ben, J.S., El Bachiri, A., Bazzoui, M., Bazzoui, E.A. and Sher, F. (2024). Smart conducting polymer innovations for sustainable and safe food packaging technologies. *Comprehensive Reviews in Food Science and Food Safety*. **23(6)**: e70045. <https://doi.org/10.1111/1541-4337.70045>.
- Elgadir, M.A., Mirghani, M.E.S. and Mariod, A.A. (2024). Chitosan and chitosan-essential oil composites as edible coatings for meat and meat products: A review. *Recent Advances in Food, Nutrition and Agriculture*. **16(2)**: 109-120. <https://doi.org/10.2174/012772574x301555240503070126>.
- Etefa, O.F., Forsido, S.F. and Kebede, M.T. (2022). Postharvest loss, causes and handling practices of fruits and vegetables in Ethiopia: Scoping review. *Journal of Horticultural Research*. **30(1)**: 1-10. <https://doi.org/10.2478/johr-2022-0002>.
- Etumnu, C.E. (2016). Behavioral Determinants of Biofortified Food Acceptance: The Case of Orange-fleshed Sweet Potato in Ghana. 2016 Annual Meeting, July 31-August 2, Boston, Massachusetts 235249, Agricultural and Applied Economics Association. <https://doi.org/10.22004/AG.ECON.235249>.
- Gaikwad, D., Patil, D., Chougale, R. and Sutar, S. (2025). Development and characterization of bael fruit gum-pectin hydrogel for enhanced antimicrobial activity. *International Journal of Biological Macromolecules*. **291**: 139082. <https://doi.org/10.1016/j.ijbiomac.2024.139082>.
- García-Mahecha, M., Soto-Valdez, H., Carvajal-Millan, E., Madera-Santana, T.J., Lomelí-Ramírez, M.G. and Colín-Chávez, C. (2023). Bioactive compounds in extracts from the agro-industrial waste of mango. *Molecules*. **28(1)**: 458. <https://doi.org/10.3390/molecules28010458>.
- Garg, N., Roy, N., Chandra, R. and Ranganathan, V. (2024). Fresh sense: Transforming supply chains with low-cost and dynamic food quality sensing at the pallet-level. *Get Mobile: Mobile Computing and Communications*. **28(3)**: 9-13. <https://doi.org/10.1145/3701701.3701705>.
- Gelaye, Y. (2024). A review of storage temperature and relative humidity effects on shelf life and quality of mango (*Mangifera indica* L.) fruit and implications for nutrition insecurity in Ethiopia. *Open Agriculture*. **9(1)**: 20220296. <https://doi.org/10.1515/opag-2022-0296>.
- Geremu, M.A., Welelaw, E., Tamirat, S. and Kidane, B. (2022). Associated fungal pathogens and causes of postharvest losses in the avocado value chain in Hossana town market, Ethiopia. *African Journal of Food, Agriculture, Nutrition and Development*. **22(6)**: 20646-20667. <https://www.ajol.info/index.php/ajfand/article/view/246564>.
- Ghanbarzadeh, B., Oleyaei, S.A. and Almasi, H. (2015). Nanostructured materials utilized in biopolymer-based plastics for food packaging applications. *Critical Reviews in Food Science and Nutrition*. **55(12)**: 1699-1723. <https://doi.org/10.4317/jced.51705>.
- Gupta, P., Toksha, B. and Rahaman, M. (2022). A review on biodegradable packaging films from vegetative and food waste. *The Chemical Record*. **22(7)**: e202100326. <https://doi.org/10.1002/tcr.202100326>.
- Jahangiri, F., Mohanty, A.K. and Misra, M. (2024). Sustainable biodegradable coatings for food packaging: Challenges and opportunities. *Green Chemistry*. **26(9)**: 4934-4974. <https://doi.org/10.1039/d3gc02647g>.
- Jurić, M., Bandić, L.M., Carullo, D. and Jurić, S. (2024). Technological advancements in edible coatings: Emerging trends and applications in sustainable food preservation. *Food Bioscience*. **58**: 103835. <https://doi.org/10.1016/j.fbio.2024.103835>.
- Kamau, J.W., Schader, C., Biber-Freudenberger, L., Stellmacher, T., Amudavi, D.M., Landert, J. and Borgemeister, C. (2022). A holistic sustainability assessment of organic (Certified and non-certified) and non-organic smallholder farms in Kenya. *Environment, Development and Sustainability*. **24(5)**: 6984-7021. <https://doi.org/10.1007/s10668-021-01736-y>.
