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# Intelligent & edible biopolymer-based packaging technologies for postharvest shelf-life enhancement of litchi (*Litchi chinensis*) fruit: a comprehensive review

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Litchi (*Litchi chinensis*) is a sub-tropical fruit of high nutrition and commercial value, but its quality and safety deteriorate during storage due to physical, chemical, enzymatic, and microbial damage. The shelf-life can be improved by various methods such as sulfur (SO<sub>2</sub>) fumigation, cold storage, gamma irradiation, high-pressure processing, edible packaging, etc. SO<sub>2</sub> fumigation is one of the most explored methods for preserving litchi fruit but due to its negative environmental and human health effects, its application is limited. Edible and intelligent coatings and films comprised of various biopolymers can be a promising solution to prolong the shelf-life of litchi and they help to achieve SDGs 12.3 (halve per capita global food waste at the retail and consumer levels), 13.2 (integrate climate change measures into national policies, strategies, and planning) and 14.1 (prevent and significantly reduce marine pollution of all kinds). This article reviews the recent advances in using different biopolymers to develop intelligent & edible films and coatings to improve the storage life of litchi fruit. Edible packaging based on polysaccharides, proteins, lipids, additives, nanoparticles, etc. has been examined. These protective layers reduce the respiration and transpiration rates, protect against mechanical stress, microbial contamination, enzymatic browning and UV light, and enhance the quality by adding bioactive agents, nanomaterials, probiotics, etc. The opportunities to use bioactive compounds, essential oils and plant extract in various biopolymeric edible coatings are explored. Finally, regulatory aspects associated with edible intelligent packaging have been discussed. Overall, the application of edible and intelligent packaging can be a potential alternative for delaying the degradative changes, extending the shelf-life, and reducing the economic losses caused by the spoilage of litchi.

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## Sustainability spotlight

This review highlights the role of intelligent and edible packaging technologies in reducing postharvest losses of litchi, a highly perishable fruit. By compiling and critically analyzing recent advances in biopolymer-based films and coatings, natural antioxidant incorporations, and intelligent freshness indicators, the paper provides a sustainable framework for replacing synthetic packaging with eco-friendly alternatives. Such insights promote waste reduction, extend fruit shelf-life, and lower environmental impacts associated with plastic use. The review aligns with the UN Sustainable Development Goals, particularly SDG 12.3, SDG 13.2 and SDG 14.1, by encouraging sustainable material choices and resource-efficient food preservation practices that can guide both researchers and industry toward greener innovations.

## 1. Introduction

Litchi (*Litchi chinensis*) is a non-climacteric fruit that is an extremely popular horticulture produce among its consumers due to its unique taste, distinctive flavor, and attractive pink appearance. This fruit has high commercial value in the international and domestic market due to its numerous health benefits and high consumer demand.<sup>1</sup> Litchi is a source of several nutrients including vitamins, phenolics, flavonoids,

sugar, and minerals. Litchi is a rich source of antioxidants due to the presence of a broad range of phenolics and flavonoids which are highly effective against human health problems like heart diseases, dyspepsia, diabetes and smallpox.<sup>2,3</sup> Litchi is particularly recommended to be consumed during pregnancy in order to meet the nutritional requirements for maternal health. This fruit is extremely susceptible to spoilage and can only be stored for a maximum period of 2–3 days under normal atmospheric conditions and 3–5 days under cold storage conditions.<sup>4</sup>

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Historical accounts state that litchi seed, pulp, and whole fruit were utilised in herbal remedies in China.<sup>5</sup> The market value of this fruit is reported as USD 7.10 billion in 2024 and is expected to reach USD 9.27 billion by 2029 which is equivalent to a compound annual growth rate (CAGR) of 5.5% during the time scale of 2024–29.<sup>6</sup> However, the short shelf life of this fruit limits its full potential both in terms of economics as well as nutritional value. Pericarp browning, fungal infestation, textural loss, weight decay, and microcracking development are major problems associated with the shelf life and storage of fruit. The fast pericarp browning of litchi fruit is mainly

reported due to the high action of enzymes found namely polyphenol oxidase (PPO) and peroxidase (POD).<sup>7,8</sup> Therefore, one of the major challenges associated with the producer is maintaining the appealing red-pink color of this fruit, especially during importing this internationally. A wide group of fungi have been reported for major post-harvest diseases associated with fruit deterioration by various research communities actively working with this fruit.<sup>9–11</sup>

To date, different conventional practices have been implemented to remove these post-harvest problems including SO<sub>2</sub> fumigation,<sup>12</sup> refrigeration,<sup>13</sup> irradiation process<sup>14</sup> and controlled and modified atmosphere packaging.<sup>15</sup> Sulfur fumigation is a commercial technique to address the issues of fungal growth and browning of litchi fruit. However, consumer preference, government regulation regarding sulfur use and environmental problems have recently raised a lot of questions about its application.<sup>16</sup> Petroleum-based plastic packaging has been utilized for processed food and farm produce for decades because of its cost effectiveness, production simplicity, convenience for users, and favourable chemical characteristics. Nevertheless, consumer demands have shifted toward eco-friendly, renewable, biodegradable, and sustainable packaging materials because of growing public awareness of plastics' use of non-renewable resources, safety concerns, and huge accumulations and contaminations in the environment. Adopting edible films and coatings is one way to meet the current demand which could apply to a wide range of horticulture produce including litchi for enhancing their shelf life (reducing post-harvest loss).

In the last 2 decades, edible films and coatings for fruits and vegetables have attracted the attention of a large scientific



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community due to its various properties including biodegradability, biocompatibility, sustainable nature, and increase in the awareness of people toward human health and environment. Along with these unique and important properties, edible films and coatings maintain the organoleptic quality of coated components for longer periods. The efficacy of these novel edible composite films incorporating supplemental functional substances hinges upon the inherent physical and chemical properties, as well as the biological activity, of the additives themselves and the edible film matrix, in addition to their encapsulation. The edible coating is a thin extra layer applied on the surface of horticulture produce which can be consumed along with fruits and vegetables,<sup>17–19</sup> whereas the use of edible films is applicable as an inner layer that directly interacts with the foods in packages that consist of non-edible films.<sup>20</sup> Their main mechanism includes the regulation of respiration and transpiration phenomena associated with fruits and vegetables along with microbes and browning control. Edible coating formulation has been reported for various fruit commodities as a sustainable approach for enhanced shelf-life including apples, avocados, strawberries, cherries, and oranges.<sup>21–23</sup> This type of packaging is based on polysaccharides (e.g., cellulose, starch, chitosan, and gums), protein (whey and milk protein), and lipids (waxes and oils) and may contain active components for active edible coating. In a manner analogous to conventional packaging films, active packaging possesses the capability to offer both barrier and mechanical safeguards for food products. Furthermore, active packaging has been engineered to extend the shelf life and enhance the quality of food items through the release of antioxidants and antimicrobials or the absorption of O<sub>2</sub>, CO<sub>2</sub>, ethylene, and various odors. Active packaging (active edible films and coatings) introduces antioxidant, antimicrobial, and UV-resistant properties which could be the potential solution for browning and fungal attack problems on litchi fruit.

