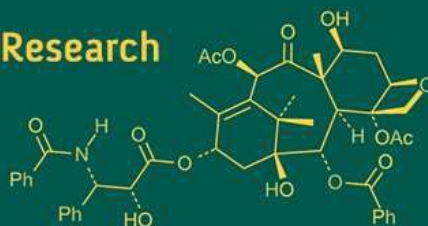
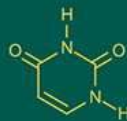


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Reducing post-harvest losses through engineering innovation

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Abstract

Post-harvest losses hinder global food security and sustainability, causing economic and environmental harm. Engineering improvements can solve these issues throughout the post-harvest supply chain. Modern storage technology has transformed perishable commodities preservation. Modified atmosphere storage (MAS) and controlled atmosphere storage (CAS) systems maintain appropriate temperature, humidity, and gas composition, prolonging food shelf life and preventing spoiling. With smart sensors and IoT connectivity, these systems can monitor and control storage conditions in real time, allowing quick interventions and lowering environmental losses. Transportation engineering has increased food delivery efficiency and safety. Advanced packaging materials include biodegradable and active packaging defend against physical damage and spoilage. Refrigerated transport systems keep perishable commodities cool from farm to consumer, while route optimization algorithms and GPS monitoring devices prevent delays and spoilage. These advances improve distribution, reducing food loss. Processing technology also help reduce post-harvest losses. Precision sorting, automated grading, and enhanced drying have changed food processing. Optical sorting machines employ advanced cameras and sensors to precisely detect and discard faulty or undesired materials, guaranteeing that only quality goods advance in processing. Freeze-drying and high-pressure processing preserve food's nutritional content and shelf life, reducing waste and optimizing produce utilization. Engineering improvements are crucial to solving post-harvest losses and complex issues. These technologies improve storage, transportation, and processing, boosting food quality and durability and making the food supply chain more sustainable and efficient. These technical solutions must be developed and used to reduce post-harvest losses and ensure food security. Investing in post-harvest management research and development can help overcome emerging difficulties and meet global food security goals.

Keywords: Spoilage, delays, sorting, quality, engineering, food, precision, losses, MAS

Introduction

Because of the ever-increasing population all over the world, there is a considerable gap between the quantity of food that is available and the amount that is required. This gap is growing at an alarming rate. It is anticipated that by the year 2050, the size of the human population would have expanded from 7 billion to 9.7 billion, with the majority of this expansion taking place in countries that are not yet deemed to be developed ^[1]. In order to accommodate this growth, it is required to boost the productivity of food production by seventy percent. It is possible to accomplish this goal by either increasing the crop productivity or reducing the quantity of trash that is generated ^[2]. There are measurable quantities of food that are lost throughout the postharvest process, and these losses may be broken down into two categories: quantity and quality. The term "postharvest losses" (PHL) is used to describe these kinds of losses. A determined effort is being made to reduce these losses to the fullest degree that is practically possible under the circumstances ^[3]. Among the many actions that make up PHL, harvesting is one of the activities that are included. This category includes later acts such as consumption, availability, access, and usage of the product or service ^[4]. The study of PHL has the potential to enhance food security by providing sustainable ways that may increase food production while simultaneously reducing food losses and waste. This might be accomplished via several means. Several different approaches might be used to reach this goal ^[5]. PHL reduction is often more cost-effective than expanding food production, and it has the potential to yield bigger returns than improvements in agricultural production rates because of its ability to create larger returns.

Moreover, there is the possibility of a rise in agricultural output rates ^[6]. One of the goals that the United Nations has established as part of the Sustainable Development Goals is to cut the amount of food that is wasted and lost all over the world by fifty percent by the year 2030. This aim was established as part of the Sustainable Development Goals. On the other hand, research on PHL has not gotten the attention that it deserves; less than five percent of the cash that is committed to agricultural research all over the world is devoted to tackling this problem ^[7]. This is a significant gap in the research community. In order to accomplish the purpose of this review, an analysis of the current literature on PHL will be carried out. This study will include a discussion of the factors that contribute to it, as well as technology and prospective techniques for its reduction. Additionally, it addresses issues about phytosanitary hazards both on and off farms, as well as the social and environmental aspects of PHL. Finally, it discusses the implications of PHL. In addition to the aforementioned topics, this particular topic as well is discussed ^[8].

Post-harvest losses refer to the reduction in the quantity or quality of agricultural produce between the time of harvest and consumption. These losses can occur during harvesting, handling, processing, storage, and transportation. They encompass physical losses, such as spoilage and damage, as well as qualitative losses, like deterioration in taste, texture, and nutritional value. Post-harvest losses affect a wide range of products, including fruits, vegetables, grains, and livestock products, and can be attributed to various factors including inadequate infrastructure, poor handling practices, and environmental conditions ^[9, 10].