- Kansal, M., Singh, P., Chaurasia, P., Dwivedi, A. and Ali, S. (2024). Blockchain-Powered Food Supply Chain Tracking: A Paradigm Shift for Transparency, Accountability and Quality Assurance Through Block Trackers. In: 2024 2nd International Conference on Disruptive Technologies (ICDT). IEEE. pp. 194-200. <https://doi.org/10.1109/ICDT61202.2024.10489045>.
- Kansanga, M.M., Mohammed, K., Batung, E., Ansumah, S.S. and Luginaah, I. (2023). Lost harvest: Examining the association between postharvest food loss and food insecurity in semi-arid Ghana. *International Journal of Sustainable Development and World Ecology*. **30(7)**: 776-791. <https://doi.org/10.1080/13504509.2023.2198507>.
- Kikulwe, E.M., Okurut, S., Ajambo, S., Nowakunda, K., Stoian, D. and Naziri, D. (2018). Postharvest losses and their determinants: A challenge to creating a sustainable cooking banana value chain in Uganda. *Sustainability*. **10(7)**: 2381. <https://doi.org/10.3390/su10072381>.

- Kouadia, A.M.J., Abo, K. and Kouadio, K.T. (2019). Evolution des infections naturelles sur les mangues, les avocats et les bananes en Côte d'Ivoire et principaux champignons responsables. *Journal of Applied Biosciences*. **134(1)**: 13710. <https://doi.org/10.4314/JAB.V134I1.8>.
- Kumar, S. and Sharma, S.C. (2024). Intelligent transportation storage condition assessment system for fruits and vegetables supply chain using internet of things enabled sensor network. *International Journal of System Assurance Engineering and Management*. pp. 1-15. <https://doi.org/10.1007/s13198-024-02437-1>.
- Lei, X., Zhu, K., Liu, H., Jiang, W., Zhang, K., Zhao, J., Zeng, K. and Li, F. (2024). Eco-friendly packaging film with integrated functions of high-efficiency radiation cooling and sustained-release antimicrobial activity. *Chemical Engineering Journal*. **496**: 153430. <https://doi.org/10.1016/j.cej.2024.153430>.
- Mabe, F.N., Mumuni, E. and Sulemana, N. (2021). Does smallholder farmers' awareness of sustainable development goal 2 improve household food security in the Northern Region of Ghana? *Agricultural and Food Science*. **10(1)**. <https://doi.org/10.1186/S40066-020-00281-7>.
- Mäki, A., Salonen, N., Kivisaari, M., Ahonen, M. and Latva, M. (2023). Microbiota shaping and bioburden monitoring of indoor antimicrobial surfaces. *Frontiers in Built Environment*. **9**: 1063804. <https://doi.org/10.3389/fbuil.2023.1063804>.
- Makule, E.E., Dimoso, N. and Tassou, S.A. (2022). Precooling and cold storage methods for fruits and vegetables in Sub-Saharan Africa-A review. *Horticulturae*. **8(9)**: 776. <https://doi.org/10.3390/horticulturae8090776>.
- Marasinghe, W.N., Jayathunge, K.G.L.R., Dassanayake, R.S., Liyanage, R., Bandara, P.C., Rajapaksha, S.M. and Gunathilake, C. (2024). Structure, properties and recent developments in polysaccharide-and aliphatic polyester-based packaging-A review. *Journal of Composites Science*. **8(3)**: 114. <https://doi.org/10.3390/jcs8030114>.
- Matche, R.S. and Singh, Y. (2023). Recent Trends in Materials and Coatings for Food Packaging and Storage. In: *Engineering Aspects of Food Quality and Safety*. Cham: Springer International Publishing. pp. 249-279. https://doi.org/10.1007/978-3-031-30683-9_9.
- Mayanja, I. and Oluk, I. (2023). Intermediate technologies: The key to eradicating post-harvest losses (PHLs) in Sub-Saharan Africa (SSA). *Journal of Advances in Food Science and Technology*. **10(4)**: 64-74. <https://doi.org/10.56557/jafsat/2023/v10i48419>.
- Mensah, F.P., Konyannik, B.Y., Semanu, M., Aboagye, E.K., Kwawu, N., Patricia, K. and Salifu, A.J. (2025). Identification and management of postharvest pathogens in tomato (*Solanum lycopersicum*) using low-cost botanical treatments and affordable storage solutions in Sub-Saharan Africa. *European Journal of Nutrition and Food Safety*. **17(11)**: 150-174. <https://doi.org/10.9734/ejnf/s/2025/v17i111901>.