A new category of food packaging materials known as intelligent packaging combines the protective function of traditional edible films with the capacity to detect and convey variations in food quality. Intelligent packaging is made to interact with its surroundings and provide visible or quantifiable cues regarding the freshness, safety, or spoilage of food, in contrast to conventional packaging, which merely serves as a passive barrier.<sup>24,25</sup> These systems are especially useful for perishable goods like fruits, vegetables, dairy products, and seafood, where quality degradation happens quickly and often goes undetected until it is too late.

The application of various packaging materials on various fruits and vegetables is also extensively discussed in numerous research articles.<sup>26–28</sup> For researchers, identifying a desirable film and coating component for a specific horticulture product can be a challenging task. These components and materials for a particular fruit must be identified based on data scattered across a wide range of literature. There has been no detailed review of edible films and coatings suitable for litchi fruit recently, that is why this review was planned. The use of various intelligent & edible films and coatings on litchi fruit is summarized and analyzed in this paper. This review aims to

cover various major post-harvest challenges associated with the litchi fruit which limits the shelf life of this fruit significantly along with their preservation technique. This review discusses about the emerging sustainable intelligent and edible biopolymer-based packaging technologies to replace conventional treatments including sulfur fumigation, application of fungicides, and irradiation treatments for enhancing post-harvest storability of litchi fruit which is in accordance with Sustainable Development Goals 12, 13 and 14. Also, the required properties of edible films and coatings for maintaining the desired nutritional and quality parameters of litchi fruit for shelf-life enhancement will be discussed. This paper will cover applications of different edible coating formulations which were developed by researchers for prolonging the storage life of litchi fruit and reducing its postharvest loss. This is an essential step towards achieving SDG 12.3 which is with regard to reducing global food losses and waste. Additionally, biodegradable polymeric food packaging is an environment-friendly technology that can lead to low carbon footprint, greenhouse gas emission and microplastic generation, and brings us a step closer towards SDG 13.2 and 14.1. The overall discussion will help in choosing better components for intelligent and edible coating formulation and standardization.

## 2. Brief overview of the litchi fruit

Litchi fruit is a member of the Sapindaceae family which includes fruits like logans and mangosteen which are believed to originate from the southern part of current China.<sup>29,30</sup> The litchi fruit is characterized by a thin and sturdy peel that easily peels away, revealing a pearl-white, jelly-like pulp with a delightful taste resulting from the harmonious combination of acids and sugars.<sup>31</sup> With a high fiber content and low protein and lipid amount, litchi is an excellent source of carbohydrates (~16.5 g/100 g). The fruit possesses a higher level of various micronutrients including phenolics (~178 mg GAE/100 g), flavonoids (~54 mg QE/100 g), tannins, carotenoids, minerals (iron, phosphorous, and calcium), and vitamins (mainly C and trace amounts of A and K).<sup>32</sup> It has been shown *in vitro* and *in vivo* that litchi has valuable bioactivities such as antioxidant, antimicrobial, antidiabetic, nontoxic, anticancer and antidiabetic characteristics.<sup>22,33,34</sup> Besides being consumed as fresh produce it is utilized in various processed forms including canned litchi, litchi juice & wine, litchi honey, and pickles. Litchi pericarp (15% of fruit weight) which is discarded as waste also contains a significant amount of bioactive compounds (phenolics, flavonoids, and tannins).<sup>35</sup>

It is widely produced in tropical and subtropical regions, with major producers located in Asia, Africa, and the Americas. The two largest producers are China (~70% of total production) and India followed by countries like Thailand, Vietnam, Bangladesh, and South Africa.<sup>3,36</sup> India produces 737 200 metric tons of litchi and produces 7.43 metric tons per hectare at present on an area of about 99 170 hectares.<sup>37</sup> It is interesting to note that despite the smaller output, Vietnam has become the world's second-largest exporter of litchis in the year 2018. The demand for Vietnamese litchi is increasing due to better fruit



quality than China and India.<sup>38</sup> According to FAOSTAT 2020, the United States imports a majority of litchi, driven by the market demand for exotic fruits.<sup>39</sup> The total size of the European litchi import sector is estimated to fluctuate between ~20 000 and 25 000 tonnes per year. Madagascar is recognized as the primary supplier of litchi to the European region, introducing a significant amount of exotic fruits, predominantly litchi, totalling ~15.5 thousand tonnes in 2017.<sup>40</sup>

As a non-climacteric fruit after harvesting, litchi stops ripening and becomes insensitive to exogenous ethylene. Once this fruit reaches full maturity on the tree, it must be harvested.<sup>41</sup> One crucial factor in determining when to harvest the fruit is its color (red pericarp color and flattened tubercle).<sup>42</sup> Another factor that decides when to harvest the litchi fruit (optimum condition) is the maturity index parameter (ratio of TSS and TA). The optimum value of TSS and TA for the harvesting is reported as 19° brix and ~0.3–0.4%, respectively.<sup>43</sup> However, these criteria will vary from cultivar to cultivar, country to country, and climate area to climate area. In tropical countries like India, post-harvest problems of fruits are of utmost importance. Litchi fruit is highly perishable, with a shelf

life of two to three days at ambient temperature. The main factors preventing the growth of litchi-based farming and industries have been identified as pericarp browning, desiccation problems, chilling injury, fungal growth, and post-harvest decay. The pericarp browning of fruit is a major concern because consumers base their acceptance of it on its appearance. The quantitative and qualitative losses in litchi fruits from harvest to consumption have a significant impact, diminishing fruit availability and elevating transportation and marketing costs per unit. The average cumulative loss experienced within the supply chain of litchi varies between 35.3% and 43.8%, indicating significant inefficiencies and challenges in the preservation and distribution processes of this particular fruit commodity.<sup>44</sup> In this context, edible films and coatings can be a viable and sustainable solution to resolve this issue.

