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Advanced packaging technology for fresh fruit: from anti-damage and preservation to intelligent monitoring

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ABSTRACT

Background: Mechanical damage during postharvest circulation of fresh fruits remains a major obstacle limiting industry advancement. Effective packaging plays a vital role in mitigating mechanical injury, reducing spoilage, and extending shelf life. Although technologies are advancing, a systematic review is urgently needed to integrate recent progress in anti-damage, preservation, and intelligent packaging, and to support the development of more effective and sustainable packaging solutions.

Scope and approach: This paper summarises the damage-causing factors including mechanical damage, physical and chemical responses and environmental factors of fresh fruits. Focusing on the core challenges of packaging, we systematically review the research of anti-damage packaging (buffer material design, compressive structure optimisation and innovation research), fresh packaging (modified-air packaging, active packaging, slow-release technology and material innovation), and intelligent packaging (freshness indicator, radio frequency identification (RFID) temperature recording, traceable labels).

Key findings and conclusion: Fresh fruit packaging is in a critical leap towards interdisciplinary integration and functional integration. Modern packaging technology has shown considerable effectiveness in a wide range of applications. Anti-damage packaging enables effective control of transport vibration, impact and compression stress. Preservation packaging can significantly extend the shelf life of fruit and improve the efficiency of nutritional value retention. Intelligent packaging has achieved real-time monitoring of the quality of fresh fruit status and dynamic feedback. This review highlights the transformative potential of packaging technologies for high quality development of the modern fruit supply chain and for promoting more sustainable and data-driven fruit packaging technologies.

1. Introduction

Fresh fruits are a critical part of global agricultural production and consumption. Maintaining their quality throughout postharvest handling, transportation, storage, and retail is essential for ensuring product value and reducing losses. However, due to their high moisture content, rapid respiration, and delicate tissue structure, fresh fruits are highly prone to mechanical damage, physiological deterioration, and microbial contamination. These issues frequently lead to spoilage, quality decline, and nutrient loss (Al-Dairi et al., 2022; Reynoud et al., 2023). It is estimated that 25–30 % of fruit and vegetable losses occur along the entire supply chain, from packaging to consumption, causing substantial economic and resource losses (Yu et al., 2024). Therefore, developing advanced and intelligent packaging technologies is crucial for preserving quality, extending shelf life, and improving supply chain efficiency.

In recent years, fruit packaging technologies have evolved toward interdisciplinary integration, involving materials science, biomechanics, food engineering, and information technology. Anti-damage packaging aims to reduce external and internal injuries caused by mechanical forces. Preservation packaging focuses on delaying senescence and microbial spoilage. Intelligent packaging enables real-time monitoring of

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product and environmental conditions. Despite these advances, current packaging systems still face challenges such as poor adaptability, unclear performance interactions, and limited environmental sustainability. A comprehensive review of their development trends and integration pathways is urgently needed to guide future innovation.

This review lies in its cross-disciplinary and systematic perspective that comprehensively summarises research progress over the past five years in three key areas of fruit packaging: damage prevention, freshness preservation, and intelligent monitoring, thereby overcoming the limitations of previous reviews that often focused on a single aspect. Key aspects include packaging materials, structural design, functional mechanisms, and system integration. The aim is to identify current limitations, clarify technical bottlenecks, and outline future research directions. Compared with existing literature, this review presents four major innovations. First, it not only synthesizes the most recent advances over the past five years but also explores the molecular mechanisms underlying fruit damage, such as the regulatory roles of R2R3-MYB and NAC transcription factors, and links these biological insights with the design of active and intelligent packaging systems, bridging mechanistic studies and packaging engineering. Second, it highlights the transformative potential of artificial intelligence-driven material design, biomimetic structures, and molecular-level active interventions in advancing the optimisation of protective and preservative packaging, moving beyond traditional methods that primarily rely on experimental iteration. Third, it critically examines the key challenges of translating laboratory innovations into industrial applications, including the safety assessment of nanomaterials, cost-effectiveness (see Table S1), and consumer acceptance. Finally, it proposes a forward-looking framework for the development of multi-functional integrated packaging systems that synergistically combine protection, preservation, and real-time monitoring. Through this holistic and prospective approach, the review not only provides a comprehensive roadmap for understanding the evolution of fruit packaging technologies but also lays a theoretical and practical foundation for future innovations in reducing food loss and advancing sustainable intelligent packaging.

2. Damage causing factors of fresh fruits and the core challenges of packaging

Fresh fruits are highly susceptible to structural and functional damage during postharvest transport caused by external mechanical loads and environmental changes. Biomechanics (mechanical damage) will trigger a series of physiological and biochemical abnormalities such as cell rupture, juice exudation, enzymatic browning and flavour deterioration. These damages rapidly reduce the appearance quality and nutritional value of fresh fruits, accelerate the rate of decay, and ultimately lead to loss of commodity value and higher market wastage. In particular, the complexity of routes and the drastic fluctuations of temperature and humidity in the transport environment can increase the extent of damage. Fruits are significantly more sensitive to mechanical stresses and environmental pressures because of maturity differences and tissue fragility. Therefore, the main damage-causing factors in fresh fruit include biomechanical factors, physiological and biochemical factors, and environmental factors (Fig. 1).

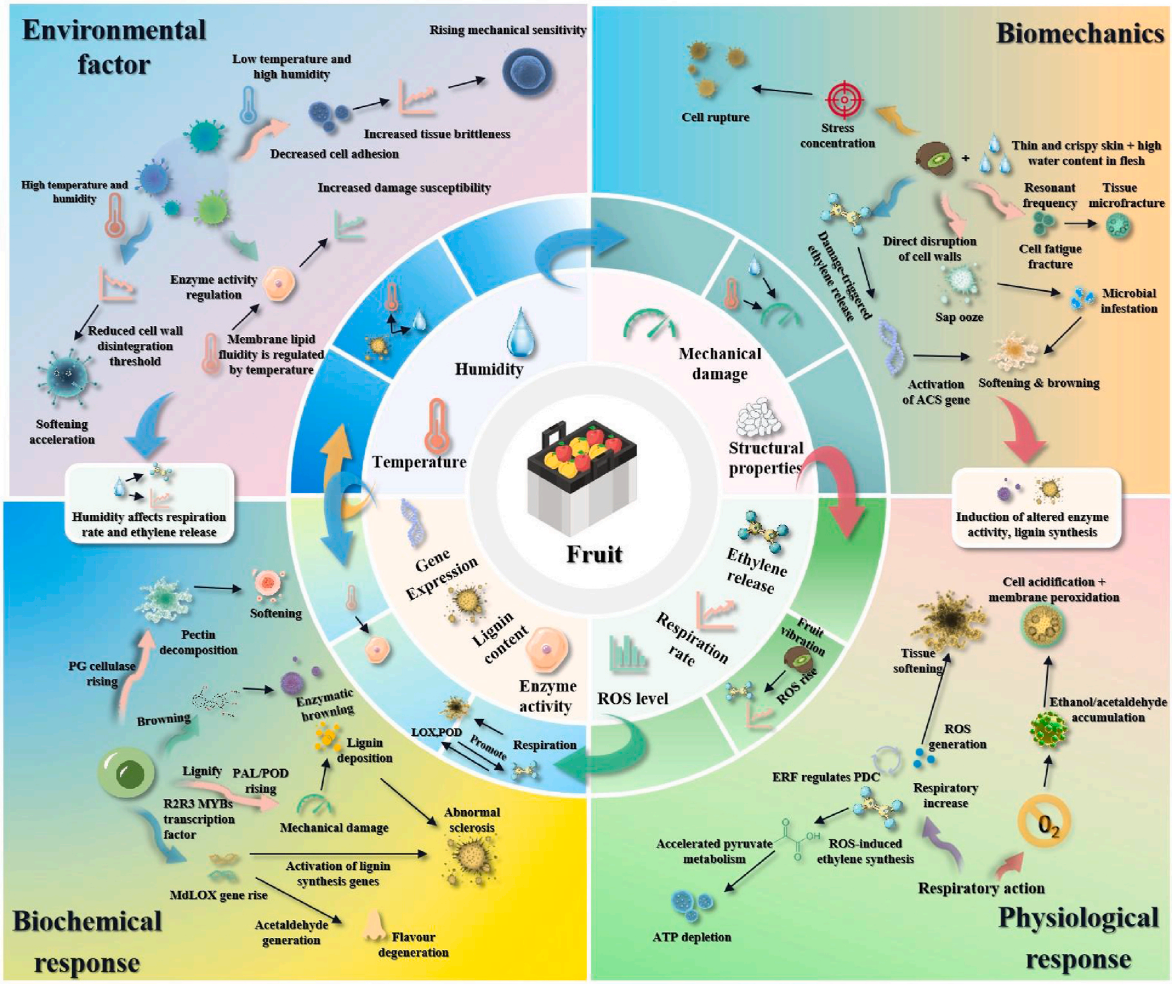

Fig. 1. The main damage-causing factors in fresh fruit.

2.1. Biomechanics

Mechanical damage mainly arises from static compression, dynamic impact and transport vibration, and the mechanism of action is closely related to the viscoelasticity of the fruit tissue (Al-Dairi et al., 2022). It has been shown that when the external force exceeds the biological yield stress, the fruit undergoes a progressive damage process of elastic deformation, plastic deformation to cell rupture (An et al., 2020). Compression forces often occur when fruit are stacked or in contact with packing containers, especially when fruit are in contact with each other or collide with hard objects, which can easily lead to localised compression injuries (Lin et al., 2023). The impact force comes mainly from falls or collisions encountered during transport, especially during handling or loading and unloading. Collisions of fruit with other objects or containers may lead to problems such as rupture of the skin and deterioration of the flesh (Lin et al., 2023). Vibration damage is impact injury caused by fruit colliding with each other or with packaging, or abrasion caused by fruit rubbing against other surfaces (Wang et al., 2019). When the transport vibration frequency resonates with the intrinsic frequency of the fruit, the acceleration of the fruit may increase dramatically. When the stacking pressure exceeds a critical threshold, it triggers an exponential expansion of cell wall microcracks, resulting in severe damage (Al-Dairi et al., 2022).

2.2. Physiological and biochemical factors

Under external forces, mechanical damage of fresh fruit can initiate a cascade of physiological and biochemical changes that severely compromise fruit quality. These include visible symptoms like skin breakage and juice exudation, as well as internal degradation such as loss of firmness, acids, nutrients, and volatiles, ultimately accelerating decay and reducing market value (Fernando et al., 2018; Lin et al., 2023; Wei et al., 2019).

Meanwhile, damage triggers multiple physiological responses. Cell membrane disintegration prompts polyphenol oxidase (PPO) to contact the substrate to trigger browning (Li & Thomas, 2014). Up-regulation of ethylene synthesis genes (1-aminocyclopropane-1-carboxylic acid (ACC), ACC-synthase (ACS), 1-aminocyclopropane-1-carboxylic acid oxidase (ACO)) expression accelerate fruit softening (Xu et al., 2020). Lignin synthesis-related enzyme (phenylalanine ammonia-lyase (PAL), peroxidase (POD), cinnamyl alcohol dehydrogenase (CAD)) activities surge after impact, leading to abnormal fruit hardening (Kamdee et al., 2014). Metabolic disorders induced by the injury promote the expression of lipoxygenase pathway genes (e.g. MdLOX-like), leading to the accumulation of off-flavours such as hexanal, which further reduces the commercial value (Lin et al., 2021). Critically, these damage responses are regulated at the molecular level. Transcription factors such as R2R3-MYB and NAC have been identified as master regulators controlling the expression of genes involved in lignin and ethylene biosynthesis in response to mechanical stress (Kamdee et al., 2014; Nieuwenhuizen et al., 2021).