- Mishra, R., Tripathi, P., Kumar, P., Rajpoot, P.K., Verma, S. and Aman, A.S. (2024). Innovations and future trends in storage pest management. *Journal of Experimental Agriculture International*. **46(5)**: 155-165. <https://doi.org/10.9734/jeai/2024/v46i52366>.
- Mohanapriya, R., Kalpana, R. and Aravinth, K.V. (2024). Quality enhancement of fruits and vegetables through organic cultivation: A review. *Agricultural Reviews*. **45(2)**: 207-217. doi: 10.18805/ag.R-2351.
- Morse, T., Masuku, H., Rippon, S. and Kubwalo, H.W. (2018). Achieving an integrated approach to food safety and hygiene-meeting the sustainable development goals in Sub-Saharan Africa. *Sustainability*. **10(7)**: 2394. <https://doi.org/10.3390/SU10072394>.
- Muñoz-Tebar, N., Pérez-Álvarez, J. A., Fernández-López, J. and Viuda-Martos, M. (2023). Chitosan edible films and coatings with added bioactive compounds: Antibacterial and antioxidant properties and their application to food products: A review. *Polymers*. **15(2)**: 396. <https://doi.org/10.3390/polym15020396>.
- Nath, S. (2024). Biotechnology and biofuels: Paving the way towards a sustainable and equitable energy for the future. *Discover Energy*. **4(1)**: 8. <https://doi.org/10.1007/s43937-024-00032-w>.
- Ni, C. and Friedman, D.C. (2024). Transforming trash: Strategies to develop waste into a feedstock for a circular bioeconomy. *Biofuels, Bioproducts and Biorefining*. **18(5)**: 1085-1092. <https://doi.org/10.1002/bbb.2586>.
- Palumbo, M., Attolico, G., Capozzi, V., Cozzolino, R., Corvino, A., de Chiara, M.L.V. and Cefola, M. (2022). Emerging postharvest technologies to enhance the shelf-life of fruit and vegetables: an overview. *Foods*. **11(23)**: 3925. <https://doi.org/10.3390/foods11233925>.
- Pawar, R. and Rana, V.S. (2019). Manipulation of source-sink relationship in pertinence to better fruit quality and yield in fruit crops: A review. *Agricultural Reviews*. **40(3)**: 200-207. doi: 10.18805/ag.R-1934.
- Phillip, M., Achenbach, P., Addala, A., Albanese-O'Neill, A., Battelino, T., Bell, K.J. and DiMeglio, L.A. (2024). Consensus guidance for monitoring individuals with islet autoantibody-positive pre-stage 3 type 1 diabetes. *Diabetes Care*. **47(8)**: 1276-1298. <https://doi.org/10.2337/dci24-0042>.
- Picot-Allain, C.M.N., Ramasawmy, B., Neetoo, H., Ramful-Baboolall, D. and Emmambux, M.N. (2022). Drivers and barriers for commercial uptake of edible coatings for fresh fruits and vegetables industry- A review. *Food Reviews International*. **39(4)**: 1-34. <https://doi.org/10.1080/87559129.2021.2012795>.
- Pirzada, T., de Farias, B.V., Mathew, R., Guenther, R.H., Byrd, M.V., Sit, T.L. and Khan, S.A. (2020). Recent advances in biodegradable matrices for active ingredient release in crop protection: Towards attaining sustainability in agriculture. *Current Opinion in Colloid and Interface Science*. **48**: 121-136. <https://doi.org/10.1016/j.cocis.2020.05.002>.
- Qiao, J., Zhang, M., Qiu, L., Mujumdar, A.S. and Ma, Y. (2024). Visual early warning and prediction of fresh food quality deterioration: Research progress and application in supply chain. *Food Bioscience*. **58**: 103671. <https://doi.org/10.1016/j.fbio.2024.103671>.
- Rajal, H. and Varma, S. (2024). Edible coatings: A novel approach to extending the shelf life of fruits and vegetables. *Journal of Advances in Biology and Biotechnology*. **27(7)**: 25-37. <https://dx.doi.org/10.9734/jabb/2024/v27i7963>.

- Ravindran, N., Singha, P. and Singh, S.K. (2024). Food Design using Biopolymers. In: *Advances in Biopolymers for Food Science and Technology*. Elsevier. pp. 41-61. <https://doi.org/10.1016/B978-0-443-19005-6.00003-7>.