Statistical Impact on Global Food Security and Economy

Globally, post-harvest losses are a significant concern. According to the Food and Agriculture Organization (FAO), approximately 14% of global food production is lost after harvest but before reaching the consumer ^[11]. This translates to about 1.3 billion tons of food annually, worth around \$940 billion. In developing countries, where infrastructure and technology are often lacking, post-harvest losses can reach up to 40% for certain crops. This not only impacts food availability but also exacerbates food insecurity, particularly in regions where food resources are already scarce. Economically, these losses reduce the income of farmers and increase the cost of food for consumers, contributing to inefficiencies in the global food supply chain ^[12].

Economic Implications for Farmers and the Supply Chain

Addressing post-harvest losses is crucial for improving the economic viability of farming operations and the overall efficiency of the food supply chain. For farmers, reducing losses means increased revenue from higher yields and reduced waste. Improved handling and storage practices can lower costs associated with spoilage and damage, enhancing profitability ^[13]. On a broader scale, reducing post-harvest losses can lead to more stable food prices and increased availability, benefiting both producers and consumers. Effective management of these losses can also mitigate the economic burden on the entire supply chain, from logistics to retail ^[14].

Environmental Impact of Wasted Resources and Energy

The environmental implications of post-harvest losses are significant. Wasted food represents not just a loss of edible produce but also a worthless investment in resources such as water, energy, and land. For instance, the production of food that ultimately goes to waste contributes to unnecessary greenhouse gas emissions and environmental degradation ^[15]. Moreover, the disposal of spoiled food adds to the burden on waste management systems and can lead to increased methane emissions from landfills. By addressing post-harvest losses, we can reduce the environmental footprint of agriculture, contribute to sustainable resource use, and help combat climate change ^[16].

How Engineering Solutions Can Address Inefficiencies and Improve Storage, Handling, and Transportation

Engineering innovations play a pivotal role in mitigating post-harvest losses by addressing inefficiencies in storage, handling, and transportation. Advanced engineering solutions, such as temperature-controlled storage systems and automated handling technologies, can significantly reduce spoilage and damage. For example, modern refrigeration systems and controlled atmosphere storage can maintain optimal conditions for preserving perishable produce ^[17]. Automated sorting and packing systems minimize physical handling and reduce damage during processing. Additionally, smart transportation solutions, including temperature-regulated vehicles and GPS-based route optimization, ensure that produce is transported under ideal conditions, minimizing losses during transit. By integrating these engineering advancements, the agricultural sector can enhance efficiency, extend shelf life, and ultimately reduce post-harvest losses ^[18].

Understanding Post-Harvest Losses

Post-harvest losses encompass various forms of waste and deterioration that occur from the time of harvest until the produce reaches the consumer. Understanding these losses is crucial for developing effective strategies to minimize them and improve the efficiency of the food supply chain ^[19].

Types of Post-Harvest Losses

Physical Losses

Physical losses refer to the tangible reduction in the amount of produce due to spoilage and damage. These losses can occur at multiple stages:

- **Spoilage:** This involves the decay or deterioration of produce due to microbial activity (Bacteria, fungi, and moulds) or enzymatic processes. Spoilage can be accelerated by factors such as inadequate temperature control, high humidity, and poor sanitation. For instance, fruits and vegetables may develop mould or rot if not stored properly ^[20].
- **Damage during Handling and Transport:** Physical damage often occurs during the handling and transportation phases. Rough handling, inadequate packaging, and improper loading and unloading can cause bruising, crushing, and other forms of mechanical damage. For example, delicate fruits like berries can be easily crushed during transport if not handled with care, leading to a significant reduction in marketable quality ^[21].

Quantitative Losses: Quantitative losses involve a reduction in the measurable aspects of produce, including:

- **Loss of Weight:** Weight loss can occur due to moisture loss, a common issue with fruits and vegetables. This can result from improper storage conditions or prolonged exposure to air. For example, root vegetables like carrots may lose weight and become less marketable if they dry out ^[22].
- **Loss of Volume:** Volume loss can result from shrinkage or drying, affecting the overall quantity available for sale. This is particularly relevant for products like grains and pulses, where prolonged exposure to moisture or poor storage conditions can lead to a reduction in volume ^[23].
- **Nutritional Quality:** Post-harvest losses can also affect the nutritional value of produce. The breakdown of vitamins, minerals, and other nutrients can occur due to factors such as prolonged storage, exposure to light, and temperature fluctuations. For instance, vitamin C content in fruits can degrade over time if not stored under optimal conditions ^[24].