In the future, in-depth analysis of molecular regulatory networks like the metabolic pathways mediated by R2R3-MYB transcription factors may provide novel theoretical underpinnings and practical pathways for designing active and intelligent packaging systems. Existing researches have shown that ethylene scavengers or PPO inhibitors can effectively delay the ripening and browning processes of postharvest fruits (Gaikwad et al., 2020; Sui et al., 2023). If they are further combined with functional packaging materials, it is expected to achieve targeted intervention in biochemical cascade reactions induced by mechanical damage. Theoretically, if specific transcription factors are confirmed to promote lignin deposition or ethylene synthesis during the damage response (e.g., R2R3-MYB transcription factors regulating injury responses), future research may explore empowering packaging systems through specific inhibitors or RNA interference (RNAi) strategies to achieve targeted regulation of key metabolic pathways. However, such approaches remain confined to experimental research stages and face significant challenges regarding biosafety and cost-feasibility. Concurrently, the development of intelligent packaging is evolving from a single detection mode towards a closed-loop regulatory system integrating detection and response. Integrating highly sensitive biosensors into packaging systems to monitor early molecular markers of damage, such as transient ethylene release or reactive oxygen species accumulation, could significantly enhance the proactive protective efficacy of packaging against fruit quality deterioration (Yan et al., 2024). Coupling intelligent packaging with controlled-release modules for antioxidants or antimicrobial agents would achieve synergistic effects (Du et al., 2023). Although these strategies remain at the exploratory stage, their potential applications offer new avenues for deepening the integration between molecular biology and food packaging engineering.

2.3. Environmental factors

Temperature and humidity regulation affects damage susceptibility through altering cell membrane permeability and enzyme activity. Humidity variations exacerbate water loss from the fruit, injure epidermal cell membranes and alter the permeability of cell membranes, leading to increased susceptibility to mechanical damage (Mutari & Debbie, 2011). High temperatures accelerate the respiration of fresh fruit, making it softer and more susceptible to bruising under mechanical forces such as vibration (Al-Dairi et al., 2022). High temperatures and humidity can exacerbate fresh fruit metabolism and microbial reproduction, making the epidermis soften and rot, and reducing resistance to mechanical damage. Meanwhile, high temperature and humidity promote an increase in polygalacturonase and pectin methylesterase activity, leading to a lower threshold for cell wall disintegration (Martínez & Civello, 2008; Noichinda et al., 2007). Although low-temperature storage can retard metabolism, inappropriate combinations of temperature and humidity (e.g., high humidity and low temperature) can exacerbate hydration of cell wall structures and contribute to a decrease in intercellular adhesion (Li & Chen, 2017). The suitable temperature and humidity can delay the ripening and senescence of fresh fruits, and maintain fruit firmness and resistance to mechanical damage.

2.4. The core challenge of fresh fruit packaging

In conclusion, fresh fruits are extremely susceptible to structural and functional damage during postharvest transport because of external mechanical loads and environmental changes. The damage causing factors mainly include biomechanical factors, physiological and biochemical factors and environmental factors. Packaging is essential for controlling the rate of mechanical damage, spoilage and extending the shelf life of fresh fruits. Therefore, based on the damage-causing factors, comprehensive performance demands are placed on the packaging system. Firstly, anti-damage is the basic requirement. Packaging needs to have excellent performance of vibration isolation and compression resistance. The purpose is that the impact and compression loads that may be generated during transport can be effectively dispersed and absorbed, avoiding deformation or rupture of the fruit tissue. Secondly, preservation of freshness is crucial. Packaging should have good ability to regulate temperature and humidity to maintain the appropriate microenvironment for the fruit, slow down the metabolic rate and inhibit the process of physiological deterioration. In addition, there are higher requirements for the sustainability of packaging materials. Reducible and recyclable green materials should be prioritised to reduce the burden of packaging waste on the environment. On this basis, intelligent packaging has become an essential development direction for fresh fruit packaging.

3. Anti-damage packaging technology for fresh fruits

Fresh fruit in the supply chain transport and storage links are very susceptible to mechanical impact, vibration environmental stress and other factors, resulting in quality deterioration and economic losses. Scientific design of damage prevention packaging has become an important path to improve the efficiency and economic benefits of fruit circulation. In recent years, the relevant research is mainly focused on the structural design of packaging, optimisation of material buffer performance and development of green packaging, and has gradually built up a more systematic research system of anti-damage packaging.

3.1. Traditional packaging technologies and applications for damage prevention

3.1.1. Buffer material design

Vibration damping packaging design can be divided into two categories. One category is packaging design mainly to prevent impact damage. Materials with strong compression capacity and high elasticity should be selected, which are suitable for products whose impact damage strength is higher than the vibration damage strength. The other category is packaging design that focuses on vibration damping. It should choose materials with strong attenuation capacity and high damping characteristics, which are suitable for products with low brittle value due to fatigue damage easily caused by long-term transport vibration. Existing buffer materials mainly include expanded polystyrene (EPS), expandable polyethylene (EPE), polyethylene terephthalate (PET), moulded fibre, polyurethane (PU), corrugated cardboard, polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP).

Foamed materials foams have been proven in many studies to have excellent vibration damping properties, especially EPS. It was found that EPS buffer material performed well in the protection of kiwifruit, apple and pear fruits through free fall test, impact test, etc (Wang et al., 2022). Meanwhile, the material elastic modulus, diameter, mesh size, initial collision speed, and ambient temperature of EPE foam packaging net will affect the fruit collision damage, and the damage volume of the fruit will also increase (An et al., 2023). In addition, bio-based buffer materials (e.g., nanocellulose composite film) play an important role in the field of anti-damage due to their degradability, good mechanical properties, flexibility and high specific strength advantages. This material can reduce fruit damage during transport and storage by dispersing stress and absorbing impact energy (Jafarzadeh et al., 2023).

3.1.2. Optimisation of the anti-damage structure

The structural optimisation of anti-damage packaging mainly includes the way and design of the packaging structure. The stability and support of the packaging structure has an important impact on the anti-damage capability, for example, corrugated boxes with rectangular ventilation holes have inadequate performance (Ambaw et al., 2022). Some researchers used plastic dividers combined with PU and EPE foams to design structural packaging that reduces the transport damage of orange. Wang et al. (2022) found that the combination of EPS trays and EPE mesh covers provided the optimal anti-damage capability for pears compared to the combination of corrugated cardboard and EPE mesh covers, EPS trays and paper packs, EPS trays, and corrugated cardboard and paper packs. Lin et al. (2020) tested the anti-damage performance of packaging for peaches and showed that the combination of polyurethane and corrugated board construction outperformed the combination of EPE and corrugated board as well as the corrugated board box alone. Fernando et al. (2020) found that one-piece corrugated boxes provided the best mechanical buffering protection for bananas, further emphasising the importance of the overall structure of the package for vibration propagation control.

3.2. Advancements in anti-damage packaging for fresh fruit

The innovation of anti-damage packaging for fresh fruits lies at the core of solving the problem of physical damage to fruits during transport and storage through the cross integration of materials science and engineering technology. In recent years, the research focus has shifted from traditional petroleum-based materials to biodegradable composites, and the integration of nanotechnology, computer simulation and other cutting-edge methods has significantly improved the functionality and environmental compatibility of packaging systems (Fig. 2) (Jafarzadeh et al., 2023; Perera et al., 2024).

3.2.1. Material advancements

In terms of material innovation, nano-enhanced biopolymers show significant advantages. The film formed by the combination of bacterial cellulose (BC) and protein isolates extracted from sunflower meal (SFMPI) showed a 64.5 % increase in tensile strength, a 75.5 % increase in Young's modulus and a 131.5 % increase in elongation at break, while water solubility and water vapour permeability were reduced by 32.5 % and 14.1 %, respectively, compared to pure SFMPI (Efthymiou et al., 2022). This material effectively absorbs external impact energy and reduces collision damage to fresh fruit during transport through the interfacial enhancement effect of nanofibres. Similarly, the mechanical properties of nanocomposite film of silk protein with 2D covalent organic frameworks (COFs) are enhanced. It also enables real-time monitoring of fruit spoilage through colour change, achieving the dual functions of damage warning and active protection (Fig. 2C) (Han et al., 2023). In addition, eugenol loaded gelatin nanofibers (ELGNs) prepared by electrospinning technique can extend the shelf life of fresh meat up to 9 days, dispersing the stresses through a homogeneous fibre structure (Yilmaz et al., 2022). The same principle applies to damage prevention packaging for fruits with high moisture content.

Functional integration is another innovative direction. Active packaging materials based on plant byproducts (e.g. polyphenols from peels, cereal bran extracts) not only have antioxidant and antimicrobial properties, but their natural fibre network also enhances the toughness of the film through hydrogen bonding cross-linking. For example, a COF-Silk film loaded with hexanal reduces soya mould growth by four orders of magnitude at high temperatures and high humidity. This combination of anti-microbial properties and mechanical protection is particularly suitable for fresh fruit storage and transport in tropical climates (Han et al., 2023). Notably, nanocoating technology and micro-nano-bubbles can synchronously inhibit the respiratory intensity and alleviate mechanical stress in fruits by regulating gas permeability (Shan et al., 2023). Their synergistic effect could extend the shelf life of bananas (Fig. 2F). In addition, bio-based packaging materials containing nanoclay and biodegradable food packaging materials with porous nanomaterials (metal-organic frameworks) not only improve the mechanical and barrier properties, but also prolong the biodegradation time of the packaging materials (Fig. 2A and B) (Jafarzadeh et al., 2023; Perera et al., 2024).

Despite the significant potential of nano-enhanced materials in terms of mechanical and functional properties, their application in food contact materials remains a central challenge for industrial implementation due to safety concerns. Nanoparticles may migrate into food, posing potential risks to consumer health. Current safety assessments of nanomaterials primarily focus on migration testing, toxicological evaluation, and exposure assessment (Wang et al., 2025). However, globally, there is still a lack of fully harmonized standards and clearly defined limits for nanomaterials. Many biopolymer-based nanocomposites are considered to exhibit improved biocompatibility owing to their natural origin and biodegradability, yet their long-term exposure risks and metabolic pathways in the human body require further investigation (Wang et al., 2025). Establishing standardized and comparable testing methodologies, coupled with interdisciplinary efforts to develop comprehensive risk-benefit assessment frameworks, will be crucial for facilitating the commercial adoption of nanomaterial-based packaging.

Beyond traditional experimental and simulation methods, artificial intelligence (AI) and machine learning (ML) are increasingly becoming pivotal tools in driving the design of next-generation anti-damage packaging materials. By efficiently processing huge datasets of material

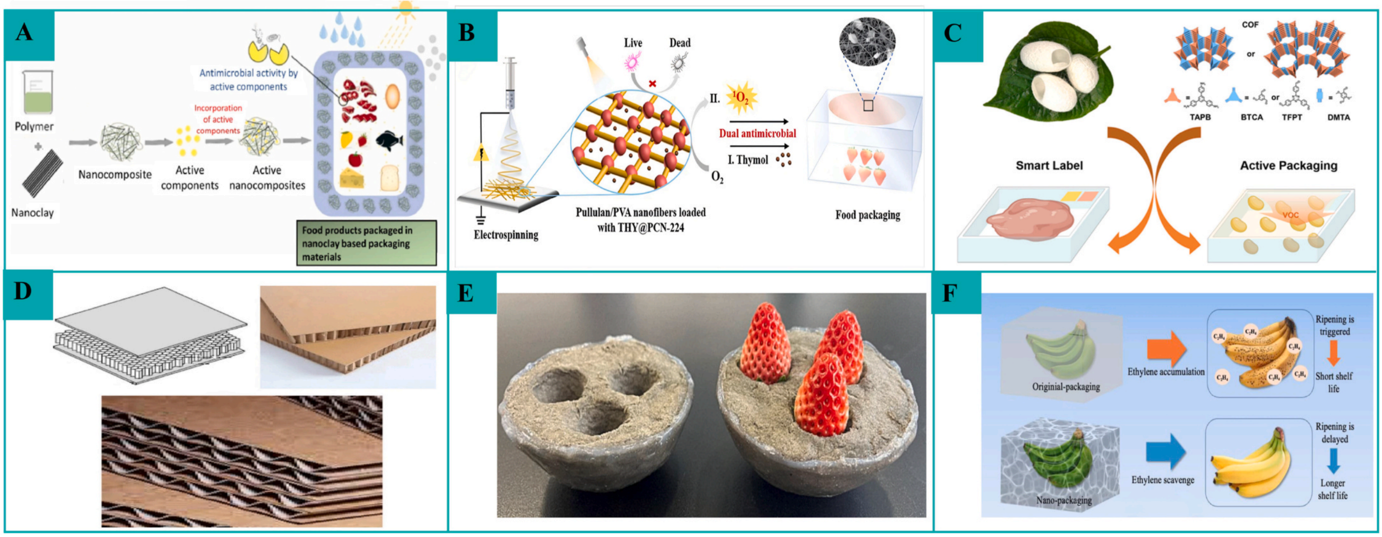

Fig. 2. Innovative research and application of loss prevention packaging. A. Schematic representation of developing active nanocomposites using nanoclay and antibacterial agents (Perera et al., 2024). B. The preparation principle of biodegradable food packaging materials with porous nanomaterials (metal-organic frameworks) (Jafarzadeh et al., 2023). C. Biodegradable climate-adapted packaging materials - silk protein-covalent organic frameworks composite film (Han et al., 2023). D, Bionic-inspired honeycomb composite cardboard system (Pirsa, 2024). E. Biomimetic hierarchical composites inspired by natural pomelo peel (Hu et al., 2024). F. Mechanism of nano-packaging to extend shelf life of fruit (Shan et al., 2023).

properties (such as tensile strength, Young's modulus, damping performance) and formulation parameters, AI can significantly accelerate the screening and optimisation process for composite materials. Predictive models based on neural networks or random forests can infer the mechanical and barrier properties of nanocomposites based on the type, concentration, and surface modification of nanofillers, thereby reducing extensive trial-and-error experimentation (Champa-Bujaico et al., 2024; Rafiee et al., 2024). Simultaneously, AI-driven multi-objective optimisation algorithms can balance conflicting design goals within complex design spaces, such as achieving high strength alongside biodegradability and antimicrobial activity.