- Rimpika, S. and Ajender, D.P. (2021). Vulnerability of temperate fruit production to climate change: Adaptation and mitigation measures: A review. *Agricultural Reviews*. **42(2)**: 190-196. doi: 10.18805/ag.R-2016.
- Rostamabadi, H., Demirkesen, I., Colussi, R., Roy, S., Tabassum, N., de Oliveira Filho, J.G. and Falsafi, S.R. (2024). Recent trends in the application of films and coatings based on starch, cellulose, chitin, chitosan, xanthan, gellan, pullulan, arabic gum, alginate, pectin and carrageenan in food packaging. *Food Frontiers*. **5(2)**: 350-391. <https://doi.org/10.1002/fft2.342>.
- Rozas, B., Bruna, J. E., Guarda, A., Galotto, M.J., Reyes, C., Valenzuela, X. and Torres, A. (2025). Bio-based coatings on cellulosic materials resistant to humidity and fats. *Polymers*. **17(20)**: 2755. <https://doi.org/10.3390/polym17202755>.
- Rutta, E.W. (2022). Understanding barriers impeding the deployment of solar-powered cold storage technologies for post-harvest tomato losses reduction: Insights from small-scale farmers in Tanzania. *Frontiers in Sustainable Food Systems*. <https://doi.org/10.3389/fsufs.2022.990528>.
- Samanta, K.K., Basak, S. and Chattopadhyay, S.K. (2015). Potentials of Fibrous and Nonfibrous Materials in Biodegradable Packaging. In: *Environmental Footprints of Packaging*. Singapore: Springer Singapore. pp. 75-113. https://doi.org/10.1007/978-981-287-913-4_4
- Schmidt, K., Mwaigwisya, S., Crossman, L. C., Doumith, M., Munroe, D., Pires, C. and Livermore, D.M. (2017). Identification of bacterial pathogens and antimicrobial resistance directly from clinical urines by nanopore-based metagenomic sequencing. *Journal of Antimicrobial Chemotherapy*. **72(1)**: 104-114. <https://doi.org/10.1093/jac/dkw397>.
- Schmidt, V.M., Pinchbeck, G., McIntyre, K.M., Nuttall, T., McEwan, N., Dawson, S. and Williams, N.J. (2018). Routine antibiotic therapy in dogs increases the detection of antimicrobial-resistant faecal *Escherichia coli*. *Journal of Antimicrobial Chemotherapy*. **73(12)**: 3305-3316. <https://doi.org/10.1093/jac/dky352>.
- Sharma, R., Kumar, A., Sepelha, S. and Kapoor, R. (2024). Nutrient management in subtropical fruit production: A review. *Agricultural Reviews*. **45(4)**: 645-652. doi: 10.18805/ag.R-2461.
- Sibanda, S. and Workneh, T.S. (2020). Potential causes of postharvest losses, low-cost cooling technology for fresh produce farmers in Sub-Sahara Africa. *African Journal of Agricultural Research*. **16(5)**: 553-566. <https://doi.org/10.5897/AJA R2020.14714>.
- Singh, A.K., Rawat, M., Mani, G., Gautam, R., Raj, R., Shah, I. and Kumar, V. (2025). Postharvest physiology of mango crops: Understanding ripening, quality and storage strategies. *Applied Fruit Science*. **67(2)**: 1-14. <https://doi.org/10.1007/s10341-025-01273-2>.
- Soni, A., Das, P.K. and Kumar, S. (2023). Selection of waste plastics for incorporation in agro-waste as sustainable building construction materials concerning circular economy: An integrated MCDM approach. *Clean Technologies and Environmental Policy*. **25(9)**: 2929-2949. <https://doi.org/10.1007/s10098-023-02539-7>.
- Sørensen, J.F.L. and Jørgensen, H.P. (2022). Rural development potential in the bioeconomy in developed countries: The case of biogas production in Denmark. *Sustainability*. **14(17)**: 11077. <https://doi.org/10.3390/su141711077>.
- Strecker, K., Bitzer, V. and Kruijsen, F. (2022). Critical stages for post-harvest losses and nutrition outcomes in the value chains of bush beans and nightshade in Uganda. *Food Security*. **14(2)**: 411-426. <https://doi.org/10.1007/s12571-021-01244-x>.