Qualitative Losses

Qualitative losses refer to changes in the sensory and aesthetic attributes of produce:

- **Changes in Taste:** The flavour profile of produce can be adversely affected by post-harvest conditions. For example, overripe fruits may become overly sweet or develop off-flavours due to enzymatic changes or microbial contamination ^[25].
- **Changes in Texture:** Texture changes can occur due to moisture loss or softening. Vegetables might become limp or mushy, while fruits may lose their crispness or become mealy. These changes can make the produce less appealing to consumers ^[26].
- **Changes in Appearance:** Visual quality, including colour and shape, can be compromised by post-harvest losses. Discoloration, wrinkling, or blemishes can reduce the marketability of produce. For example, potatoes might develop sprouting or greening, affecting their appearance and quality ^[27].

Common post-harvest losses in fruits, including their causes and potential solutions ^[28, 29, 30, 31]:

Fruit	Post-Harvest Losses	Causes	Potential Solutions
Apples	Bruising, decay, shrinkage	Mechanical damage, poor storage conditions	Use of protective packaging, controlled atmosphere storage
Bananas	Ripening too quickly, bruising	Ethylene exposure, rough handling	Use of ethylene absorbers, careful handling, proper ripening conditions
Berries	Mould, rot, dehydration	High moisture, inadequate ventilation	Improved ventilation, moisture control, use of antimicrobial treatments
Citrus Fruits	Sunburn, decay, weight loss	Excessive heat, high humidity, physical damage	Use of shade nets, proper ventilation, regular inspection
Grapes	Mould, decay, shrivelling	High humidity, poor air circulation	Controlled atmosphere storage, proper ventilation, timely harvesting
Mangoes	Ripening too quickly, bruising	Ethylene exposure, rough handling	Controlled ripening, careful handling, optimal storage conditions
Pears	Decay, bruising, shrivelling	Mechanical damage, poor storage conditions	Use of cushioning materials, controlled atmosphere storage
Pineapples	Decay, sunburn, weight loss	High temperatures, physical damage	Proper packaging, shaded storage, temperature control
Tomatoes	Softening, rot, dehydration	High humidity, temperature fluctuations	Use of cooling systems, proper ventilation, moisture control
Watermelons	Decay, loss of firmness, sunburn	Physical damage, excessive heat	Use of proper handling techniques, shaded storage, temperature regulation
Pomegranate	Sunburn, decay, bruising	Exposure to sun, physical damage	Use proper handling technique and cover the individual fruit

Common post-harvest losses in vegetables, including their causes and potential solutions ^[32, 33, 34, 35, 36]:

Vegetable	Post-Harvest Losses	Causes	Potential Solutions
Carrots	Shrivelling, decay, sprouting	Low humidity, poor storage conditions	Controlled atmosphere storage, proper humidity control
Cabbage	Wilting, decay, discoloration	High humidity, temperature fluctuations	Proper ventilation, temperature control, regular inspection
Cucumbers	Softening, decay, sunburn	Excessive heat, high humidity	Use of cooling systems, shaded storage, moisture control
Lettuce	Wilting, decay, discoloration	High temperatures, poor handling	Use of cool storage, proper handling, moisture control
Onions	Sprouting, decay, weight loss	High humidity, improper storage conditions	Controlled atmosphere storage, proper ventilation
Potatoes	Sprouting, decay, shrivelling	Excessive moisture, high temperatures	Use of temperature-controlled storage, moisture control
Peppers	Softening, decay, sunburn	High temperatures, poor handling	Use of cooling systems, proper handling, shaded storage
Spinach	Wilting, decay, loss of freshness	High temperatures, high humidity	Controlled atmosphere storage, proper ventilation, timely processing
Tomatoes	Softening, rot, dehydration	High humidity, temperature fluctuations	Use of cooling systems, proper ventilation, moisture control
Zucchini	Softening, decay, sunburn	High temperatures, excessive moisture	Use of cooling systems, proper ventilation, moisture control

Common post-harvest losses in floriculture, including their causes and potential solutions [37, 38, 39, 40]:

Flower	Post-Harvest Losses	Causes	Potential Solutions
Roses	Wilting, browning, decay	High temperatures, low humidity, poor handling	Use of floral preservatives, proper hydration, controlled storage
Orchids	Dropping petals, decay, wilting	Excessive moisture, high temperatures, poor handling	Proper hydration, controlled environment, careful handling
Lilies	Bud drop, wilting, decay	Temperature fluctuations, high humidity, mechanical damage	Controlled storage conditions, proper ventilation, careful handling
Tulips	Softening, wilting, leaf drop	High temperatures, low humidity, poor water uptake	Use of floral preservatives, controlled storage, proper hydration
Carnations	Wilted stems, fading, decay	Low humidity, high temperatures, improper handling	Use of floral preservatives, controlled humidity and temperature
Gerberas	Wilting, decay, softening	High temperatures, low humidity, poor water uptake	Use of floral preservatives, controlled environment, regular hydration
Chrysanthemums	Leaf drop, wilting, decay	Temperature fluctuations, low humidity, improper handling	Controlled storage conditions, proper handling, use of floral preservatives
Sunflowers	Wilting, drooping, decay	High temperatures, low humidity, rough handling	Use of floral preservatives, controlled environment, careful handling
Daisies	Wilting, decay, loss of freshness	High temperatures, low humidity, improper storage	Proper hydration, controlled storage conditions, use of floral preservatives
Anthuriums	Softening, colour fading, decay	High temperatures, low humidity, rough handling	Controlled atmosphere storage, proper hydration, use of floral preservatives

Causes of Post-Harvest Losses

Post-harvest losses can be attributed to various factors that affect the quality and quantity of agricultural produce. Identifying and understanding these causes is essential for implementing effective solutions to minimize waste and improve food security. The primary causes of post-harvest losses include inadequate storage facilities, poor handling and transportation practices, and environmental factors [41].