3.2.2. *Optimisation of the structural design*

The optimisation of structural design mainly relies on computational simulation technology to achieve breakthroughs. The virtual prototyping approach combines computational fluid dynamics (CFD) and computational heat transfer (CHT) to predict the compression strength and cooling efficiency of the box within hours. The optimised design resulted in an increase in freight density to 1720 kg/per reefer, a 17 % increase in pre-cooling efficiency and a 30 % reduction in energy consumption (Ambaw et al., 2022). This data-driven design can accurately match the mechanical properties of different fruits. For example, simulating the elastic-viscoplastic behaviour of fruits under compression through finite element analysis (FEM) can guide the determination of optimal conditions (e.g. materials) for the packaging design of different produce and predict the volume of fruit bruising (Du et al., 2019).

In addition, bionic design has become a hotspot of current research. Bionic design is based on biomimicry and takes the appearance, structure, colour and function of living creatures in nature as the research target, so as to provide new design ideas, creative thoughts and system architecture. Honeycomb composite cardboard systems and pomelo peel bionic composites inspired by the principles of bionics have been shown to have excellent anti-damage capabilities (Hu et al., 2024; Pirsa, 2024). Honeycomb composite paperboard systems form a honeycomb-like structure by arranging and bonding several consecutive sheets of corrugated core paper in parallel and perpendicular rows (Fig. 2D) (Pirsa, 2024). Composite paperboard is made by bonding multiple layers of paperboard, and adjacent layers can be deviated at an angle. This structure has high intensity, balanced strength in different directions, and significantly improved load-carrying capacity, compressive strength, tear strength and buffer properties. Biomimetic hierarchical composites inspired by natural pomelo peel is used to enhance the mechanical damage resistance and freshness of fruits (Fig. 2E) (Hu et al., 2024). The mesocarp is a layered honeycomb sponge structure, consisting of absorbent cotton with microfibres and chitin with nanofibres. This structure is soft and elastic, with an irrecoverable strain of only 12.25 % after 5000 compression cycles that facilitates the absorption of external forces. The exocarp is a dense filamentous hydrogel that resists puncture and disperses external forces. The two layers of the pericarp are bonded by hydrogen bonding-induced mechanical interlocking and strong interfacial interaction to avoid decomposition. The material can protect strawberries from mechanical damage such as impact and vibration. The antimicrobial and hydrophilic properties of the mesocarp and the physical barrier of the exocarp extended the shelf life to 21 days, which was much longer than the 9 days of the control.

Integrated simulation and multidisciplinary cross-fertilisation have become key paths to improve packaging performance and efficiency. Future challenges will focus on balancing production at scale with economics. Despite the excellent laboratory performance of nanomaterials, their acid digestion preparation processes (e.g. the acquisition of 56 nm nanostructures) still suffer from high energy consumption and low yields (Efthymiou et al., 2022). Next, the accuracy of computer simulation depends on the parameters of the ontological model of agricultural products. While most of the available data focus on bulk fruits such as apples and tomatoes, the mechanistic database for tropical speciality fruits (e.g. mango, durian) is not yet complete. Finally, at the regulatory level, nanoparticle migration risk assessment and certification standards for degradable materials still need to be established in an interdisciplinary and collaborative manner.

4. Preservation packaging technology for fresh fruits

4.1. *Conventional preservation packaging technologies and applications*

Fresh fruit in the supply chain transport and storage links are very susceptible to mechanical impact, vibration and environmental stress and other factors, resulting in quality deterioration and economic losses. Scientific design of damage prevention packaging has become an important path to improve the efficiency and economic benefits of fruit circulation. In recent years, the relevant research is mainly focused on the structural design of packaging, optimisation of material buffer performance and development of green packaging, and has gradually built up a more systematic research system of anti-damage packaging.

4.1.1. *Modified atmosphere packaging (MAP)*

MAP, as an important preservation technology to extend the shelf life and maintain the quality of fresh fruits, has made remarkable progress in recent years in gas regulation, material innovation and synergistic application. The core principle is to inhibit microbial growth, enzymatic reactions and intervene in the physiological and metabolic processes of the fruit by regulating the ratio of gases such as O_2, CO_2 and N_2 in the package. For the respiratory characteristics of different fruits, the combination of low O_2 and high CO_2 can effectively inhibit ethylene synthesis and respiratory strength, and delay quality deterioration. For example, low O_2 with high CO_2 reduces the respiratory intensity of pomegranate while maintaining fruit total phenols, total flavonoids, and anthocyanins content (Shi et al., 2025a, 2025b). Under 14–19 kPa O_2 and 2–3 kPa CO_2 conditions, the respiratory peak of cherry tomatoes was delayed, and hardness and colour deterioration were reduced by 37 % and 18 %, respectively (Paulsen et al., 2019). However, it is important to be vigilant that high concentrations of CO_2 may trigger a decline in the organoleptic quality of some fruits (e.g. papaya) (Tabassum & Khan, 2020).

In terms of packaging materials, microporous film achieves a dynamic balance between the respiration rate and gas exchange of fruits owing to its adjustable permeability characteristics. Composite nanofilm significantly extend the microbiological stability of freshly cut fruits. For example, composite film filled with nanobentonite (1–3 %) extended the microbiological stability of freshly cut lettuce to 9 days in a modified atmosphere at 4 °C, a more than twofold improvement over the control (Farahanian et al., 2023). Bio-based biodegradable materials also showed advantages in quality retention and environmental friendliness. Among them, packaging with polylactic acid (PLA) and biodegradable materials are excellent in maintaining the antioxidant activity of tomatoes (Zhou et al., 2019).

In synergistic technologies, MAP combined with ultrasound, ozone pre-treatment and edible coatings can enhance bacteriostatic preservation, and maintain nutritional and structural stability of the fruit. Strawberries, raspberries and blueberries pretreated with ozonated water in combination with MAP showed significant reductions in the number of yeasts and moulds and better preservation of total and individual anthocyanins in blueberries (Pinto et al., 2020). Ultrasound (20 kHz, 10 min) coupled with MAP effectively reduced the loss of weight, hardness, total soluble solids content and total discolouration of cucumber while maintaining cell wall integrity (Fan et al., 2019). In addition, the integration of edible coatings (e.g., composite system of chitosan-thyme essential oil) with MAP further inhibited water migration and microbial proliferation of freshly cut papaya through a dual barrier effect (Tabassum & Khan, 2020). Table 1 summarises the latest developments in MAP applications for fruit preservation.

Despite demonstrating considerable potential, the large-scale application and industrialisation of MAP still face significant limitations and challenges. First, cost remains a particularly critical barrier. The initial investment and operating expenses associated with high-performance packaging materials (e.g., nanocomposite films, biodegradable PLA) and pre-treatment technologies (e.g., ultrasound, ozone) are considerably higher than those of conventional plastic packaging, which may discourage adoption, especially among small and medium-sized enterprises. Second, regulatory and standardization issues pose another major constraint. For example, the absence of globally harmonized guidelines for the safety evaluation and migration behavior of nanomaterials (e.g., nano-bentonite) in food-contact applications, as well as for active packaging incorporating essential oils, creates considerable uncertainty for market entry. Third, MAP needs to maintain its freshness in a low temperature environment. If the temperature fluctuates too much, it may cause anaerobic bacteria breeding, quality deterioration and other safety hazards. Finally, consumer acceptance remains a critical consideration. Although biodegradable materials offer clear environmental benefits, their mechanical strength and barrier performance are often inferior to conventional plastics, which may compromise package appearance or functionality and diminish user experience. In addition, consumer skepticism toward concepts such as nanotechnology or ozone treatment can further hinder widespread adoption. Therefore, future technological advances should extend beyond performance improvements to include thorough economic assessments, the establishment of clear regulatory frameworks, and enhanced consumer education, all of which are essential to overcoming the barriers to industrialisation.

4.1.2. *Active packaging technology*

In recent years, with the development of the application of nanotechnology and natural extracts, antimicrobial active materials, natural antimicrobial carriers and slow-release release systems have become a research hot spot (Fig. 3). These technologies not only improve the stability and utilisation efficiency of active ingredients, but also enhance the intelligent response and environmental adaptability of packaging materials.

4.1.2.1. Antimicrobial active materials. The main action mechanism of antimicrobial active materials is to inhibit the growth of microorganisms, so as to extend the shelf life of food. Current research focuses on the application of natural antimicrobial components, the development of nanomaterials and the construction of multi-component composite systems. Plant-derived antimicrobials such as neem oil and thymol are of interest because of their broad spectrum and environmental friendliness (Kumar et al., 2022). The active components in neem oil (e.g. neemin) can exert an inhibitory effect by disrupting the structure of microbial cell membranes. However, its photosensitivity and potential impact on food organoleptic qualities such as flavour and colour limit its direct application in food systems to some extent. To address this issue, nanoemulsification techniques have been introduced to improve stability. For example, neem oil was combined with biopolymers such as chitosan and starch to form nanoemulsions, which not only enhanced the antimicrobial activity but also improved its adhesion in food coatings (Kumar et al., 2022; Rojas et al., 2023). Similarly, thymol can be efficiently loaded into PLA film by supercritical fluid impregnation. This modulates the release kinetic behaviour and significantly enhances the antimicrobial properties of the material, especially showing excellent results in inhibiting *Gram*-positive bacteria (Rojas et al., 2023).

Nanotechnology gives materials enhanced antimicrobial activity through high specific surface area and surface effects. Nanoparticles (e.g. silver, zinc oxides) can achieve efficient bacterial inhibition through mechanisms such as the release of metal ions, the generation of reactive oxygen species, or the direct destruction of microbial DNA (Manikandan & Min, 2023). For example, nanocarrier systems (e.g., nanoliposomes) can encapsulate naturally occurring antimicrobial components (e.g., polyphenolic compounds), increasing bioavailability and reducing negative impacts on food matrices through targeted release (Fig. 3A) (Manikandan & Min, 2023). However, the potential toxicity and high cost of chemically synthesised nanoparticles have prompted researchers to turn to green synthesis routes, such as the reduction of metal precursors using plant extracts, but the scale-up of production still faces technical bottlenecks. To compensate for the limitations of single antimicrobial mechanisms, composite antimicrobial strategies are gradually emerging. For example, nanomaterials are combined with non-thermal processing technologies (e.g., cold plasma treatment, ultra-high pressure treatment). A fencing effect can be formed to synergistically inhibit microbial growth through multiple action mechanisms, which significantly enhances the efficiency of bacterial inhibition and has a low impact on food quality (Kaur et al., 2024).

Beyond their antimicrobial role, packaging materials incorporating natural bioactive compounds are also important for slowing oxidative

Table 1
The summary of the latest developments in MAP applications for fruit preservation.