### 3. Postharvest losses related to litchi

In this section, we have provided a concise summary of key mechanisms that contribute to litchi fruit deterioration as depicted in Fig. 1. These mechanisms must be considered when

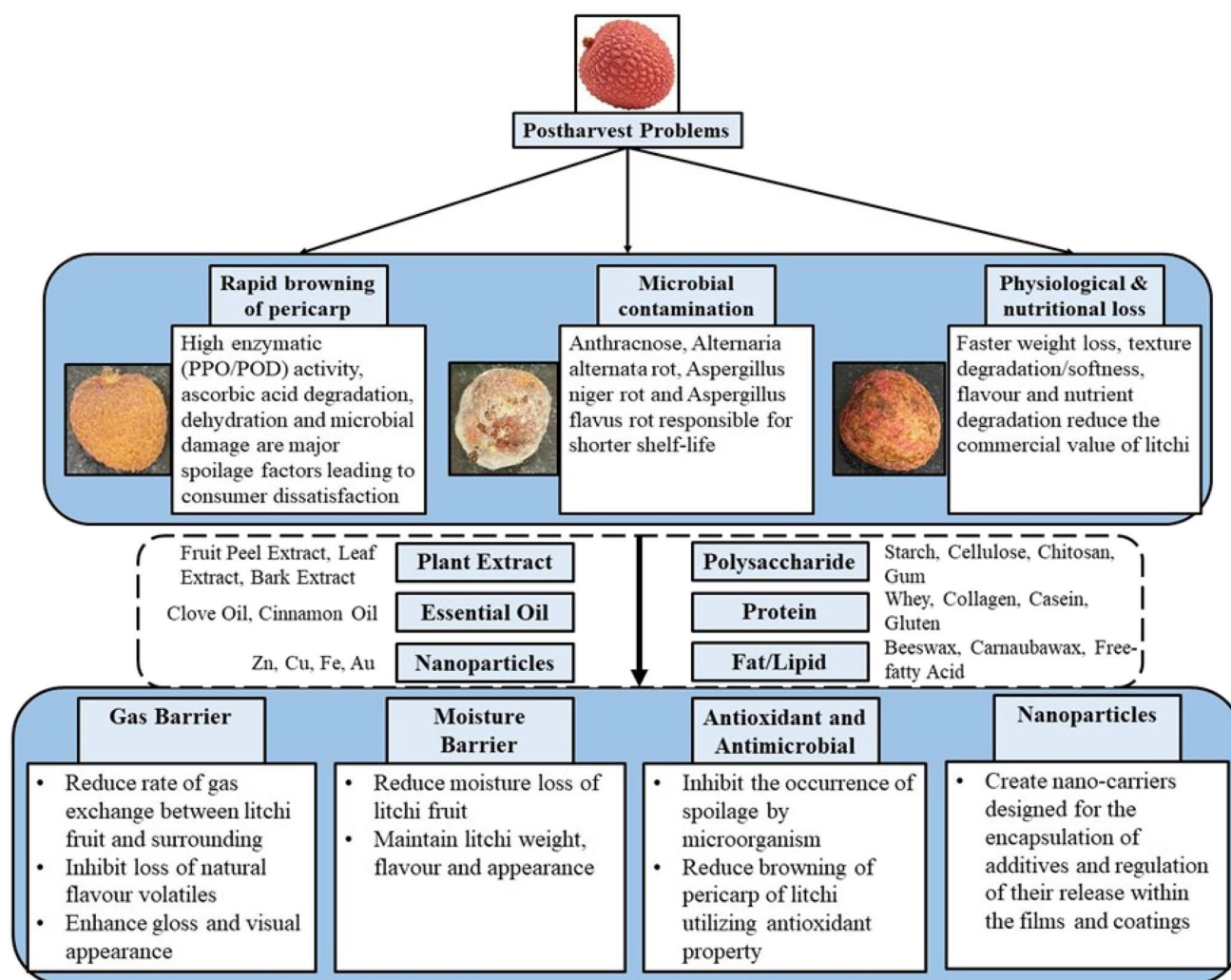


Fig. 1 Postharvest problems of litchi and its shelf-life enhancement using edible packaging.



developing effective edible coatings to enhance the shelf life, quality, and safety of litchi.

### 3.1 Pericarp browning

In litchi fruit, browning is a postharvest physiological disorder that has a significant impact on the fruit's quality and marketability. This change happens quickly, with about half of the fruit's skin turning brown within 12 hours of harvesting when kept at room temperature.<sup>45</sup> This is an accelerated process that completely browns the skin after the 2<sup>nd</sup> or 3<sup>rd</sup> day after storage at room temperature (>20 °C).<sup>3</sup> Associated phenomena for pericarp browning are desiccation, mechanical damage,<sup>46</sup> fungal attack,<sup>47</sup> high activity of PPO and POD enzyme<sup>48</sup> and unsuitable low temperature (injury caused by chilling).<sup>49</sup> High activities of polyphenol oxidase and peroxidase enzymes have been reported as a major cause of browning of the pericarp due to oxidation degradation of the red color pigment (anthocyanins). The activity of the PPO enzyme is reduced by the application of several types of antioxidants and is enhanced with the divalent cations of calcium and magnesium. Numerous studies have reported the PPO activity/amount variation with time for establishing the direct relationship between the PPO and browning effect on the pericarp of fruits. The activity of PPO (polyphenol oxidase) in litchi fruit storage appears to be unpredictable based on numerous studies. These findings highlight the inconsistent nature of PPO activity in litchi fruit storage, with some studies showing an increase,<sup>4</sup> others indicating no significant change, and others reporting a gradual reduction. A study performed by Qinqin *et al.*<sup>50</sup> reported that POD is involved in the enzymatic browning of litchi fruit due to its ability to oxidize 4-methyl catechol in the presence of H<sub>2</sub>O<sub>2</sub>, thereby forming brown polymeric pigments. The author's research findings support the hypothesis that both PPO and POD play a role in litchi pericarp browning. Recent findings have reported that when the activities of PPO and POD were inhibited, it resulted in a delay in the browning process of litchi pericarp.<sup>51,52</sup>

Ascorbic acid degradation is reported as another factor that is responsible for the browning of the fruit pericarp. The overall mechanism is still not well understood, but it has been concluded that hydrogen peroxide is produced from the degradation of ascorbic acid which accelerates the oxidative degradation of anthocyanins. An increase in ascorbic acid oxidation has been reported with an increase in pericarp browning. However, a smaller amount of ascorbic acid in mature fruit pericarp makes it a non-significant factor for browning problems.<sup>53</sup>

Water loss and pH change are also correlated with the browning development of the pericarp.<sup>54</sup> Underhillab *et al.*<sup>55</sup> have studied the effect of water loss and pH change on pericarp browning and concluded that both these events increase the browning significantly. The pH of the pericarp tends to rise with moisture loss; after 48 hours at 25 °C and 60% relative humidity, it reaches a range of ~4.15–4.52. The presence of anthocyanins, which give litchi their red colour, is impacted by this pH shift. Recently, a study was conducted by Liu *et al.*<sup>56</sup> to

establish a relationship between water loss from the pericarp and browning development of the pericarp of packed and unpacked litchi. In the end the researchers concluded that both these phenomena are highly correlated ( $R \sim 0.92$  &  $0.65$ ). Since water loss was significantly low ( $p < 0.05$ ) for unpacked litchi as compared to packed ones, it was concluded in the end that packaging affects the browning significantly. However, whether this water loss is of biological significance is still not very clear.