Inadequate Storage Facilities**1. Insufficient Infrastructure**

- **Lack of Proper Storage Facilities:** Many regions, particularly in developing countries, lack adequate infrastructure for storing agricultural produce. Traditional storage methods may not protect produce from environmental elements, leading to increased spoilage and loss. For instance, open-air storage or poorly constructed warehouses may fail to regulate temperature and humidity, resulting in accelerated deterioration [42].
- **Limited Capacity:** Storage facilities may be inadequate in capacity, forcing producers to store excess produce in suboptimal conditions or sell it quickly at lower prices. This lack of capacity can lead to overstocking, where produce is not handled or stored efficiently, increasing the risk of loss [43].

2. Poor Temperature and Humidity Control

- **Inadequate Climate Control:** Effective storage requires controlling temperature and humidity to maintain the quality of perishable produce. Many storage facilities lack advanced climate control systems, leading to conditions that promote spoilage. For example, fruits and vegetables may rot if stored in environments with high humidity or fluctuating temperatures [44].
- **Lack of Insulation:** Poor insulation in storage facilities can lead to temperature variations, affecting the shelf life of stored produce. Without proper insulation, the internal environment may not be maintained consistently, leading to temperature extremes that accelerate spoilage of perishables [45].

Poor Handling and Transportation Practices**1. Inadequate Handling Procedures**

- **Rough Handling:** Improper handling during harvesting, sorting, and packing can cause physical damage to produce. For example, dropping or throwing produce can lead to bruising, cuts, and other forms of mechanical damage that reduce quality and marketability [46].
- **Lack of Training:** Farmers and workers may lack proper training on handling techniques, leading to inefficient practices that increase losses. Training on gentle handling and proper sorting can significantly reduce damage and waste [47].

2. Inefficient Transportation

- **Suboptimal Packaging:** Poorly designed packaging may fail to protect produce during transportation. Inadequate packaging can lead to crushing, bruising, or exposure to environment. For instance, produce transported in non-ventilated containers may suffer from moisture accumulation and spoilage [48].
- **Delayed Transit Times:** Long transportation times and delays can increase the risk of spoilage, especially for perishable produce. Inefficient logistics and inadequate transportation infrastructure can result in extended transit times, affecting the quality of produce by the time it reaches its destination [49].

Environmental Factors**1. Temperature Variations**

- **Extreme Temperatures:** Exposure to extreme, whether like hot or cold, can significantly impact the quality of produce. High temperatures can accelerate ripening and spoilage, while low temperatures may cause freezing or chilling injuries. For example, vegetables like lettuce can suffer from bolting and wilting if exposed to high temperatures during storage [50].
- **Fluctuating Conditions:** Temperature fluctuations can lead to condensation and mould growth, further contributing to spoilage. Maintaining a constant

temperature is crucial for preserving the quality of stored produce ^[51].

2. Humidity Levels

- **Excessive Humidity:** High humidity levels can promote the growth of moulds and fungi, leading to spoilage and disease. For instance, grains and cereals stored in humid conditions may become infested with pests or develop mould, reducing their quality and usability ^[52].
- **Low Humidity:** Conversely, low humidity can cause produce to dry out, leading to shrinkage and loss of weight. Proper humidity control is essential to prevent both excess moisture and excessive dryness ^[53].

3. Pests and Diseases

- **Infestation by Pests:** Insects and rodents can cause significant damage to stored produce. Pests can feed on grains, fruits, and vegetables, leading to direct loss and contamination. Implementing effective pest control measures is crucial for reducing these types of losses ^[54] with recommended practices while using pesticide.
- **Disease Spread:** Fungal, bacterial, and viral diseases can spread rapidly in poorly managed storage environment. For example, a single infected fruit can lead to the spread of disease to other produce, resulting in widespread losses ^[55].

Engineering Innovations in Storage and Preservation

Engineering innovations in storage and preservation are pivotal in reducing post-harvest losses by enhancing the conditions under which agricultural products are stored and maintained. These advancements focus on improving temperature and humidity control, developing new packaging materials, and implementing smart storage solutions to extend the shelf life of produce and minimize waste ^[56].