Preservation technology	Application methods	Test Item	Testing Performance	Shelf life	Applications	Reference
EMAP + natural porous diatomite + PEI + CNFs.	Film-sealed freshness box with built-in sensor for CO_2 monitoring.	Gas transport, selectivity, fruit quality and sensor response.	The atmosphere reached equilibrium within 24 h. The O_2 transmission rate of $DgP_{7.5}$ reached 43.33 $ccm^{-2}\cdot day^{-1}$ bar^{-1} and CO_2/O_2 selectivity reached 1.56.	Extended to 5 days for lychee and 3 days for plums.	Lychee and plums.	Yang et al. (2023)
A facile and biomimetic strategy: PLLA or chitosan porous microspheres as gas "switches" or "stomata" in a shellac film.	Made into surface coatings or packaging film.	Gas permeability, antimicrobial, antioxidant, mechanical properties, water vapour transmission rate, etc.	The air control, antibacterial and waterproof effect is good and reusable.	Extended to 45 days for orange, 10 days for mango, 48 h for waxberry and 72 h for cherry.	5 fruits of different respiratory metabolisms.	Zhou, Wu, et al. (2021)
CO_2 in-situ escaping microporous structure + PEI antimicrobial.	Covering and sealing the microporous antimicrobial nanocellulose film at the window of the packaging container.	Gas transmission rate, porosity, antimicrobial rate, fruit quality.	Porosity of 79.6 %, O_2/CO_2 transport rate of 115.57 and 145.91 $cm^3/m^2\cdot day\cdot bar$, antimicrobial rate of >98 %.	Extended to 25 days for green plums and 6 days for loquats longer than PET.	Green plums and loquats.	Zhou, Yang, et al. (2023)
Nano metal-organic frameworks (MOFs) as gas "Switches" to prepare nanoMOFs/CMC/Zein.	Covering the composite film of nanoMOFs/CMC/Zein on packaging containers.	Gas permeability, water vapour permeability, mechanical properties, antimicrobial properties, weight loss rate, pH, soluble solids, colour.	CO_2/O_2 selectivity of 8.65 ± 1.63, water vapour permeability of 2.17×10^{-13} kg $m\cdot m^{-2}\cdot s^{-1}\cdot Pa^{-1}$, tensile strength of 21.5 ± 0.7 MPa and antimicrobial inhibitorywring radius of 5.3 ± max. 0.6 mm.	Extended to at least 7 days for mango.	Mango.	Geng et al. (2024)
CDs + DCNC + multifunctional chitosan.	Film-covered packaging, stored under light.	Gas selectivity, mechanical properties, antimicrobial rate, fruit quality indicators.	CO_2/O_2 selectivity of 14.1, tensile strength of 40.11 MPa, antimicrobial rate of more than 86 %.	Extended to 10 days for winter jujube.	Winter jujube.	Liu et al. (2025)
Cur-PS/CS with leaf stomata structure.	Store at 15–20 °C.	Gas permeability, mechanical properties, antimicrobial and oxidation resistance, weight loss, pH and colour.	Tensile strength of 51.54 MPa, CO_2/O_2 selectivity of 5.51, antimicrobial inhibitory ring diameter of more than 7.8 mm, antioxidant activity of 91.03 %, and delayed colour loss.	Extended to 5 days for cherrie and apple slices.	Non-climacteric fruit (cherries) and climacteric fruit (apple slices).	Xie et al. (2024)
Nanochitin/poly (ethylene glycol) as the "inner film", on a base paper surface, with the base paper serving as the "outer shell".	Cover the packaging container and store at 25 ± 3 °C.	Gas transmission rate, mechanical properties, weight loss rate, pH, titratable acid, soluble solids, etc.	CO_2/O_2 selectivity of 1.65–3.71, gas permeability ranging from 2000 to 14000 $cm^3\ m^{-2}\cdot d^{-1}\cdot 0.1\ MPa^{-1}$, improved tensile strength, 38.89 % marketability after 8 days, and 30.56 % decay rate.	Extended to 8 days for litchi at 25 ± 3 °C.	Litchi.	Peng et al. (2025)
A zein/gelatin-coated PE active film, which can release antimicrobial components and regulate gases and microorganisms.	Make the film into bags and store at 6 °C.	Gas concentration, weight loss rate, hardness, total colony count, volatile components, bacterial community.	Inhibition of rotting bacteria, retention of terpenoids such as α-cubene, reduction of off-flavour production for longan; Accumulation of ethyl esters (0.154–0.184 μg/g) and reduction of typical fruity esters for strawberries.	Extended to 18 days for longan and 6 days for strawberry.	Longan and strawberries.	Cai et al. (2022)
EPT + TPU, preparation of packaging film by scratch coating.	Store at 4 ± 1 °C and 85 %–95 % humidity.	Gas permeability, contact angle, mechanical properties, weight loss, hardness, soluble solids, etc.	CO_2/O_2 separation coefficient of 8.2, moisture permeability of 133.32 $g/(m^2\cdot 24\ h)$, contact angle of 7°, delayed the decline in hardness and nutrient loss of kiwifruit, and vitamin C content of 75.10 μg/mL after 40 days.	Extended to 40 days for kiwifruit.	Kiwifruit.	Sha et al. (2024)
A new plant leaf-mimetic shellac-based MAP: TA-CPM + chitosan porous microspheres.	Seal the TA-CPM/shellac packaging film and store at 25 °C, 61 % humidity.	Gas concentration, weight loss rate, colour, browning index, PPO activity, antioxidant content, etc.	0.05 % TA-CPM/Shellac coating optimizes atmosphere to preserve litchi quality by delaying browning and decay.	Extended to 8 days for lychee.	Litchi.	Ma et al. (2021)
EMAP: LDPE + γ-PGA + plasma-modified	5 % γ-PGA/LDPE film stored at 4 °C, 95 % humidity.	Gas concentration, respiration rate, weight loss rate, hardness, electrolyte leakage rate, MRI moisture distribution	CO_2/O_2 selectivity up to 9.04, respiration rate reduced by 29.37 %, weight loss reduced by 31.65 %, hardness loss reduced by 42.98 %	Extended to 12 days for fresh-cut papaya	Fresh-cut papaya	Tsai et al. (2025)
SPEEK + PEG + PVDF	Store at 5 °C and 85 %–90 % humidity.	Gas concentration, respiration rate, good fruiting rate, weight loss rate, hardness, and vitamin C content.	CO_2/O_2 partition coefficient of 6.21, 29.37 % reduction in respiration rate, 31.65 % reduction in weight loss, 80 % good fruit after 30 days.	Extended to 30 days for cherry tomato.	Cherry tomato.	Zhu et al. (2024)

Note: EMAP, Equilibrium modified atmosphere packaging; PEI, polyethyleneimine; CNFs, Cellulose nanofibers; PLLA, poly(l-lactic acid); CMC, carboxymethylcellulose; Cur-PS/CS, curcumin-porous starch/chitosan; EPT, polyvinyl alcohol; TPU, thermoplastic polyurethane; γ-PGA, poly-gamma-polyglutamic acid; LDPE, low density polyethylene; SPEEK, sulfonated polyether ether ketone; PVDF, polyvinylidene fluoride; PEG, polyethylene glycol.

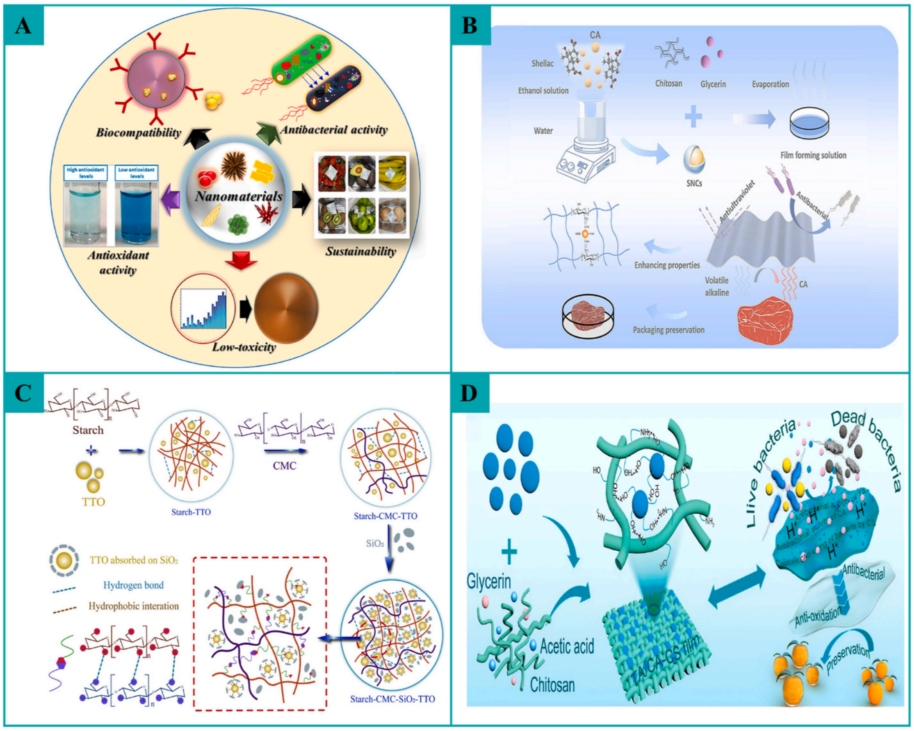

Fig. 3. Major preservation packaging research and applications. A. Polysaccharide-based nanomaterials in food packaging (Manikandan & Min, 2023). B. Schematic diagram of the formation mechanism of slow-release multifunctional packaging film (Wang et al., 2024a, 2024b, 2024c). C. Schematic diagram of the formation mechanism of slow-release tea tree essential oil solid preservative (Tian et al., 2023). D. Engineering multifunctional slow-release packaging systems by self-assembly technology (Zhang et al., 2024).

deterioration and protecting fruits from light-induced damage. Plant-derived essential oils such as thymol and eugenol, together with polyphenols including quercetin and catechin, are well-established natural antioxidants (Vieira1 et al., 2022). By scavenging free radicals and chelating metal ions, they help suppress enzymatic browning associated with PPO activity, reduce non-enzymatic browning, and mitigate lipid oxidation and the loss of vitamins. In addition, nanomaterials such as titanium dioxide (TiO_2) and zinc oxide (ZnO) not only provide antimicrobial effects but also act as efficient ultraviolet (UV) shields, absorbing or scattering radiation that can otherwise lead to color fading, flavor loss, and photooxidation (Vieira1 et al., 2022).

Regardless of the significant progress in the research of active materials, there are still some key issues. Consumer awareness and acceptance of nanotechnology and chemically synthesised antimicrobial agents in foodstuffs represent a significant barrier. Whilst green synthesis is the prevailing trend, public concerns regarding the potential health risks of nanoparticles must be addressed through transparent communication and rigorous safety certification. Meanwhile, the standardisation and stability of natural ingredients still present unresolved issues, such as the use of neem oil, which lacks uniform standards in long-term safety assessments of composite nanomaterials. A more critical issue lies in the absence of globally harmonized regulations regarding migration limits, toxicological evaluation, and labelling of nanomaterials in food contact applications. Such discrepancies create considerable uncertainty, thereby constraining the commercialization of emerging technologies. In addition, there is a lack of the industrial-scale application of composite technologies, for example, the high cost of cold plasma equipment, which makes it difficult to promote in small and medium-sized enterprises. While the green synthesis of nanomaterials (e.g., silver nanoparticles) is environmentally advantageous, it remains constrained by high production costs, stringent purification procedures, and major difficulties in scaling from laboratory to industrial levels. These constraints not only heighten technical and economic pressures but also pose significant barriers to small- and medium-sized enterprises.

4.1.2.2. Natural antimicrobial carriers. Natural antimicrobial carrier technology aims to address the problems of poor stability, uncontrolled release and low bioavailability of natural active ingredients. Current research focuses on the development of nanocarriers, bio-based polymers and structured encapsulation systems as platforms for antimicrobial agents (Bahrami et al., 2019). These carriers themselves possess distinct material properties.