### 3.2 Fungal infestation

Fungal attack is one of the most visible factors in the litchi fruit industry causing major post-harvest loss which lowers fruit value resulting in consumer rejection and economical loss. Generally, litchi is ready for harvest during the hot and humid season. However, this time of the year also makes them highly perishable and potentially susceptible to fungi infection. The coarse consistency of the litchi pericarp offers an optimal surface for the attachment of conidia and the proliferation of fungi. The litchi aril possesses a diminished pH level, elevated sugar concentration, and abundant nutrients, all of which are conducive to the flourishing of fungal entities, particularly *Penicillium* spp. This results in the fruit quickly decaying, losing its value for sale, and not surviving long.<sup>57</sup> Various species of fungi have been reported to cause different diseases to the fruit including *Alternaria*, *Botryodiplodia*, *Penicillium* species and *Colletotrichum gloeosporioides*.<sup>16</sup>

The primarily reported disease affecting the litchi fruit is anthracnose among several other fruit rots (caused by various species of fungus). Anthracnose is a postharvest lychee disease that is prevalent globally and is primarily caused by the fungal pathogen *Colletotrichum gloeosporioides*, with occasional contributions from *C. acutatum*.<sup>58</sup> Lychee anthracnose is characterized by browning of the pericarp, where the infection is usually localized. The fleshy part of the lychee, or aril, is usually unaffected and collapses only sometimes. While infections may arise during cultivation in the field, they typically remain latent until post-harvest stages. In the year 2015 pathogens responsible for this disease were separated and identified in Oaxaca, Mexico as *Colletotrichum gloeosporioides* Penz.<sup>59</sup> They reported anthracnose as the brown lesion on the fruit's outer surface. Zhao *et al.*<sup>60</sup> reported the first case of anthracnose disease in China and explained that a brown spot developed on the fruit or the leaves of the litchi. This experiment concluded that the main pathogen responsible for this disease is *Colletotrichum karstii* (a newly identified pathogen) along with *C. gloeosporioides*.

Additionally, there are various other fruit rots which are responsible for the postharvest deterioration of the litchi fruit. Kumar *et al.*<sup>61</sup> studied the effect of *Alternaria alternata* pathogen on litchi fruit in India (Bihar) and concluded that this pathogen causes fast and complete drying of the outer pericarp. According to the authors it is estimated that around 40% of the fruits get damaged by *Alternaria alternata*. *Aspergillus niger* rot and *Aspergillus flavus* rot are also reported in various literature studies which cause a severe damage during postharvest storage of the fruit. *Aspergillus niger* rot first manifests as a light brown



lesion encircling the fruit's stalks, which subsequently turns deep brown. Four to five days after infections, black conidial heads can be distinguished. In the affected areas some white marks are often observed.

### 3.3 Additional factors responsible for postharvest changes

Accelerated water and firmness loss are two physiological parameters which limit the shelf life of litchi fruit. Water loss from the fruit increases weight loss, whereas firmness loss results in the textural loss of litchi fruits. Because of these losses (sensorial loss) the overall acceptability by the consumer is highly diminished.<sup>2</sup> In various experimental studies it is well concluded that when litchi fruit was used as the control and was compared with other preservation techniques such as edible coating, MAP packaging and refrigerated condition storage, a significantly high weight and firmness loss was observed.<sup>62,63</sup> The phenomenon of water reduction in litchi fruit is a manifestation of the respiration rates and the intricate interplay with the surrounding environment. The decrease in litchi firmness as the fruit ripens is predominantly attributed to a biochemical mechanism characterized by the breakdown of pectin and cellular elements through the action of hydrolytic enzymes, known as hydrolases. Additionally, this process is impacted by variables like loss of weight and moisture, which play a role in the reduction of tissue volume and damage to the fruit's skin.<sup>64</sup> There is also a correlation given by the researchers in which excess water loss in litchi and other logan fruits contributes to the browning of the pericarp.<sup>65,66</sup> Additionally, litchi fruit manifests a discernible physiological detriment (postharvest damage) when subjected to suboptimal temperatures below 10 °C (above the freezing temperature) referred to as the chilling injury. The fruit tissues lose strength, because they are unable to perform normal metabolic functions required at this reduced temperature and result in dysfunction.<sup>49</sup>

## 4. Intelligent & edible film and coating preservation mechanism for litchi fruit postharvest storability

This section provides an overview of the key parameters, working mechanisms, and essential functional attributes

(as illustrated in Fig. 2) of the developed edible films and coatings intended for litchi preservation. The discussion focuses on crucial properties such as physical barrier and mechanical strength, which maintain the structural integrity of the film and protect the fruit from external stress; controlled moisture and gas exchange, which help to regulate respiration and prevent dehydration; antioxidant and antimicrobial activity, which inhibits oxidative degradation and microbial spoilage; and UV-resistant properties, which safeguards bioactive components from photodegradation.

### 4.1 Physical barrier and mechanical strength

Edible films and coatings create a protective external layer (like the existing natural cuticle layer) for fruits and vegetables after complete drying. This created barrier separates the external layer of produce and open environment or prevents direct contact.<sup>67,68</sup> As a result, the fruit is less susceptible to direct exposure to detrimental elements in the external surroundings, microbes, pollution (dust) and other impurities. Thus, optimized edible films and coatings on litchi fruit will reduce fungal decay resulting in enhanced shelf life. When a chitosan based edible coating with pomelo extract and citric acid was applied on litchi fruit, fungal growth was reduced significantly.<sup>69</sup> The film formed on the surface of the produce possesses some mechanical strength, which is a desirable requirement during the transportation of the fruits. Several factors such as tensile strength, elongation, plasticizer concentration and type, molecular weight of the film, solvent classification, and thickness of the coating influence the mechanical strength of a film.<sup>70</sup> A study conducted on transportation of litchi from Muzaffarpur (Bihar) to Delhi concluded that 15.8% of fruits get damaged (compressed, bruised and attacked by fungi) in transit.<sup>61</sup> In this context, mechanical strength provided by the applied film and coating can significantly overcome this loss due to the stress developed in fruits during transportation.