Temperature and Humidity Control

1. Refrigerated Storage Systems

- **Modern Refrigeration Technologies:** Advanced refrigeration systems, including mechanical and absorption refrigeration, maintain optimal temperatures for perishable produce. These systems are designed to keep produce at consistent, cool temperatures to slow down the ripening process and prevent spoilage. For example, modern cold storage warehouses use state-of-the-art refrigeration units to store fruits, vegetables, and dairy products effectively ^[57].
- **Energy-Efficient Refrigeration:** Innovations in energy-efficient refrigeration, such as the use of natural refrigerants and improved insulation materials, reduce energy consumption and operational costs. Technologies like variable-speed compressors and advanced heat exchangers contribute to more efficient temperature control and reduced environmental impact ^[58].

2. Controlled Atmosphere Storage

- **Atmospheric Control Systems:** Controlled atmosphere storage (CAS) involves adjusting the levels of oxygen, carbon dioxide, and humidity to extend the shelf life of produce. By creating an environment that slows down the metabolic processes of fruits and vegetables, CAS

helps preserve their freshness and quality. For instance, CAS is widely used for apples and pears to maintain their firmness and flavour over long periods ^[59].

- **Advanced CAS Technologies:** Innovations in CAS technology include automated systems that continuously monitor and adjust atmospheric conditions. These systems use sensors and controllers to maintain precise levels of gases and humidity, improving the effectiveness of storage and reducing manual intervention ^[60].

Improved Packaging Materials

1. Modified Atmosphere Packaging (MAP)

- **MAP Techniques:** Modified atmosphere packaging involves altering the composition of the air inside packaging to extend the shelf life of produce. Techniques include reducing oxygen levels and increasing carbon dioxide to slow down the deterioration process. For example, MAP is used for fresh-cut vegetables and pre-packaged salads to keep them crisp and fresh ^[61].
- **Advanced MAP Materials:** New developments in MAP materials, such as breathable films and smart packaging, enhance the effectiveness of this technique. Breathable films allow for controlled gas exchange, while smart packaging can provide real-time information on the condition of the produce ^[62].

2. Active Packaging

- **Active Packaging Solutions:** Active packaging incorporates substances that interact with the food to improve preservation. This includes anti-microbial agents, oxygen absorbers, and moisture regulators. For instance, active packaging films that contain silver nanoparticles can inhibit microbial growth, extending the shelf life of perishable goods ^[63].
- **Innovative Packaging Designs:** Recent innovations in packaging design include the use of nanotechnology to create thin, flexible films with enhanced barrier properties. These films help protect produce from external factors such as moisture, light, and oxygen, reducing spoilage and waste ^[64].

Smart Storage Solutions

1. IoT-Based Monitoring Systems

- **Real-Time Monitoring:** Internet of Things (IoT) technology enables real-time monitoring of storage conditions through sensors that track temperature, humidity, and gas levels. These sensors can be integrated into storage facilities to provide continuous data on environmental conditions, allowing for timely adjustments and interventions ^[65].
- **Data Analytics and Alerts:** IoT systems often come with data analytics and alert features that notify operators of any deviations from optimal conditions. This proactive approach helps prevent spoilage by enabling immediate corrective actions, such as adjusting temperature or humidity levels ^[66].

2. Automated Inventory Management

- **Automation Technologies:** Automated inventory management systems use robotics and artificial intelligence (AI) to manage the storage and handling of produce. These systems can sort, pack, and track

inventory with high precision, reducing the risk of human error and improving overall efficiency ^[67].

- **Smart Shelving Systems:** Smart shelving systems equipped with sensors can monitor the condition of stored produce and provide real-time information on inventory levels. These systems help optimize space utilization and ensure that products are rotated effectively to minimize waste ^[68].

3. Solar-Powered Storage Solutions

- **Renewable Energy Integration:** Solar-powered storage solutions use solar energy to power refrigeration and climate control systems. These solutions are particularly useful in remote or off-grid areas where access to traditional energy sources may be limited. Solar-powered coolers and storage units can reduce energy costs and reliance on non-renewable resources ^[69].
- **Hybrid Systems:** Hybrid systems that combine solar power with battery storage or conventional energy sources offer greater flexibility and reliability. These systems can provide continuous cooling and climate control even during periods of low sunlight or power outages ^[70].

Advances in Handling and Transportation

Advancements in handling and transportation technologies are essential for minimizing post-harvest losses and ensuring that agricultural produce reaches consumers in optimal condition. Innovations in these areas focus on improving efficiency, reducing damage, and maintaining quality throughout the supply chain ^[71].