Carriers such as nanoemulsions, solid lipid nanoparticles and nanofibres primarily enhance the solubility and stability of antimicrobial agents (Bahrami et al., 2020). For example, nanoliposomes can effectively load and protect lactobacillus peptides and can effectively inhibit the growth of Listeria monocytogenes (Sadeghi et al., 2023). Natural polymers such as chitosan and whey protein are considered ideal matrices for encapsulating natural antimicrobial agents, as they exhibit excellent biodegradability, biocompatibility, film-forming ability, and compatibility with bioactive compounds, which collectively enhance the stability and controlled release of antimicrobial agents (Barbosa-Nuñez et al., 2025). It was confirmed that the chitosan-essential oil composite coating enhanced the bactericidal effect and inhibited volatilisation through electrostatic action, further improving the freshness retention performance (Eranda et al., 2024). Multi-stage delivery systems (e.g. core-shell structured nanoparticles, lipid-protein hybrid carriers) can represent complex carrier architectures that integrate the advantages of multiple materials.

Although natural polymers such as chitosan and whey protein are abundant, the cost of high-purity materials suitable for food-grade applications remains relatively high. The large-scale production of carriers such as nanoemulsions and liposomes requires precise equipment and stringent process control (e.g., homogenization pressure and temperature), and most production still remains at the laboratory or pilot scale, making it difficult to meet the demands of large-scale, continuous food industry production. While certain technologies, such as high-pressure homogenization, have been applied in the dairy industry, controlling particle size and energy consumption remains a key challenge for the production of food-grade nanocarriers. Moreover, regulatory authorities generally consider any novel carrier material as a new substance, and obtaining approval is often a lengthy and expensive process. Currently, most natural antimicrobial carrier systems do not have formal safety certification as food additives or food contact materials, which constitutes a major obstacle to their commercialization. Future research should focus on the development of low-cost green materials, the construction of multi-stimulus response systems and the establishment of a unified evaluation system, in order to accelerate its translation from the laboratory to industrialisation and to promote the development of sustainable antimicrobial solutions in the food and medical fields (Bahrami et al., 2019).

4.1.2.3. Slow-release technologies. Slow-release technology, often built upon the carrier systems described in section 4.1.2.2, has received widespread attention in the field of fruit preservation because of its advantages of controlled release of active substances to extend the freshness period of fruits and maintain their quality. It focuses on the design and engineering of systems to precisely control the release kinetics of active substances (Fig. 3B) (Wang et al., 2024a, 2024b, 2024c). A key aspect of this technology is conferring environmental responsiveness (e.g., pH, moisture, or enzymes) to achieve intelligent or on-demand release.

The slow-release technology mainly employs structures such as nanocapsules, microcapsules and multilayer film structure to carry antimicrobial agents, antioxidants and other functional ingredients (Tian et al., 2023). For example, the combination of nanocarriers with active packaging materials such as electrospun nanofibres can achieve release on demand (Bahrami et al., 2019). Tea tree essential oil adsorbed by silica nanoparticles and embedded in a starch-carboxymethylcellulose network enables continuous release in MAP and extends pineapple shelf life (Fig. 3C) (Tian et al., 2023). Radiation-cooled coatings that combine tannins with acidified eclogite nanotubes significantly enhance strawberry freshness through a dual mechanism of thermoregulation and slow release (Lei et al., 2024). In addition, the self-assembled system of tannin-cinnamaldehyde/chitosan film based on modulated release of dynamically reversible C-O bonds could retain the active function and extend shelf life of citrus fruits by nearly 1.9-fold (Fig. 3D) (Zhang et al., 2024). The implementation of these functionalities is contingent upon specific fabrication methodologies. Nanocapsules are typically synthesised through techniques such as nanoprecipitation or emulsion-solvent evaporation, enabling the encapsulation of active compounds within polymeric matrices (Zhou et al., 2023a, 2023b). Microencapsulation is conventionally achieved via spray-drying or complex coacervation processes (Weng et al., 2024). Multilayer films are commonly engineered using layer-by-layer (LbL) assembly or electrospinning technologies, which facilitate the construction of sophisticated architectures for tailored release profiles (Ali et al., 2024; Cui et al., 2024).

The challenges of controlled-release technology involve not only encapsulation efficiency but also its potential impact on the sensory properties of food. Many plant essential oils, such as thymol and cinnamaldehyde, may slowly release during storage even after encapsulation, altering the food's original flavor and aroma, which may be unacceptable to consumers. Future research should treat sensory neutrality as a key performance indicator. Furthermore, careful cost-benefit analysis is needed, as technologies such as multilayer films and functionalized nanocapsules inevitably increase packaging costs. Whether the additional cost can be justified by the reduction in food waste from extended shelf life is a key consideration for producers and retailers. In the future, we should focus on improving system stability and degradability to optimise organoleptic compatibility, and promote its sustainable application in food preservation to reduce wastage and enhance food safety.

4.2. Advancements of preservation and packaging technologies for fresh fruits

With the continuous development of preservation technology for fresh fruits, the functionality and environmental friendliness of packaging materials are becoming the focus of research and application. Currently, advancements in preservation packaging are mainly reflected in four directions, including the development and application of edible coatings, the functional expansion of gelatin/chitosan composite film, the structural optimisation of nanocellulose-reinforced film and the green transition of bio-based barrier materials (Figs. 4 and 5). These technologies perform well in extending shelf life, inhibiting microbial growth, regulating gas exchange and reducing quality deterioration. They represent an important trend in the evolution of fresh fruit packaging from traditional materials to high performance and sustainability.

4.2.1. Edible coatings

Edible coatings can inhibit water evaporation, gas exchange and microbial growth by forming a biodegradable barrier on the surface of the fruit to maintain its freshness and nutritional value (Ruan et al., 2024). Coating materials are mostly derived from natural biopolymers such as chitosan, pectin, sodium alginate, whey protein and lipids. These materials are biocompatible and environmentally friendly and can be combined with antimicrobials, antioxidants and other functional ingredients to enhance freshness (Fig. 4C) (Ribeiro et al., 2024; Sapna et al., 2024). Chitosan-based coatings are widely used in fruits such as strawberries, tomatoes and mangoes to significantly inhibit bacteria, prevent water loss and delay ripening (Ali et al., 2024; Wei et al., 2024). Multi-layer coating technologies (e.g. layers of chitosan-sodium alginate, carboxymethyl cellulose and chitosan) are effective in extending the shelf life of citrus fruits by modulating gas permeability (Du et al., 2022).

The introduction of nanotechnology further enhances the mechanical strength and functionality of the coating. The incorporation of metal oxides or nanoemulsions not only improves the barrier properties, but also achieves a slow release of the active ingredients, thus enhancing the antimicrobial and antioxidant effects of the coating (Xavier et al., 2025). Application examples showed that a composite coating of garlic extract with gum arabic extended shelf life and increased vitamin C content in guava (Anjum et al., 2020). In tropical fruits such as mangoes and bananas, coating technology also slows ripening, reduces respiration rates and maintains organoleptic quality (Fig. 4A and B) (Tavassoli-Kafrani et al., 2022; Wei et al., 2024). Adding ingredients such as plant essential oils to edible coatings can also enhance the antimicrobial freshness of fruits (Sapna et al., 2024).

Nevertheless, the technology still suffers from insufficient barrier properties and flavour impact. To overcome these limitations, polymer compounding and nanomaterial synergies have been developed to optimise coating properties. Meanwhile, the use of agricultural by-products, such as fruit peels, to prepare coating materials can help reduce plastic use and food waste, and also fits the trend of the food industry's transition to a circular bioeconomy. However, consumer acceptance remains a critical yet underexplored challenge. Despite their technical and environmental advantages, the market success of these coatings depends largely on public perception. Concerns over safety, odour, sensory changes, or the health implications of nanotechnology can hinder adoption. Clear labelling, educational initiatives, and transparent communication are needed to build trust. Moreover, cost considerations and functional reliability under real-world conditions will ultimately influence whether these advanced coatings achieve widespread commercial adoption.

4.2.2. Protein/chitosan composite film

Protein/chitosan composite film are an ideal alternative to traditional plastic packaging due to their excellent biocompatibility, degradability and versatility. Among these, gelatin/chitosan composite

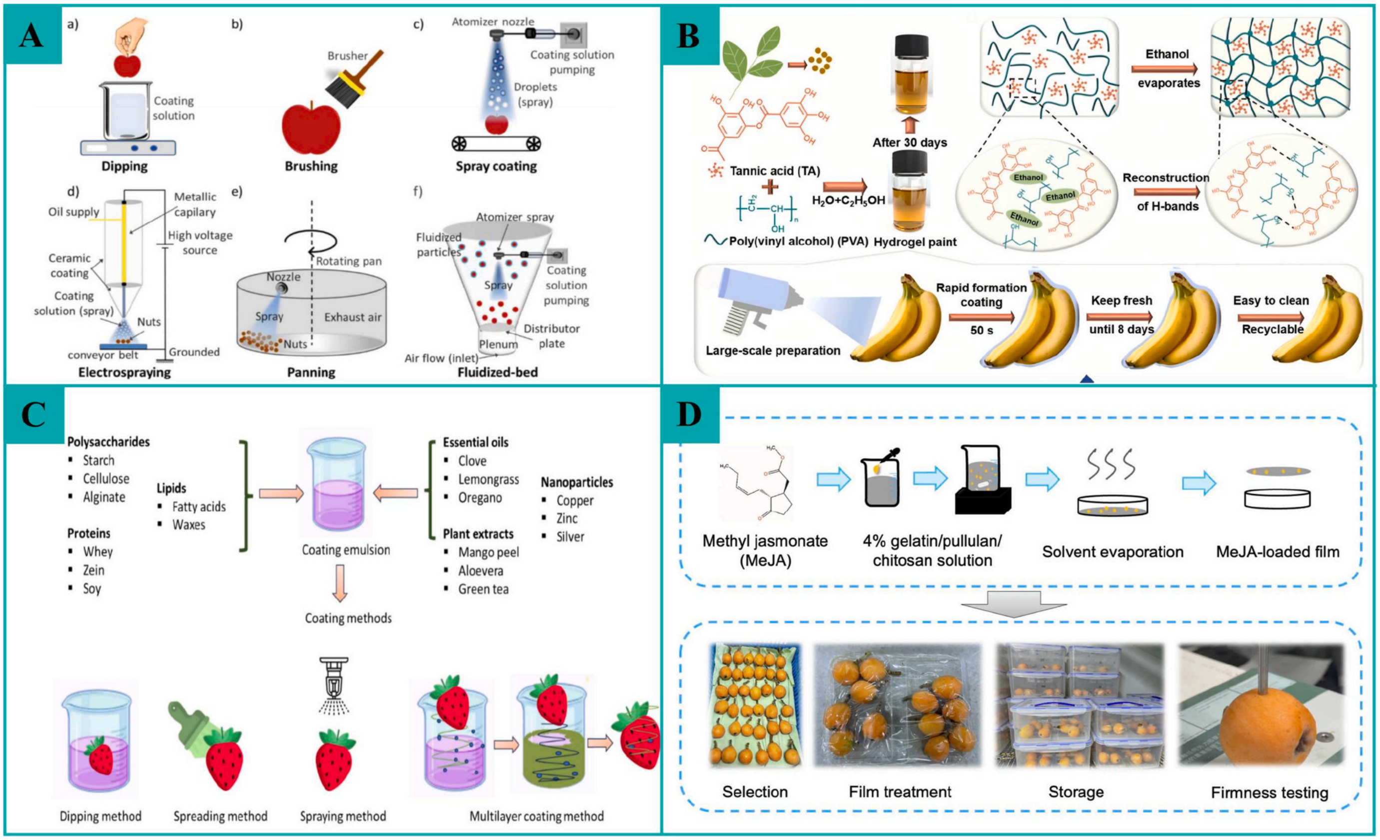

Fig. 4. Research and application of edible coatings and gelatin/chitosan composite film. A. Typical coating methods for fruits and vegetables (Tavassoli-Kafrani et al., 2022). B. The process for obtaining hydrogel cling film in banana preservation (Wei et al., 2024). C. Different macromolecules, bioactive agents and methods employed for the fabrication of edible coatings and application of edible coating in strawberry preservation (Sapna et al., 2024). D. Preparation of composite biofilm loaded with methyl jasmonate and application during loquat fruit storage (Cai et al., 2024).