A carrageenan based film utilizing grapefruit essential oil was formulated for active edible packaging. The amount of carrageenan was kept constant at 2% and grapefruit essential oil was varied from 0.1 to 0.3%. The tensile strength increases from 65 to 98 MPa as the amount of oil increases.<sup>71</sup> This enhancement in tensile strength was due to the presence of the

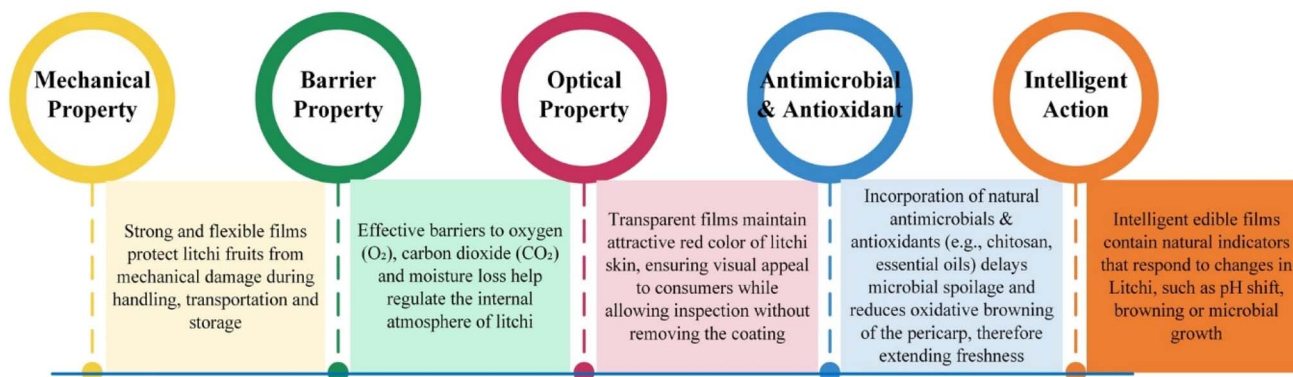


Fig. 2 Functional properties offered by edible films and coatings for prolonging the storability of litchi fruit.



large range of ketones and phenolics in grapefruit essential oil. Similarly, sericin, chitosan and carbon dot based edible film exhibited maximum tensile strength and elongation at break of 11.63 MPa and 54.71% respectively, which further was applied as an edible coating on litchi fruit and has significantly enhanced its shelf life up to 6 days at open storage (25 °C and 85% RH).<sup>72</sup>

## 4.2 Controlled moisture and gas exchange

Desiccation is a vital problem associated with the limited shelf life of litchi fruits, which is also one of the factors responsible for the browning action of the pericarp and rapid weight loss of the litchi fruits.<sup>73</sup> Edible films and coatings in this context are particularly important to regulate the rate of water and gaseous losses. The efficacy of a high-quality coating and film is determined by its ability to regulate the transfer of mass between the internal composition of the fruit and the external surroundings. This migration phenomena involves the passage of water vapor *via* transpiration, the flow of gases through respiration, the dispersion of gases, and specific volatile organic compounds.<sup>70</sup> The water vapor permeability (WVP) of the edible film is significantly influenced by the hydrophobic characteristics of the polymer matrix used in its preparation, whereas the gas permeability of the edible film is significantly influenced by the cohesive energy, free volume, and crystallinity of the polymer matrix.<sup>74</sup> The gas permeation in biopolymeric films is governed by the interplay of sorption and diffusion mechanisms, which are intricately influenced by the molecular dimensions and structural characteristics of the diffusing species.<sup>75</sup> Mathematically, gaseous transfer can be formulated by Fick's law of gas diffusion and Henry's law of solubility as shown in eqn (1) and (2) respectively.

$$J = -\frac{Ddc}{dx} \quad (1)$$

$$P = C/S \quad (2)$$

In eqn (1),  $J$  is the gas diffusion,  $D$  is the diffusivity constant and the other term is the concentration gradient. In eqn (2),  $P$  is the permeability,  $C$  is the permeate concentration and  $S$  is the solubility.

Thereby, matrix selection is a very technical component for any produce while developing edible films and coatings for an optimum level of gaseous and water vapor transfer rate. A proficiently formulated coating that exhibits effective water vapor and oxygen permeability is of greater importance in inhibiting textural deterioration, desiccation of fruits, reduction in size, as well as chemical or enzymatic processes, thereby ensuring the longevity of litchi fruit freshness. Increase in film thickness and lipid content cause WVP to reduce. When carnauba wax was incorporated into arrowroot starch and an edible film was developed, it was observed that WVP decreases from 6.7 to 3.6 ( $\times 10^{-7}$ ) g H<sub>2</sub>O per m h per Pa when the fraction of carnauba wax increases in the film.<sup>76</sup> Recently, shellac (SH) and oleic acid (OA) were plasticized and a cast film was developed for efficacy in packaging application. Here, shellac was

kept fixed and oleic acid was varied from 0 to 50%. SH-OA 10% shows 2.55 g per m<sup>2</sup> per day WVTR as compared to 8.83 g per m<sup>2</sup> per day of only the neat SH film. The improved barrier was probably due to the absence of any crack and hole on the surface and the amphiphilic nature of oleic acid. However, when the concentration of oleic acid was increased from 10% to 50%, then again there was enhancement probably related to an increase in free volume.<sup>77</sup> A film of chitosan (CH) and cinnamon (CN) nano emulsion was prepared and its functionalisation by cold plasma treatment was performed. The CH and CH-CN in the developed film showed OTR less than 0.05 cm<sup>3</sup> per m<sup>2</sup> per day probably due to the well-arranged hydrogen bond structure.<sup>78</sup>

However, the developed film and coating should not completely block the passage of O<sub>2</sub> and CO<sub>2</sub> to maintain optimum level of oxygen to reduce potential fermentation development. Therefore, an ideal edible film or coating substance must possess semi-permeability to respiratory gases and inhibit respiration while avoiding unwanted fermentation.

## 4.3 Antioxidant and antimicrobial properties

The antioxidant and antibacterial characteristics play a crucial role as functional attributes of edible films and coatings. These properties are essential in inhibiting the oxidation of food and safeguarding it against microbial spoilage respectively, thereby preserving food quality and ultimately prolonging its shelf life. In the context of litchi fruit, these two active properties play an important role in shelf-life preservation, as antioxidants and antimicrobials can be highly effective against browning (reduce oxidation/activity of PPO/POD) and the fungal infestation problem of the litchi fruit, respectively. The active component is obtained through both synthetic (butylated hydroxy anisole (BHA), butylated hydroxytoluene (BHT), butyl hydroquinone (TBHQ) *etc.*) and natural sources (plant extracts and essential oils).<sup>29</sup> These phytochemical actions in plant extracts and essential oils are due to the presence of phenolics, flavonoids and tannins.<sup>79,80</sup> In recent times, there has been a growing interest among producers and consumers in the biodegradable packaging system that utilizes natural antioxidant and antimicrobial agents. Resources for active components include natural additives and extracts made from plants, herbs, spices, animals, and microorganisms.