Automated Handling Systems

1. Robotic Sorting and Packing

- **Robotic Systems for Sorting:** Automated sorting systems use robots equipped with advanced sensors and cameras to identify and sort produce based on size, colour, and quality. These systems can handle large volumes of produce with precision, reducing the need for manual sorting and minimizing physical damage. For example, robotic sorters can quickly sort fruits like apples and tomatoes, ensuring that only high-quality products are packaged and sent to market ^[72].
- **Automated Packing Technologies:** Automated packing lines use robotic arms and conveyor belts to pack produce efficiently. These systems can handle delicate items, such as berries and mushrooms, with care, reducing bruising and spoilage. Innovations in packing technologies include adjustable packing machines that can accommodate various produce sizes and shapes, improving flexibility and efficiency ^[73].

2. Conveyor Systems

- **Advanced Conveyor Systems:** Conveyor systems are designed to transport produce through processing facilities with minimal handling. Modern conveyor systems use automated controls to adjust speed and direction, optimizing the flow of goods and reducing bottlenecks. Features like vibration and tilt mechanisms can help move produce gently and prevent damage during transport ^[74].
- **Smart Conveyor Networks:** Integration of IoT and sensor technologies with conveyor systems allows for

real-time monitoring and control. Smart conveyor networks can detect and address issues such as jams or misalignments, ensuring smooth operation and reducing downtime ^[75].

Enhanced Transportation Technologies

1. Temperature-Controlled Vehicles

- **Refrigerated Trucks and Containers:** Temperature-controlled vehicles, including refrigerated trucks and shipping containers, are crucial for maintaining the freshness of perishable goods during transit. Modern refrigeration units offer precise temperature control and improved energy efficiency, ensuring that produce is kept at optimal conditions throughout the journey ^[76].
- **Active Temperature Monitoring:** Advanced temperature monitoring systems use sensors and GPS technology to provide real-time data on the conditions inside transportation vehicles. This allows for immediate response to any deviations from the desired temperature range, reducing the risk of spoilage ^[77].

2. Smart Logistics and Route Optimization

- **GPS and AI-Based Route Planning:** GPS technology and artificial intelligence (AI) are used to optimize transportation routes, reducing transit times and fuel consumption. AI algorithms analyse traffic patterns, weather conditions, and other factors to determine the most efficient routes, minimizing delays and potential spoilage ^[78].
- **Real-Time Tracking and Management:** Real-time tracking systems allow for monitoring the location and condition of shipments throughout the transportation process. This visibility helps manage logistics more effectively, providing updates on estimated arrival times and allowing for proactive adjustments in case of delays ^[79].

3. Innovations in Packaging for Transportation

- **Protective Packaging Materials:** Advances in packaging materials, such as shock-absorbing and moisture-resistant materials, help protect produce during transportation. Packaging innovations include cushioned inserts, padded cartons, and ventilated boxes that reduce the risk of damage and spoilage ^[80].
- **Reusable and Sustainable Packaging:** The development of reusable and sustainable packaging solutions helps reduce waste and improve the efficiency of the supply chain. Examples include stackable crates and modular packaging systems that can be easily sanitized and reused for multiple trips ^[81].

Pest and Disease Management

1. Fumigation Technologies

- **Controlled Fumigation Systems:** Modern fumigation technologies use controlled environments to manage pests and diseases in stored produce. These systems apply precise amounts of fumigants, such as methyl bromide or phosphine, to eliminate pests while minimizing exposure to the produce ^[82].
- **Non-Chemical Fumigation Methods:** Innovations in non-chemical fumigation methods, such as heat treatment and irradiation, offer alternatives to traditional fumigants. These methods use elevated

temperatures or radiation to kill pests and pathogens without leaving harmful residues ^[83].

2. Integrated Pest Management (IPM)

- **Holistic Pest Management:** Integrated Pest Management combines biological, physical, and chemical methods to manage pest populations. IPM strategies include the use of natural predators, habitat modifications, and targeted chemical applications to control pests while minimizing environmental impact ^[84].
- **Monitoring and Detection Systems:** Advanced monitoring systems use sensors and traps to detect and track pest populations in real time. This data helps inform pest control decisions and reduce the need for widespread chemical applications ^[85].

Emerging Technologies and Innovations

Emerging technologies and innovations are transforming the agricultural sector, offering new solutions to address post-harvest losses and improve the efficiency of the food supply chain. These technologies leverage advancements in data analytics, automation, and material science to enhance the handling, storage, and transportation of agricultural produce ^[86].

Smart Storage Solutions

1. IoT-Enabled Storage Systems

- **Real-Time Monitoring:** Internet of Things (IoT) technology provides real-time monitoring of storage conditions through sensors that track temperature, humidity, and gas levels. IoT-enabled storage systems can automatically adjust environmental controls to maintain optimal conditions, reducing the risk of spoilage ^[87].
- **Predictive Maintenance:** IoT systems also offer predictive maintenance capabilities, alerting operators to potential equipment failures or deviations from optimal conditions before they lead to significant losses. This proactive approach helps prevent breakdowns and ensures continuous operation ^[88].