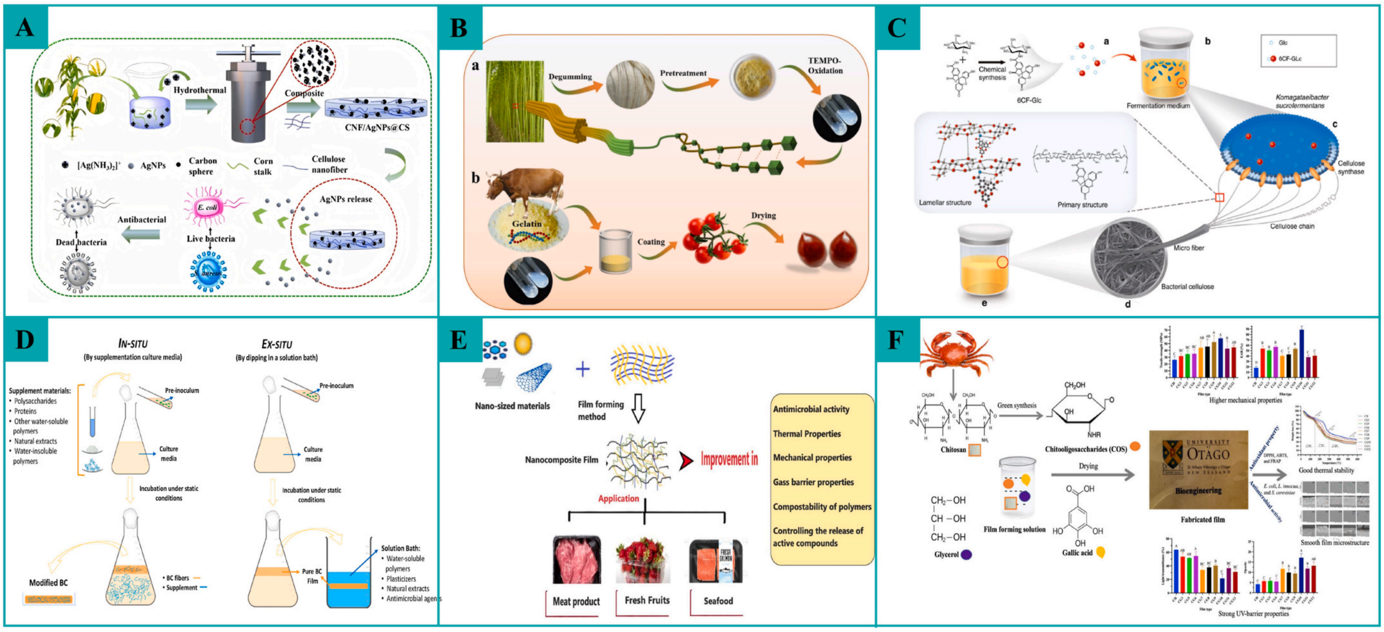

Fig. 5. Research and application of nanocellulose reinforced film with bio-based barrier materials. A. AgNPs are fixed with CNF to form composite antibacterial paper (Wang et al., 2024a, 2024b, 2024c). B. Cellulose nanofibers-gelatin film (Wang et al., 2024a, 2024b, 2024c). C. Essential oil doped nanocellulose composite packaging (Firmanda et al., 2023). D. Modifications of bacterial cellulose film (Cazón & Vázquez, 2021). E. Enhancing film properties using nanotechnology (Mahmud et al., 2022). F. Chitosan film reinforced with glycerol, chitosan oligosaccharides (COS) and gallic acid (Bhowmik et al., 2024).

film has been extensively studied. Gelatin has good film-forming properties and non-toxicity, while chitosan has both antibacterial and antioxidant functions. The combination of the two can significantly enhance the mechanical properties, barrier properties and bioactivity of the film through synergistic effects (Fig. 4D) (Cai et al., 2024). In application, the composite film has more efficacy, including reduction of water evaporation and gas exchange, inhibition of microbial growth, slowing down of fruit respiration rate and ethylene production, thus extending shelf life and maintaining the colour, firmness and nutritional quality of the fruit.

Beyond gelatin, chitosan has been successfully combined with various other proteins to create composite films with tailored functionalities for fruit preservation. Zein-based plant protein/chitosan composite films have been widely applied in the preservation of fruits such as strawberries and mangoes, effectively reducing weight loss and decay while delaying the ripening process (Li et al., 2024a, 2024b; Xiao et al., 2021). In the case of insect proteins, *Tenebrio molitor* protein (TMP) combined with chitosan has shown notable performance; for example, CS/TMP/PEE films containing propolis extract and CS/TMP/Cur films incorporated with curcumin were reported to maintain the firmness of strawberries and blueberries, respectively, and retard quality deterioration (Liu et al., 2024). Microbial protein systems, mainly derived from single-cell organisms, offer a high-yield and sustainable alternative for film formation, but their application in fruit preservation has been relatively limited. The applications of different protein/chitosan composite films in fruit preservation are summarized in Table S2.

Preparation methods include solution casting, electrospinning and layer-by-layer self-assembly techniques. Among them, layer-by-layer self-assembly can enhance the structural stability of the film and achieve the controlled release of active ingredients. The addition of functional substances (e.g. rutin, polyphenols, essential oils or nano-$CaCO_3$) can further give the film multiple functions such as antimicrobial, antioxidant and UV shielding (Roy & Rhim, 2021). For instance, incorporating polyphenol-rich plant extracts can substantially enhance the antioxidant capacity of packaging films, thereby protecting fruits against oxidative deterioration (Khanzada et al., 2024). Likewise, the incorporation of nano-$CaCO_3$ into chitosan-based films has been reported to improve their UV-shielding ability, reducing photo-induced quality loss in packaged produce (Tripathi, Kumar, & K. Gaikwad, 2024). A representative case is the incorporation of apple polyphenols as dual-function antimicrobial and antioxidant agents into a polymeric matrix of gelatin, carboxymethyl cellulose, and chitosan, which markedly improved the tensile strength, oxygen and water vapour barrier performance, and UV resistance of the composite films (Ahmad et al., 2025).

Nevertheless, challenges remain for widespread application. The mechanical strength, water resistance and release control of active substances for these composite films often require further optimisation, which varies depending on the protein source. Future research should focus on the development of modification techniques and functional additives to enhance its performance and adaptability for specific fruit types. Overall, protein/chitosan composite film as a green freshness preservation material has a broad prospect to extend the shelf life of fruits, reducing the burden on the environment and promoting the sustainable development of food packaging.

4.2.3. *Nanocellulose reinforced film*

Nanocellulose is a green, biodegradable and high performance material. Its high specific surface area, excellent mechanical strength, good film-forming properties and biocompatibility make it an ideal choice to replace traditional petroleum-based packaging materials (Wang et al., 2024a, 2024b, 2024c). Leveraging these unique nano-specific properties, nanocellulose is mainly used in antimicrobial coatings, controlled release systems, packaging reinforcement materials and intelligent packaging technologies. Currently, the food packaging materials developed based on nanocellulose include active packaging film, coating liquids, aerogels, paper-based packaging (Wang et al., 2024a, 2024b, 2024c). The combination of nanocellulose and natural antimicrobial agents such as chitosan nanoparticles can be used to prepare highly effective antimicrobial coatings, which can effectively inhibit the growth of pathogenic bacteria and extend the shelf life of fruits (Fig. 5C) (Firmanda et al., 2023). Pickering emulsion-based coatings can improve hydrophobicity and reduce mass loss during storage (Trinh et al., 2022). In controlled release, nanocellulose can be used as a carrier to achieve slow release of plant extracts or essential oils, and enhance the antioxidant and antimicrobial efficacy of the preservative during the storage period (Xu et al., 2025). Moreover, the outstanding film-forming capacity and optical clarity of nanocellulose make it a promising substrate for functional packaging. When combined with UV-absorbing nanoparticles (e.g., CeO_2) or natural pigments (e.g., flavonoids), nanocellulose can be engineered into intelligent films that maintain high transparency while providing effective UV protection, thereby safeguarding fruits from light-induced damage without diminishing their visual quality (Sani et al., 2024). In addition, nanocellulose as reinforcing filler can significantly enhance the mechanical properties and oxygen barrier of polymer film. Its carboxylation or doping with metal oxides can further enhance the water vapour and gas barrier effect, providing more comprehensive protection for fruits (Zielińska et al., 2023).

Nanocellulose is widely considered a relatively safe biobased nanomaterial, as it is derived from natural cellulose. Studies have shown that nanocellulose exhibits low cytotoxicity, and its high aspect ratio and hydrophilic surface may limit migration across biological barriers (Ghasemlou et al., 2021). Nevertheless, its safety cannot be assumed in all cases. The toxicological profile of nanocellulose can be affected by factors such as its source, preparation method, surface chemistry (e.g., TEMPO oxidation), and particle size distribution (Ahmed et al., 2025). To support the commercial application of nanocellulose, it is essential to expand toxicological data across relevant exposure scenarios and to establish specific safety standards for biobased nanomaterials. In the future, the optimisation of preparation process, research on synergistic effect of functional materials and the construction of standardisation system should be strengthened in order to promote its practical application in the field of fruit preservation.

4.2.4. *Other bio-based barrier materials*

Beyond the specific composite systems discussed in previous sections (e.g., protein/chitosan films, nanocellulose-reinforced films), a broader range of bio-based barrier materials derived from polysaccharides, proteins, and lipids are also gaining attention in the field of fruit preservation due to their degradability, biocompatibility and multifunctionality. Their mechanism of action is to extend the shelf life of fruits by regulating their respiration rate, reducing water evaporation, inhibiting microbial growth and delaying oxidative reactions.

Polysaccharide-based materials are among the most prominent. For instance, starch-based films possess good film-forming and barrier properties against gases like oxygen, and their functionality can be substantially enhanced by introducing plant extracts or nanoparticles (Fig. 5D) (Cazón & Vázquez, 2021). Alginate and pectin-based coatings form strong gels through cross-linking with nanoparticles (such as ZnO and Fe_2TiO_5), creating a selective barrier that effectively reduces moisture loss and maintains fruit firmness in applications for fresh-cut produce and whole fruits like strawberries (Rizzotto et al., 2022; Vasiljevic et al., 2024).

Lipid-based coatings (e.g., carnauba wax) and composite emulsion systems provide excellent resistance to water vapour transmission, addressing a key weakness of many hydrophilic biopolymer films. They are often applied as coatings on fruits such as citrus and apples to impart a glossy appearance and prevent desiccation (Devi et al., 2022).

The innovation of bio-based barrier materials is also reflected in their versatility and customisability. For example, additional functionalities (antimicrobial, antioxidant and nutritional enhancement, etc.) can be imparted to film by introducing natural active ingredients such as essential oils, phenolic compounds or probiotics into the film matrix (Cui et al., 2024). Bio-based film that introduce probiotics extend the freshness of the fruit while providing additional health benefits by regulating the microenvironment on the surface of the fruit and inhibiting the growth of pathogenic bacteria (Li et al., 2020). The introduction of nanotechnology, such as nanoemulsions or cellulose nanofibres, further improves the barrier and antimicrobial properties of the film (Fig. 5E) (Mahmud et al., 2022). For example, pure nanocellulose-based film significantly reduce weight loss and maintain colour and firmness in tomato preservation (Fig. 5A and B) (Wang et al., 2024a, 2024b, 2024c). Meanwhile, bio-based film developed from plant residues have realised the high-value use of agricultural waste and the green transformation of packaging materials (Sharma et al., 2024).

Despite its promising development, the technology still faces challenges such as insufficient mechanical strength, unstable water vapour barrier performance for many hydrophilic materials, high production cost and the need for clearer safety assessments of novel active substances in large-scale applications. Future research should focus on the development of high-performance, low-cost, scale-producible materials, as well as the strengthening of safety assessment and regulatory systems, in order to promote its wide application of these diverse bio-based barrier materials in fruit preservation.