The ability of films and coatings to exhibit antioxidant and antimicrobial activities is related to their capacity to release the active components, and typically, this ability is directly correlated with the concentration of the active compound present in the packaging material.<sup>81,82</sup> Antimicrobial action proceeds through two mechanisms in general: (I) *via* interfering with the chemical or biological process, (II) circumventing the natural defence mechanism/antibacterial resistance. The major action includes (I) interfering with the cell wall synthesis, (II) cell membrane degradation, (III) inhibiting DNA replication, RNA and protein synthesis, (IV) disturbing the drug delivery and metabolic pathway.

Bhatia *et al.*<sup>83</sup> developed a chia seed mucilage based edible film incorporating cinnamon oil nanoemulsion as the active



ingredient for antioxidant and antimicrobial characteristics. Incorporation of the cinnamon oil emulsion into the matrix significantly enhances the antioxidant activity ( $87.03 \pm 0.30\%$  DPPH radical scavenging capacity) and effectiveness against *E. coli* and *S. aureus*. The authors reported that increase in the antioxidant and antimicrobial capacity of the edible film could be due to the large range of bioactive compounds present in cinnamon oil. Therefore, this active edible film could significantly improve the shelf life of litchi fruit. Sajimon *et al.*<sup>84</sup> have formulated an edible film of whey protein concentrate incorporating different concentrations of a nanoemulsion of oregano essential oil (1, 2, 3, and 4% (w/w)). The formulated film shows positive inhibition against *E. coli* and *S. aureus* ( $25.36 \pm 0.52$ – $28.0 \pm 0.5$  mm) and high antioxidant properties in terms of DPPH ( $86.89 \pm 0.087\%$ ) and FRAP ( $51.24 \pm 0.031\%$ ) respectively. The high activity could be easily correlated with the presence of various phytochemicals present in oregano essential oil.

#### 4.4 UV resistance properties

The assessment of transmittance plays a crucial role in the evaluation of the optical barrier characteristics of films, indicating their efficacy in blocking UV and visible light.<sup>85,86</sup> The potential of ultraviolet (UV) radiation to shorten the shelf life of agricultural commodities is evident. Long exposure to light, especially ultraviolet light, degrades food quality through photolysis and photooxidation reactions. As a result, active oxygen and free radicals are generated, forming unpleasant odors and flavours, reducing nutritional value, and discoloring food, thereby promoting food degradation. Thus, in this context UV resistant edible films and coatings could be a potential solution for minimizing the phytochemical losses in litchi fruit and other horticulture produce.<sup>87</sup>

Abdel Aziz *et al.*<sup>88</sup> have developed an alginate based edible film containing aloe vera gel as the active component for the enhancement of antioxidant, antimicrobial and UV shielding.

The study concluded that neat alginate based edible film shows poor UV shielding properties showing UV transmission up to 90%. Thereafter, when aloe vera gel was incorporated in 50% and 66.7% volume, significantly reduced UV transmission up to 15.3 and 6.01% was obtained. This reduction was attributed to the presence of different UV absorbing substances in aloe vera gel. Chen *et al.*<sup>89</sup> have formulated a nano lignocellulosic biomass and gluten based composite film targeting the high UV barrier properties for packaging litchi fruit. Nearly 100% UV barrier was displayed by the nano lignocellulosic and gluten based composite film attributed to the presence of aromatic rings. This study concluded that fruits packed with the developed film show optimum firmness and low weight loss as compared to open and conventionally packed litchi.

#### 4.5 Intelligent action

According to our conceptual framework, a package is deemed “intelligent” if it possesses the capability to monitor the product, perceive the environmental conditions both internally and externally, and engage in communication with humans.<sup>24</sup> For instance, an intelligent package is characterized by its ability to assess the quality and safety parameters of a food product while offering timely alerts to the consumer or food producer. Intelligent edible coatings utilizing natural biopolymers, including chitosan, pullulan, and gum arabic, and integrated with pH-sensitive indicators, may be applied as a protective layer on litchi fruit. These coatings mitigate respiration, inhibit enzymatic browning, and prevent microbial proliferation, thus preserving fruit quality and enhancing shelf life. Concurrently, the intelligent components, such as anthocyanins or curcumin, react to pericarp pH fluctuations and metabolite release during spoilage, exhibiting a colorimetric change that indicates fruit freshness.<sup>25</sup> According to a research, a bilayer antibacterial chromogenic material was developed using chitosan and hydroxyethyl cellulose as the base, mulberry anthocyanins as freshness indicators, and nano-TiO<sub>2</sub> as an

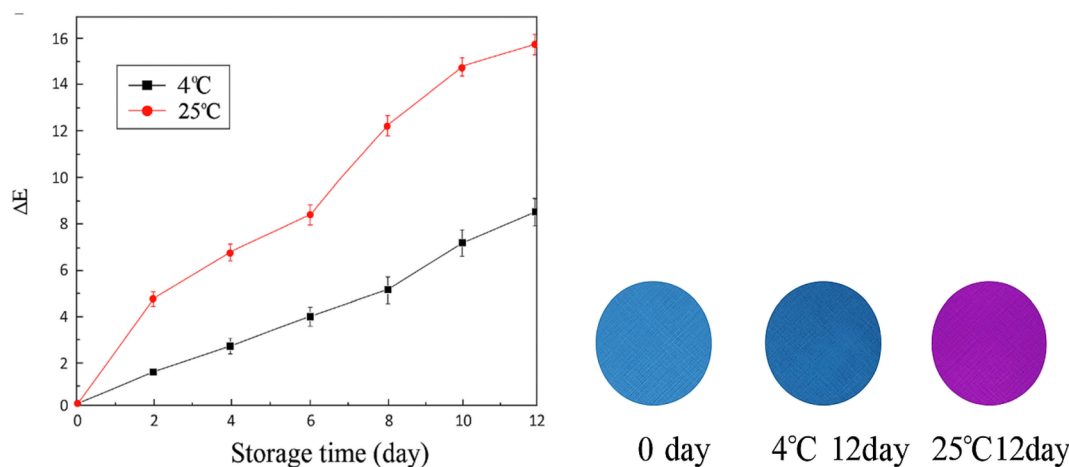


Fig. 3 Changes in chromatic aberration of a two-layer antibacterial chromogenic material in litchi fruit during storage at 4 and 25 °C for 12 days (left), and pre- & post-intelligent color modulation of this double-layered substance at 4 and 25 °C on the 12<sup>th</sup> day as compared to the 0<sup>th</sup> day (right); reproduced with permission from Luo *et al.* (2022),<sup>90</sup> open access.