- Tapia-Blácido, D.R., Maniglia, B.C. and Tosi, M.M. (2018). Transport Phenomena in Edible Films. In: *Polymers for Food Applications*. Cham: Springer International Publishing. pp. 149-192. https://doi.org/10.1007/978-3-319-94625-2_7.
- Tschirley, D.L., Ayieko, M.W., Hichaambwa, M., Goeb, J. and Loescher, W. (2010). Modernizing Africa's fresh produce supply chains without rapid supermarket takeover: Towards a definition of research and investment priorities. Food Security International Development Working Papers 93030, Michigan State University. *Department of Agricultural, Food and Resource Economics*. <https://doi.org/10.22004/ag.econ.93030>.
- Türker, D.A. (2024). Bionanomaterials in Food Packaging. In: *Bionanomaterials for Industrial Applications*. CRC Press. pp. 69-95. <https://doi.org/10.1201/9781003432791-6>.
- Union, A., Protocol, C.C.M., Assembly, E.E.A.L. and Area, F.F.T. (2014). East African Community. nd Retrieved. **29**. <https://muse.jhu.edu/book/45599>.
- Valle, L., Maddalena, L., Damonte, G., Carosio, F., Pellis, A. and Monticelli, O. (2024). Biodegradable and gas barrier polylactic acid/star-shaped polycaprolactone blend films functionalized with a bio-sourced polyelectrolyte coating. *Colloids and Surfaces B: Biointerfaces*. **236**: 113806. <https://doi.org/10.1016/j.colsurfb.2024.113806>.
- Vanaraj, R., Suresh Kumar, S.M., Mayakrishnan, G., Rathinam, B. and Kim, S.C. (2024). A current trend in efficient biopolymer coatings for edible fruits to enhance shelf life. *Polymers*. **16(18)**: 2639. <https://doi.org/10.3390/polym16182639>.
- Veiga-Santos, P. and dos Ouros, L.F. (2024). Starch-Based Packaging and Coating Polymers for Food. In: *Starch Industries: Processes and Innovative Products in Food and Non-Food Uses*. Academic Press. pp. 295-310. <https://doi.org/10.1016/B978-0-323-90842-9.00012-1>.
- Wardejn, S., Waclawek, S. and Dudek, G. (2024). Improving antimicrobial properties of biopolymer-based films in food packaging: Key factors and their impact. *International Journal of Molecular Sciences*. **25(23)**: 12580. <https://doi.org/10.3390/ijms252312580>.
- Xiao, Q. (2021). Coating and Film-Forming Properties. In: *Food Hydrocolloids*. [Fang, Y., Zhang, H., Nishinari, K. (eds)], Springer, Singapore. https://doi.org/10.1007/978-981-16-0320-4_8.
- Yogita, R.J., Prajapati, C.S., Roy, S., Abrol, P., Khan, C.A.K. and Darbha, S. (2024). Extension strategies to promote post-harvest management and value addition: A review. *Horticulture*. **50**. <https://www.doi.org/10.33545/26174693.2025.v9.i4g.4156>.
- Zaritzky, N. (2010). Edible Coatings to Improve Food Quality and Safety. In: *Food Engineering Interfaces*. New York, NY: Springer New York. pp. 631-659. https://doi.org/10.1007/978-1-4419-7475-4_27.

- Zdulski, J.A., Rutkowski, K.P. and Konopacka, D. (2024). Strategies to extend the shelf life of fresh and minimally processed fruit and vegetables with edible coatings and modified atmosphere packaging. *Applied Sciences*. **14(23)**: 11074. <https://doi.org/10.3390/app142311074>.
- Zhang, L., Zhang, J., Zhang, J., Huang, X. and Shi, J. (2025). Advances in pH-responsive release technologies in food system: Mechanisms, strategies, application forms and future directions. *Foods*. **14(22)**: 3896. <https://doi.org/10.3390/foods14223896>.
- Zhao, Z., Zhang, B., Huang, N., Sun, Y., Huai, X., Miao, J. and Zhou, X. (2025). Types of nanomaterials commonly used in food packaging, film formation techniques and recent advances in their applications. *International Journal of Food Science and Technology*. **60(1)**: wae036. <https://doi.org/10.1093/ijfood/vvae036>.
- Ziani, K., Ioniă-Mîndrican, C.B., Mititelu, M., Neacsu, S.M., Negrei, C., Morosan, E. and Preda, O. T. (2023). Microplastics: A real global threat for environment and food safety: A state of the art review. *Nutrients*. **15(3)**: 617. <https://doi.org/10.3390/nu15030617>.