Although bio-based barrier materials hold significant promise for fruit preservation, their industrialisation remains constrained by high raw material costs and challenges in large-scale production. Advancing their development requires a multifaceted approach. Material innovation using low-cost feedstocks derived from agricultural residues, such as fruit peels and crop straws, can reduce production costs. Process optimisation through continuous-flow production or 3D printing can enhance film-forming efficiency. Policy support and standardization, including certification, subsidies, and unified safety and performance evaluation systems, are essential to promote adoption. Integrating bio-based materials with nanotechnology, controlled-release systems, or smart indicators can improve functionality and added value, enhancing economic competitiveness.

4.3. AI application scenarios

The development of advanced freshness-preserving packaging is inherently a multi-parameter optimisation process, making it highly suitable for the introduction of AI technology. ML models can decipher the release kinetics of antimicrobial or antioxidant agents, thereby designing materials with precise, timed, or triggered release characteristics to ensure optimal efficacy is maintained throughout the shelf life (Jyoti et al., 2025). Concurrently, AI can transcend the limitations of traditional threshold-based alerts by analysing gas patterns monitored by sensors, including O_2, CO_2, ethylene, and volatile organic compounds (VOCs). This enables the prediction of remaining shelf life and the identification of distinct spoilage pathways (microbial or enzymatic), facilitating dynamic feedback regulation (Jyoti et al., 2025). Furthermore, AI's high-throughput virtual screening capabilities efficiently evaluate diverse formulation combinations for bio-based coatings and films. This encompasses matrices like chitosan, gelatin, and starch blended with active components such as plant extracts or essential oils. By integrating respiratory rates and perishability characteristics of different fruits, AI rapidly identifies candidate materials with the greatest application potential.

5. Intelligent packaging for fresh fruits

Intelligent packaging technology, as a cutting-edge research direction in the field of postharvest quality monitoring of fresh fruits, is expanding from traditional physical protection to information sensing and quality monitoring functions. With dynamic sensing of the physiological state for fresh fruits and environmental parameters, intelligent packaging has become an important means to improve product quality and supply chain efficiency. Currently, intelligent packaging technologies mainly include freshness indicators (e.g., freshness indicator labels, colour-changing labels for pH response), radio frequency identification (RFID) system for temperature recording and traceability labels (Fig. 6). These technologies enable real-time monitoring and visual feedback of freshness, temperature and humidity changes and whole process information during fruit storage and transport.

5.1. Freshness indicator

5.1.1. Freshness indicator labels

Freshness indicator labels can monitor the physiological and environmental conditions of fruit in real time to provide visual information on freshness to consumers and supply chain managers. The working principle is usually based on a chemical or physical mechanism that responds to gases (e.g. CO_2, ethylene) or microbial metabolic products (e.g. VOCs) released from the fruit during storage, and provides visual signals, such as a change in colour, to indicate the freshness of the fruit (Fig. 6B) (Shao et al., 2021).

Technically, freshness indicator labels rely on a variety of functional materials and sensing mechanisms. The development of colour indication technology based on CO_2 sensitive dyes is relatively mature. Using the chemical reaction between the dye and CO_2 to achieve colour change has the advantages of simple structure, low cost and high sensitivity, which makes it suitable for large-scale application (Davey et al., 2023). In materials, biodegradable and environmentally friendly materials have been adopted to fulfil the need for sustainable development. For example, cellulose and PLA composite film have good mechanical properties and biocompatibility, and can also be loaded with dyes for freshness indication (Xu et al., 2019).

Practical applications have shown that freshness indicator labels can significantly extend the shelf life of fruit and guarantee quality (Fig. 6A D and E). For example, chitosan-zearalanol protein film for fruit preservation not only extend shelf life, but also provide a visual indication of freshness through colour change (Yao et al., 2024). The application of polycaprolactone/chitosan nanofibre film in fruits demonstrated excellent antimicrobial and indication effects, achieving synergistic preservation and monitoring with the help of sustained release of functional components such as epigallocatechin gallate (Hu et al., 2023).

Nevertheless, the sensitivity, stability and ability to adapt to complex storage environments of the labels still need to be improved. Cost control and manufacturing processes also need to be optimised. Consumer acceptance remains a critical yet often overlooked barrier. The adoption of intelligent labels depends on public trust, perceived value, and price sensitivity. Without clear explanation, intelligent labels may be seen as unreliable, while added materials could raise concerns about overpackaging or sustainability. Future research can focus on the development of new functional materials, the optimisation of the indication mechanism, and intelligent and sustainable design, in order to promote the practical application and industrialisation of freshness indication labels in the field of fruit packaging. To foster market penetration, technical advances must be complemented by user-centred design, transparent communication, and validation under real-world conditions.

5.1.2. Colour-changing labels for pH response

Colour-changing labels for pH response can visually reflect the freshness and spoilage of fruits by monitoring pH changes during storage and transportation (Luo et al., 2023). Its core is pH-sensitive materials, especially the natural pigment anthocyanin. Anthocyanins show significant colour changes under different pH conditions, appearing red in acidic environments and blue or green in alkaline environments (Huang et al., 2025). Embedding anthocyanins into degradable polymers such as

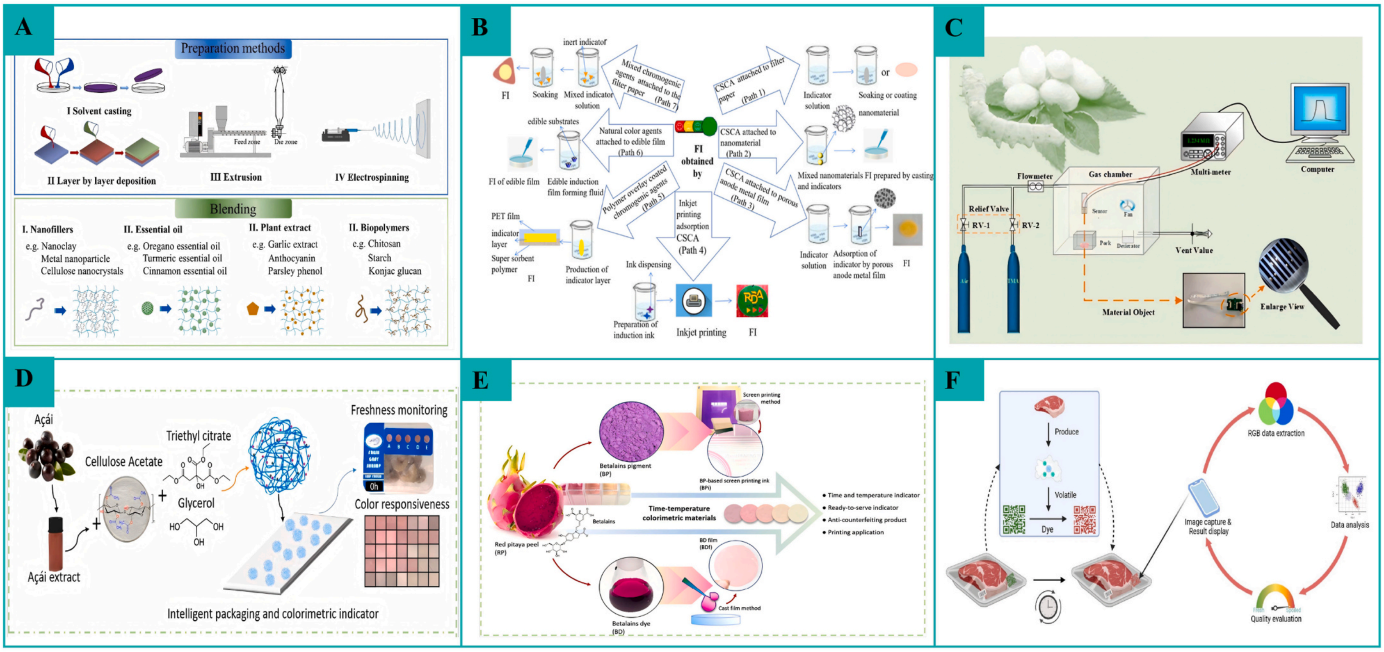

Fig. 6. Intelligent packaging research and applications. A. Preparation and improvement method of polysaccharide film (Yao et al., 2024). B. Preparation method of intelligent packaging fabrication with freshness indicator (Shao et al., 2021). C. Gas sensor (Yao et al., 2024). D. Composite intelligent packaging film based on black goji berry anthocyanins, cellulose acetate and pH colour change (Yao et al., 2024). E. Preparation method of time and temperature indicator (Yao et al., 2024). F. Schematic diagram of QR code as food quality sensor (Li et al., 2024a, 2024b). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

chitosan, starch or cellulose can produce intelligent film with both good mechanical properties and pH responsiveness, with multiple functions such as colour change indication, antimicrobial and antioxidant protection, and extended shelf life (Yong & Liu, 2020). Indicator film based on soybean isolate protein/chitosan matrix with six anthocyanin extracts were highly sensitive to ammonia and could visualise the degree of spoilage by colour change. The indicator of starch nanoparticles - bromocresol green has been applied to beef spoilage monitoring, where the colour change is highly correlated with the change in pH, total volatile base nitrogen and microbial population (Fatehi et al., 2025). This also provides a reference for its application in fruit preservation.

Despite the promising future of this technology, there are still problems of poor stability of natural pigments, and the mechanical and barrier properties of the film need to be improved, especially the pigment degradation under long-term storage and light conditions. In addition, large-scale production and cost control are also the key to its commercialization. Future research should focus on improving pigment stability, optimising film structure and achieving low-cost manufacturing, so as to promote its practical application in intelligent packaging of fruits. Technological progress alone does not ensure market success. Consumer acceptance remains a critical barrier, as colour-changing films based on natural pigments, though sustainable, may face skepticism over accuracy, reliability, or associations with spoilage. They may also be perceived as unnecessary over-packaging, raising concerns about cost, safety, or aesthetics. Clear communication and consumer education are essential, but commercial viability will ultimately depend on perceived value and willingness to pay.

5.1.3. Gas sensors

Gas sensors enable real-time monitoring of fruit freshness and quality changes by detecting VOCs released during storage and transport (Fig. 6C). Fruits will release a variety of gases such as ethylene, ethanol, acetaldehyde and ketones during ripening and spoilage (Zhao et al., 2024). These gases are important indicators of the physiological state of the fruit and are key parameters for assessing its shelf life.

The application of gas sensors in intelligent packaging of fruits mainly relies on their high sensitivity and selective response to specific gases. Currently, the common types are oxygen sensors, carbon dioxide sensors and ethylene sensors. Oxygen sensors can determine the respiration rate of the fruit and the sealing of the package by detecting changes in the oxygen concentration inside the package, thus providing visual information about the freshness of the fruit. Carbon dioxide sensors reflect the ripening and aging process of fruits by detecting fruit respiration and carbon dioxide concentration. The ethylene sensor monitors the release of ethylene gas during the ripening process to avoid premature ripening or spoilage due to ethylene accumulation.

In the technical realisation, the integration of gas sensors usually relies on advanced materials science and nanotechnology. For example, gas sensors based on 2D materials (e.g., graphene, transition metal disulfides) exhibit extremely high sensitivity and stability in detecting low concentrations of gases due to their high specific surface area and excellent electrocatalytic properties (Yu et al., 2021). Yan et al. (2024) developed a flexible and wearable chemoresistive ethylene gas sensor modified with PdNPs-SWCNTs@Cu-MOF-74 nanocomposites that can track the ripening and decay of kiwifruit. In addition, the combination of natural polymers (e.g. carboxymethyl cellulose) with functional dyes (e.g. anthocyanins) has been widely used in the development of gas sensors, which not only improves the mechanical properties and biodegradability of the sensors, but also achieves the visualisation of the response to changes in gas concentration (Zhao et al., 2022).

Despite demonstrating considerable potential in monitoring fruit freshness, the practical deployment of gas sensors remains constrained by dual limitations of versatility and cost-effectiveness. On the one hand, the types and concentration distributions of VOCs released during the ripening and decay processes vary significantly across different fruits, rendering single-gas sensors incapable of achieving universal detection across fruit categories. Consequently, future research must urgently develop multi-channel or array-based sensors, integrated with ML and pattern recognition technologies, to achieve precise analysis and classification of complex VOCs signals. This will enhance the system's applicability and robustness. On the other hand, the current high production costs of high-performance gas sensors render them more suitable for quality monitoring of high-value products such as berries and tropical fruits. With ongoing advancements in nanomaterial engineering and printed electronics, low-cost, flexible, and even biodegradable gas sensors are becoming increasingly feasible. This development offers new pathways for economically viable monitoring of medium-to-low-value fruits. In summary, future research and applications must strike a balance between technical feasibility and economic viability to drive the large-scale adoption of gas sensors within the fruit and vegetable supply chain.