antimicrobial layer. When applied to litchi, it inhibited microbial growth, delayed browning, and maintained quality. The intelligent role of mulberry anthocyanins was to respond to pH changes during deterioration, showing visible color shifts that signaled the fruit's freshness. Thus, the material functioned both as a preservative and a real-time quality indicator as represented in Fig. 3.<sup>90</sup>

## 5. Intelligent & edible films and coatings on litchi fruit

Edible films and coatings are used to enhance the storage life and quality of litchi fruit by controlling the diffusion of gases and moisture, protecting against physical, chemical and microbial damage, slowing down the deteriorative changes and improving the sensorial attributes. There are several bio-based polymers, *i.e.*, polysaccharides, proteins and lipids, plasticizers, fillers, additives and nanomaterials which are used as intelligent & edible packaging ingredients and they are mentioned below with the suitable cases of applications to litchi fruit. In Table 1, different matrices have been tabulated with their advantages and disadvantages which are important before selecting the matrix for formulation of edible films and coatings for different products. More specifically, polysaccharides form transparent, biodegradable films and coatings with good gas barrier properties but exhibit limited water resistance due to their hydrophilic nature. Lipid-based coatings provide excellent water vapor barriers and reduce moisture loss but have low mechanical strength and limited flexibility. Wax-based primary packaging effectively reduces water loss and enhances surface gloss, yet it offers weak gas barrier properties and may alter the sensory attributes of food when applied in excess. Hence, combining these materials can yield composite films with improved functional and protective properties. After developing the film solution, it is either cast or extruded to obtain the dried film that is characterised for its mechanical, WVTR, OTR, thermal, structural, optical, migration and antimicrobial properties. The coating solution is applied to litchi through dipping, spraying, brushing, *etc.* The coated litchi is then evaluated for its physiochemical, biochemical, microbial and sensory properties. The complete workflow is illustrated in Fig. 4. Furthermore, in Table 2, research conducted over the past five years has been summarized which discusses in detail about the application of various developed edible and intelligent packaging formulations on litchi fruit under both room and refrigerated storage conditions.

### 5.1 Polysaccharide-based edible coatings

Polysaccharides are long chains of monosaccharides and disaccharides as repeating units bonded by the glycosidic linkage. There are various polysaccharides, for example, chitosan, cellulose, pullulan, starch, sodium alginate, pectin, gums, *etc.*, which can be used to coat the litchi fruit and are discussed below. These biopolymers have excellent film forming properties and are abundantly available at affordable rates. They possess superior mechanical and gas barrier properties but

inferior water vapor barrier properties.<sup>141–143</sup> Therefore, they are used in combination as a composite edible packaging material to obtain the desired properties for specific applications.

**5.1.1 Chitosan-based edible coating.** Chitosan is a cationic linear polysaccharide chain of *N*-acetylglucosamine and *D*-glucosamine that is obtained by the partial deacetylation of chitin.<sup>144</sup> Chitin is primarily extracted from crab and prawn shells. Chitosan is soluble in aqueous media with a pH below 6, but insoluble at pH 6.0 to 6.5 because amines in chitosan are deprotonated and lose their charge.<sup>145</sup> It demonstrates broad-spectrum antibacterial activity, antifungal, and antioxidant properties due to which it can be used as a food additive and in edible packaging formulations. In a study, a chitosan edible coating containing citric acid and pomelo extract as additives was dip-coated on lychee fruit and stored initially at 5 °C and 95% RH for 14 days followed by 20 °C and 95% RH for 3 days.<sup>146</sup> The results suggested that 1% chitosan–citric acid and 2% pomelo extract coating reduced pericarp browning, weight loss and fungal decay by 16.5%, 28.0%, and 65.7% compared to the control lychee. This edible coating was successful in maintaining the sugar–acid ratio and increasing the shelf-life of litchi by 2 days.

Recently, Liang *et al.*<sup>147</sup> have developed a composite film of chitosan (CS), fucoidan (FU) and encapsulated cinnamaldehyde (CA). First, chitosan and fucoidan derivatives were developed and then cinnamaldehyde was added. The crude emulsion was degassed in an ultrasonic cleaning bath, then spread on a Petri dish and dried at 45 ± 1 °C for 12 h. The dried coating films were then removed and stored in a dryer at 25 °C and 50% relative humidity for future use. The coating solution was then used for coating litchi fruit and various parameters (weight, texture, colour, vitamin, phenolic content) were determined at room temperature. CA/CS–FU-0.1 coated fruit showed the least microbial growth, least weight loss and maintained the highest firmness (1.36 ± 0.05 N), researchers concluded that the high antimicrobial activity and barrier properties shown by the CA/CS–FU-0.1 film were responsible for these characteristics. Similarly, significantly higher values of vitamin C (29.14 ± 0.50 mg 100 g<sup>-1</sup>) and phenolics (8.38 ± 0.30 g kg<sup>-1</sup>) were reported for CA/CS–FU-0.1 coated litchi till the 8th day, again due to the high antimicrobial and barrier properties of the solution. Therefore, the authors concluded that CA/CS–FU-0.1 coating solution is sufficient to improve the shelf-life of litchi as compared to uncoated references (Fig. 5).

A gluten-based film with montmorillonite (MMT) and starch nanocrystals (SNCs) reinforced into chitosan was formulated by Sharma *et al.*<sup>148</sup> Thereafter, its efficacy analysis was done and finally the same was used as an edible film for shelf-life preservation of litchi up to 20 days. MMT and SNC increase the tensile strength (up to 57 MP) and reduce the water vapour transmission rate (0.68 × 10<sup>-3</sup> g m<sup>-2</sup> h<sup>-1</sup>). However, SNC/chitosan was superior to the MMT/chitosan-based film due to the excellent barrier properties. Coated litchis show superior organoleptic properties as compared to uncoated litchis: (i) lower enzyme activity (PPO/POD), (ii) higher bioactive components (anthocyanins, phenolics and flavonoids), (iii) less alteration in firmness (8.47% and 7.36%) and physiological weight



Table 1 Advantages and limitations of various biopolymers for film and coating formulations