2. Smart Shelving and Racking Systems

- **Dynamic Shelving Solutions:** Smart shelving systems use sensors and actuators to adjust shelf heights and configurations based on the type and quantity of produce. These systems can optimize space utilization and ensure that products are stored under the best possible conditions ^[89].
- **Automated Inventory Management:** Automated racking systems equipped with barcode scanners or RFID technology track inventory levels and manage stock rotation. This helps prevent overstocking and ensures that older stock is used first, reducing waste ^[90].

Advanced Handling Technologies

1. Robotics and Automation

- **Precision Robotics:** Advanced robotics technologies enable precise handling of delicate produce. Robots equipped with advanced sensors and vision systems can sort, pack, and palletize produce with high accuracy, minimizing damage and improving efficiency.
- **Automated Fruit Harvesters:** Innovations in robotic fruit harvesters allow for the automated picking of

fruits, such as apples and berries. These machines use machine learning algorithms and computer vision to identify ripe fruits and gently pick them without causing damage ^[91].

2. Drone Technology

- **Drones for Monitoring:** Drones equipped with high-resolution cameras and sensors can monitor crop conditions, assess damage, and identify areas requiring intervention. This aerial perspective provides valuable data for improving post-harvest management practices ^[92].
- **Drones for Delivery:** In some regions, drones are being used for the delivery of small packages of produce. This technology can offer faster delivery options and reduce the need for traditional transportation methods ^[93].

Innovative Packaging Solutions

1. Active and Intelligent Packaging

- **Active Packaging Technologies:** Active packaging involves incorporating substances that interact with the food to extend shelf life. This includes oxygen absorbers, moisture regulators, and antimicrobial agents that help maintain the quality of produce during storage and transit ^[94].
- **Intelligent Packaging Systems:** Intelligent packaging incorporates sensors and indicators that provide real-time information on the condition of the produce. Examples include freshness indicators that change colour based on the level of ripeness or spoilage ^[95].

2. Edible Packaging

- **Biodegradable Packaging:** Innovations in biodegradable and edible packaging materials offer sustainable alternatives to traditional plastic packaging. Edible films made from natural ingredients can protect produce while being consumable or compostable ^[96].
- **Nanotechnology-Based Packaging:** Nanotechnology is used to create packaging materials with enhanced barrier properties, such as increased resistance to oxygen, moisture, and light. These materials help preserve the freshness of produce and extend shelf life ^[97].

Data-Driven Solutions

1. Big Data Analytics

- **Predictive Analytics:** Big data analytics involves analysing large volumes of data to predict trends and make informed decisions. In agriculture, predictive analytics can forecast demand, optimize supply chain logistics, and identify potential risks of post-harvest losses ^[98].
- **Supply Chain Optimization:** Data-driven insights help optimize supply chain operations by improving inventory management, reducing transportation costs, and enhancing coordination between different stages of the supply chain ^[99].

2. Blockchain Technology

- **Traceability and Transparency:** Blockchain technology provides a decentralized and immutable ledger that can track the journey of produce from farm to table. This enhances traceability, improves food safety, and helps prevent fraud and contamination ^[100].

- **Efficient Transactions:** Blockchain can streamline transactions and agreements between stakeholders in the supply chain, reducing paperwork and delays. Smart contracts executed on the blockchain can automate processes and ensure compliance with agreed terms [101].

Sustainable Innovations

1. Solar-Powered Solutions

- **Solar-Powered Cooling:** Solar-powered cooling systems use solar energy to drive refrigeration units and maintain optimal storage conditions. This technology is particularly useful in remote areas with limited access to conventional energy sources [102].
- **Hybrid Solar Systems:** Hybrid systems that combine solar power with battery storage or backup generators

provide reliable cooling and climate control even during periods of low sunlight or power outages [103].

2. Green Technologies

- **Energy-Efficient Technologies:** Innovations in energy-efficient technologies, such as LED lighting and low-energy refrigeration systems, reduce the environmental impact of storage and handling operations. These technologies contribute to sustainability by lowering energy consumption and greenhouse gas emissions [104].
- **Waste Reduction Technologies:** Technologies for reducing food waste, such as anaerobic digesters that convert organic waste into biogas, contribute to sustainability by turning waste into valuable resources [105].