5.2. RFID system for temperature recording

As fruits are highly sensitive to temperature changes, temperature monitoring is a key element in safeguarding the quality and integrity of fruits. RFID system for temperature recording has become a research hotspot due to its wireless reading, low cost and lightweight advantages (Zuo et al., 2022). The system can monitor the temperature changes during transport and storage in real time, and realise the real-time return of information and the whole process of traceability through wireless transmission.

Compared to traditional temperature sensors with large size, high cost and limited functionality, RFID systems for temperature recording achieve higher accuracy monitoring by integrating temperature sensitive components. For example, with wax as the temperature sensing material, RFID sensors can trigger a change of state by melting the wax and triggering a change in resistance when a set threshold is exceeded (Körbitz et al., 2024). This results in a simplified structure and improved performance for large-scale fruit supply chains. In addition, the system can be combined with low-power technologies (e.g. bluetooth) or self-powered solutions to further extend the lifetime. Graphene-based flexible sensors are constructed on the surface of textile yarns through a high-speed dyeing process, featuring lightweight, washable and high flexibility. It is combined with intelligent packaging to achieve remote reading and status monitoring, promoting the intelligent development of temperature monitoring system (Afroj et al., 2019). In summary, RFID technology for temperature recording has become an ideal choice for fruit monitoring by virtue of its wireless, efficient, low-consumption and scalable advantages. With the continuous progress of technology, its application in the fruit supply chain will be more extensive, providing solid support for food safety and intelligent management.

5.3. Traceability labels

Traceability labels record information about the fruit from growing to consumption, helping to reduce food waste and supply chain losses. The technology integrates RFID, quick response (QR) codes and sensor systems to enable full monitoring of fruit (Fig. 6F) (Li et al., 2024a, 2024b). RFID labels and sensors can be embedded in packaging to monitor temperature, humidity and gas concentration in real time, extending shelf life and reducing spoilage (Zuo et al., 2022). QR codes, as a low-cost and highly flexible means, can be scanned to obtain information such as origin, production date and transport route, thus enhancing consumer trust and brand credibility (Waldhans et al., 2023).

In technical implementation, the optimisation of the label design is particularly critical. The readability of QR codes on curved packages is affected by scanning distance, size and encoding. Response surface analysis (RSM) can be applied to determine the optimal combination of parameters to improve recognition stability under different conditions (Qian et al., 2021). In addition, the development of intelligent packaging technologies, such as nanosensors, provides QR labels with the ability to detect chemical or biological changes in fruit in real time, enhancing quality monitoring and driving digital transformation of the supply chain (Wahab et al., 2024).

However, the technology still faces challenges in terms of cost, standardisation and consumer acceptance. Despite the maturity of RFID and QR codes, the spread of these technologies in developing countries and small-scale farms is still limited by financial and infrastructural constraints, as well as inconsistencies in regulations in different regions, which also increase the difficulty of application. Nonetheless, with technological advances and cost reductions, the application of traceability labelling in the fruit supply chain still holds great promise.

6. Multi-functional integrated packaging systems for fresh fruits

Although significant progress has been made in anti-damage, preservation, and intelligent monitoring technologies, the future of fruit packaging lies in the modular integration of these functions into an efficient and synergistic system. An ideal integrated packaging system should mitigate external mechanical impact, regulate the internal microenvironment, inhibit physiological decay, and enable real-time sensing and feedback of quality status, thereby shifting from passive protection to active intervention and intelligent early warning.

6.1. Current integration attempts

Multi-functional integrated packaging combines protection, preservation, and monitoring functions to achieve dynamic regulation and real-time feedback on food quality (Fig. S1). Its core lies in the use of biocompatible materials as carriers, integrated with technologies for controlled release of active compounds and environment-responsive sensing, overcoming the limitations of traditional single-function packaging.

Natural biopolymers such as nanocellulose, chitosan, and carboxymethyl cellulose are widely used in packaging due to their biodegradability and safety. They can be combined with MOFs, nanoparticles, or natural pigments to achieve antibacterial, antioxidant, and pH-responsive functions (Li et al., 2025; Yue et al., 2023). For instance, a nanocellulose-based coaxial 3D-printed label, with a core containing 1-MCP-loaded chitosan and a shell made of an anthocyanin-based composite, enables both slow-release preservation and color indication (Zhou et al., 2021a, 2021b). An Ag-MOFs@carboxymethyl filter paper composite exhibited 99.9 % antibacterial efficacy against *Escherichia coli* and *Staphylococcus aureus*, while also sensing humidity fluctuations via electrical resistance changes, enabling remote monitoring of strawberries and blueberries (Zhang et al., 2022).

Nanotechnology has further enhanced film functionality. For example, a TiO_2/chitosan/PVA composite film significantly improved UV blocking, mechanical strength, and passive cooling performance, offering a new approach for low-temperature storage and transport of tropical fruits (Liang et al., 2025). A ZIF/CMC composite film notably reduced oxygen and water vapour permeability while providing full UV protection (Yue et al., 2023). Moreover, a nanozyme system based on Cu^{2+}-lysozyme imparted SOD-like activity to the film. When combined with tannic acid and a PVA network, it significantly improved mechanical properties and preservation performance (Li et al., 2025).

Bio-inspired designs have also introduced new concepts. Inspired by the “rigid scale-flexible skin” structure of pangolins, a Col/DA/ZnO/BW composite film achieved a rigid-flexible coupling effect, combining high strength (78.64 MPa) with real-time pH-responsive monitoring and good degradability (Shi et al., 2025a, 2025b). A chitosan/nanohumic acid/curcumin coating improved compatibility with fruit peel by modulating surface roughness, significantly extending the shelf life of fruits such as lychee and mango, while also exhibiting excellent washability (Huang et al., 2022).

However, integrated systems still face multiple challenges. These include the high production costs and potential migration risks associated with certain composite systems, such as MOFs and nanoparticles. Sensing signals are often susceptible to interference from temperature and humidity, as seen in the hysteresis of anthocyanin-based color responses under high humidity conditions. Additionally, consumer acceptance of smart components remains limited due to safety concerns regarding nanomaterials and bio-enzymes.

6.2. Synergistic design principles and future breakthroughs

To achieve truly efficient and sustainable integrated packaging, system design must follow hierarchical and synergistic principles. The outer cushioning layer should provide impact resistance and vibration damping, potentially using biomimetic designs (e.g., pomelo peel-inspired hierarchical structures or honeycomb cardboard) to maximize energy absorption and stress dispersion (Hu et al., 2024). The middle functional regulation layer maintains a stable microenvironment through slow release of active substances, humidity regulation, or MAP, and may be coupled with the cushioning layer to enhance overall performance (Zhang et al., 2024). The information sensing layer enables non-invasive monitoring via RFID tags, gas sensors, or freshness indicators, providing real-time quality feedback to the supply chain and consumers (Yan et al., 2024).

The further development of multi-functional integrated packaging relies on multi-dimensional synergy among material innovation, sensing technology optimisation, and consumer acceptance. First, there is an urgent need to develop low-cost, sustainable carrier materials, such as using agricultural by-products like fruit peels and straw to produce biodegradable carriers, which would reduce production costs and enhance environmental friendliness. Second, sensing systems should evolve from single-parameter monitoring to integrated multi-signal detection, combining pH, humidity, and temperature parameters for more stable and accurate quality assessment in complex storage and transport environments. At the same time, safety verification and consumer trust remain crucial for industrial application. Long-term toxicological and migration risk assessments of nanomaterials and bioactive components must be strengthened, and transparent labeling and science communication should be used to alleviate consumer concerns about smart components. With the integration of Internet of Things (IoT) technology, such systems are expected to achieve full-chain connectivity from packaging-cloud-end-user, enabling real-time data exchange and providing core support for intelligent and refined management of the food supply chain. These strategies outline a clear path for translating laboratory technologies into practical, scalable solutions.

7. Conclusions and prospects

At present, packaging technology for fresh fruits is constantly upgraded, gradually evolving from the traditional protective function to structure-function integration, intelligent perception and green sustainable direction. From the anti-damage point of view, foam buffer materials and biomimetic composite materials show excellent performance in vibration damping and energy absorption. Structural design emphasises multi-layer combinations and FEM optimisation to achieve effective control of transport vibration, impact and compression stress. In preservation, MAP, active packaging and slow-release technology promote the upgrade of packaging material functionality, significantly extend the shelf life of fruit and enhance the efficiency of nutritional value preservation. Edible coating and gelatin/chitosan composite film have gradually become an important alternative to traditional plastic packaging due to their green degradability and freshness preservation activity. New materials such as nanocellulose reinforced film and bio-based barrier materials have further broadened the technological boundaries of preservation mechanisms. In the field of intelligent packaging, technologies such as colour-changing labels for pH response, freshness indication film, gas sensors, RFID system for temperature recording and QR codes have achieved real-time monitoring and dynamic feedback on the quality status of fresh fruits, and promoted the fruit supply chain to move towards a new stage of visualisation and digital management.

However, the current packaging technology for fresh fruit is still facing some challenges and the urgent breakthrough direction. First, the integrated design of multi-functional packaging system is still in the exploratory stage, and there are synergistic optimisation problems between material properties. Second, there is a lack of customised packaging standards for different fruit characteristics and application scenarios, limiting the adaptability and economy of technology promotion. Third, the stability, sensitivity and cost control of intelligent packaging is still a bottleneck for industrialisation, and it is necessary to further improve the maturity of the technology in new materials and system integration. Fourth, in terms of sustainability, the biodegradability and mechanical strength of green packaging materials still need to be optimised, while the safety assessment system of nanomaterials and active ingredients needs to be improved. Furthermore, consumer acceptance and education are vital for the successful implementation of advanced packaging technologies, particularly for edible coatings and intelligent indicators, which require greater transparency and communication to gain market trust. Finally, although many advanced packaging technologies have shown excellent performance at the laboratory scale, their commercialization still faces multiple challenges. For example, climate-specific COF-Silk films (Section 3.2.1) and flexible chemoresistive ethylene sensors (Section 5.1.3) are currently at TRL 4–5, having been validated in laboratory and relevant environments. The main barriers to large-scale application include the high cost of nanomaterials, limited long-term stability and safety data, the absence of standardized regulatory frameworks for nanomaterials in packaging, and the technical difficulties of integrating these systems into existing supply chains.

Future research should focus on the following directions. At the material level, the development of high-performance, biodegradable packaging materials and multifunctional nanocomposite systems should be accelerated to achieve the integration of mechanical buffering, antimicrobial preservation, antioxidant activity, environmental UV resistance, and environmental response. In structural design, bionic design and FEM methods need to be integrated to establish a multi-dimensional parameter-driven optimisation mechanism for packaging structures. In terms of intelligent packaging, advanced information technology such as IoT, big data and AI should be introduced to build a monitoring system that can sense real-time temperature and humidity, gas changes and fruit status, and create an intelligent packaging system with a traceable chain. Critically, advancing the modular integration and synergistic optimisation of anti-damage, preservation, and intelligent monitoring functionalities represents a pivotal strategy for overcoming existing technical bottlenecks and revolutionizing the paradigm of fresh fruit packaging. In evaluation methods, a ternary coupled model of mechanics-physiology-environment for packaging-fruit interaction should be established to achieve accurate prediction and optimisation of packaging performance. In addition, future research should emphasize pilot-scale demonstrations, strategies to reduce costs, and coordinated standardization to promote market adoption. The standardisation system of green packaging materials should be strengthened and its systematic interface at the levels of regulations, safety and recycling should be promoted.

CRediT authorship contribution statement

Jie Hao: Investigation, Resources, Validation, Writing - original draft. Peng Qiao: Formal analysis. Jin Wang: Resources. Minggang Wang: Resources, Investigation. Zhiguo Li: Conceptualization, Project administration, Writing - review & editing. Wenzhi Tang: Conceptualization, Supervision. Marie-Laure Fauconnier: Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

No data was used for the research described in the article.

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