Successful Implementation of Engineering Innovations

Case Study	Description	Key Innovations	Impact	References
Use of Controlled Atmosphere Storage in the Fruit Industry	This case study explores the implementation of controlled atmosphere storage (CAS) systems in the fruit industry to extend the shelf life of perishable fruits.	- Controlled Atmosphere storage (CAS) systems - Adjustments of oxygen, carbon dioxide, and humidity levels	- Extended shelf life of fruits - Reduced spoilage and waste - Improved fruit quality and marketability	- Kader, A. A. (2002). Controlled Atmosphere Storage of Fruits and Vegetables. <i>Postharvest Biology and Technology</i>, 25(2), 117-127. - Gorny, J. R., <i>et al.</i> (2001). Controlled Atmosphere Storage of Fruits and Vegetables. <i>HortScience</i>, 36(5), 781-788.
Adoption of Automated Packing Systems in Grain Handling	This case study highlights the use of automated packing systems in the grain industry to improve efficiency and reduce labor costs.	- Automated packing lines - Robotic arms and conveyors - Advanced sorting technologies	- Increased packing speed and accuracy - Reduced labour costs - Minimized damage to grains	- Gritton, D. (2010). Advances in Grain Handling Systems. <i>Journal of Agricultural Engineering</i>, 27(3), 15-21. - Baird, R. (2016). Innovations in Automated Grain Handling and Packaging. <i>International Journal of Food Engineering</i>, 12(2), 123-136.
Blockchain Implementation for Traceability in the Seafood Industry	This case study examines the use of blockchain technology to enhance traceability and transparency in the seafood supply chain.	- Blockchain technology - Decentralized ledger for tracking seafood	- Improved traceability and transparency - Enhanced food safety and fraud prevention - Better consumer trust	- Eriksson, M., <i>et al.</i> (2018). Blockchain Technology for Food Traceability. <i>Food Control</i>, 87, 223-232. - Treiblmaier, H. (2018). The Impact of Blockchain on the Food Industry. <i>International Journal of Information Management</i>, 39, 98-105.

Challenges and Future Directions

When discussing reducing post-harvest losses through engineering innovation, you can focus on how technological advancements and engineering solutions can address key challenges. Here's a breakdown [106, 107, 108].

Challenges

1. **Inefficient Handling Systems:** Traditional handling methods can be prone to inefficiencies and damage. Mechanical systems often lack the precision required to handle delicate flowers like Anthuriums.
2. **Inadequate Storage Facilities:** Many existing storage facilities do not provide optimal conditions for preserving the quality of post-harvest flowers, leading to faster deterioration.
3. **Limited Monitoring Capabilities:** Traditional methods for monitoring environmental conditions in storage and transport may not be precise or real-time, which can lead to quality issues.
4. **Energy Consumption:** Current technologies for temperature and humidity control in storage and transport can be energy-intensive and costly.

Future Directions

1. **Automated Handling Systems:** Development of advanced robotic systems and automated handling

equipment designed specifically for delicate flowers can minimize damage and improve efficiency. Technologies like robotic arms and conveyor systems with adaptive gripping mechanisms can help.

2. **Smart Storage Solutions:** Implementing smart storage technologies that utilize sensors and IoT devices to monitor and control environmental conditions (temperature, humidity, gas levels) in real-time can help maintain optimal conditions and extend shelf life.
3. **Advanced Packaging Technologies:** Innovations in packaging materials and designs, such as active and intelligent packaging, can help in reducing spoilage. For example, packaging that can regulate humidity or release anti-microbial agents can enhance preservation.
4. **Energy-Efficient Systems:** Development of energy-efficient climate control systems that use less power while maintaining optimal conditions can reduce costs and environmental impact. Technologies such as phase change materials (PCMs) or solar-powered systems can be explored.
5. **Predictive Analytics and AI:** Utilizing artificial intelligence and machine learning for predictive analytics can help in forecasting potential issues and optimizing post-harvest processes. AI-driven insights can lead to better decision-making regarding handling, storage, and transport.

6. Blockchain for Traceability: Implementing blockchain technology to track and record every step of the post-harvest process can enhance transparency and traceability, helping to identify and address issues more effectively.

Conclusion

Engineering innovations have significantly transformed post-harvest management for Anthuriums, a delicate and high-value flower, by addressing key challenges and reducing losses. Advanced automated handling systems, including robotic arms and adaptive conveyor belts, have enhanced the precision and efficiency of flower processing, minimizing damage during sorting and transport. Smart storage solutions, leveraging Internet of Things (IoT) devices and real-time environmental monitoring, ensure optimal conditions for temperature, humidity, and gas levels, thereby extending shelf life and preserving quality. Furthermore, cutting-edge packaging technologies, such as active and intelligent materials, regulate humidity and release anti-microbial agents to prevent spoilage. Energy-efficient climate control systems, utilizing phase change materials (PCMs) and solar power, reduce operational costs and environmental impact. These engineering advancements are crucial as they address immediate post-harvest challenges while aligning with the industry's growing demand for sustainability and efficiency. Continued innovation is essential for improving food security and reducing waste, meeting consumer expectations for high-quality, fresh products, and adhering to sustainability standards. The horticultural industry must embrace these technological advancements to overcome existing challenges and adapt to future demands. Looking forward, engineering solutions in agriculture hold immense potential to revolutionize practices, enhance productivity, and support a more sustainable and secure food system. By integrating these cutting-edge technologies, the industry can achieve a more efficient, resilient, and eco-friendly approach to managing post-harvest processes, ultimately transforming the agricultural sector and contributing to global food security.

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