Matrix	Advantages	Limitations	References
Cellulose and its derivatives ( <i>e.g.</i> , hydroxypropyl methylcellulose – HPMC)	<ul style="list-style-type: none"> <li>• Better film-forming properties</li> <li>• High transparency and mechanical strength</li> <li>• Biodegradable, non-toxic and inexpensive</li> </ul>	<ul style="list-style-type: none"> <li>• Poor WVTR properties</li> <li>• Requires plasticizers to improve flexibility</li> </ul>	91–93
Starch	<ul style="list-style-type: none"> <li>• Abundant and cost-effective</li> <li>• Film forming properties and good barrier to O<sub>2</sub> and CO<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>• Poor water resistance</li> <li>• Poor mechanical properties thus requires modification or blending with other materials</li> </ul>	94–96
Chitosan	<ul style="list-style-type: none"> <li>• Antimicrobial/antioxidant properties</li> <li>• Excellent film-forming ability, mechanical strength and gaseous barrier properties</li> </ul>	<ul style="list-style-type: none"> <li>• Solubility issues in water</li> <li>• High permeability to water molecules</li> <li>• At higher concentrations sensory properties get affected</li> </ul>	97 and 98
Pectin	<ul style="list-style-type: none"> <li>• Good film-forming properties</li> <li>• Excellent gelling agent/emulsifier and thickener</li> <li>• Good barrier to O<sub>2</sub> and CO<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>• Less mechanical strength</li> <li>• Poor barrier to water vapour</li> </ul>	99–101
Alginate	<ul style="list-style-type: none"> <li>• Good gel-forming ability, used as a thickening and emulsifying agent</li> <li>• Biodegradable and non-toxic</li> </ul>	<ul style="list-style-type: none"> <li>• Weak mechanical properties</li> <li>• Requires calcium ions for gel formation or crosslinking process</li> </ul>	102 and 103
Pullulan	<ul style="list-style-type: none"> <li>• Excellent film-forming ability and barrier to O<sub>2</sub> and CO<sub>2</sub></li> <li>• High transparency and flexibility</li> </ul>	<ul style="list-style-type: none"> <li>• Weak water vapor barrier properties</li> <li>• High price, low solubility</li> </ul>	104–106
Carrageenan	<ul style="list-style-type: none"> <li>• Good gel-forming and film-forming properties, low cost</li> <li>• Enhances biodegradability and non-toxic</li> <li>• Better mechanical and UV protection properties</li> </ul>	<ul style="list-style-type: none"> <li>• Sensitive to moisture</li> <li>• Requires plasticizers for improved flexibility</li> </ul>	107 and 108
Xanthan gum	<ul style="list-style-type: none"> <li>• Good film-forming ability and inexpensive</li> <li>• High viscosity and stability</li> </ul>	<ul style="list-style-type: none"> <li>• Poor resistance to water</li> <li>• Requires blending with other materials to improve properties</li> </ul>	109
Guar gum	<ul style="list-style-type: none"> <li>• Biodegradable and non-toxic</li> <li>• Good film-forming properties</li> <li>• Biodegradable and non-toxic</li> <li>• Good viscosity and stability</li> </ul>	<ul style="list-style-type: none"> <li>• Highly hydrophilic</li> </ul>	110 and 111
Agar	<ul style="list-style-type: none"> <li>• Excellent gel-forming and film-forming properties</li> <li>• Biodegradable and non-toxic</li> <li>• Transparent and flexible</li> </ul>	<ul style="list-style-type: none"> <li>• Highly brittle</li> <li>• Poor mechanical and barrier properties</li> </ul>	112–114
Dextran	<ul style="list-style-type: none"> <li>• Good film-forming properties</li> <li>• Biodegradable and non-toxic</li> <li>• High water solubility</li> </ul>	<ul style="list-style-type: none"> <li>• Requires blending with other materials to improve properties</li> <li>• Poor mechanical strength</li> </ul>	115 and 116
Beeswax	<ul style="list-style-type: none"> <li>• Superhydrophobic exhibiting good water barrier properties</li> <li>• Biodegradable and derived from renewable sources</li> <li>• Suitable for use in vegan and vegetarian products (GRASS approved)</li> </ul>	<ul style="list-style-type: none"> <li>• Poor mechanical strength</li> <li>• Low melting temperature and gaseous barrier</li> </ul>	117–119
Carnauba wax	<ul style="list-style-type: none"> <li>• High gloss and excellent moisture barrier (highly hydrophobic)</li> <li>• Biodegradable and food-grade (GRASS approved)</li> </ul>	<ul style="list-style-type: none"> <li>• Brittle at room temperature</li> <li>• Difficult to process without emulsifiers</li> </ul>	120–122
Shellac wax	<ul style="list-style-type: none"> <li>• Excellent gloss and moisture barrier</li> <li>• Derived from natural sources</li> <li>• Biodegradable (GRASS approved)</li> </ul>	<ul style="list-style-type: none"> <li>• Brittle and requires plasticizers for flexibility</li> <li>• Limited heat resistance</li> </ul>	123 and 124



Table 1 (Contd.)

Matrix	Advantages	Limitations	References
Rice bran wax	<ul style="list-style-type: none"> <li>• Good barrier properties</li> <li>• Biodegradable and derived from renewable sources</li> <li>• Suitable for use in vegan and vegetarian products (GRASS approved)</li> </ul>	<ul style="list-style-type: none"> <li>• Moderate mechanical strength</li> <li>• Limited availability and higher cost compared to some other waxes</li> </ul>	125 and 126
Gelatin	<ul style="list-style-type: none"> <li>• Good mechanical strength and transparency</li> <li>• Low cost</li> </ul>	<ul style="list-style-type: none"> <li>• Highly hygroscopic</li> <li>• Animal derived, possible concern for vegetarians/vegans</li> </ul>	127–129
Whey protein	<ul style="list-style-type: none"> <li>• Good film-forming properties</li> </ul>	<ul style="list-style-type: none"> <li>• Moderate barrier properties to gases and moisture</li> </ul>	130–132
Soy protein	<ul style="list-style-type: none"> <li>• Flexible film, resistance to oil</li> <li>• Good mechanical properties</li> <li>• Renewable and biodegradable</li> </ul>	<ul style="list-style-type: none"> <li>• Possible allergenicity</li> <li>• Poor moisture barrier properties</li> </ul>	130 and 131
Casein	<ul style="list-style-type: none"> <li>• Excellent film-forming properties</li> <li>• Good mechanical strength and transparency</li> </ul>	<ul style="list-style-type: none"> <li>• Sensitive to moisture</li> <li>• Derived from animal sources</li> </ul>	133–135
Collagen	<ul style="list-style-type: none"> <li>• Good film-forming ability</li> <li>• Biocompatible and biodegradable</li> </ul>	<ul style="list-style-type: none"> <li>• Poor mechanical strength</li> <li>• Requires crosslinking agents</li> </ul>	136 and 137
Corn zein	<ul style="list-style-type: none"> <li>• Excellent water barrier properties</li> <li>• Medium gas barrier, resistance to oil</li> </ul>	<ul style="list-style-type: none"> <li>• Brittle nature</li> <li>• Insoluble in water</li> </ul>	138–140

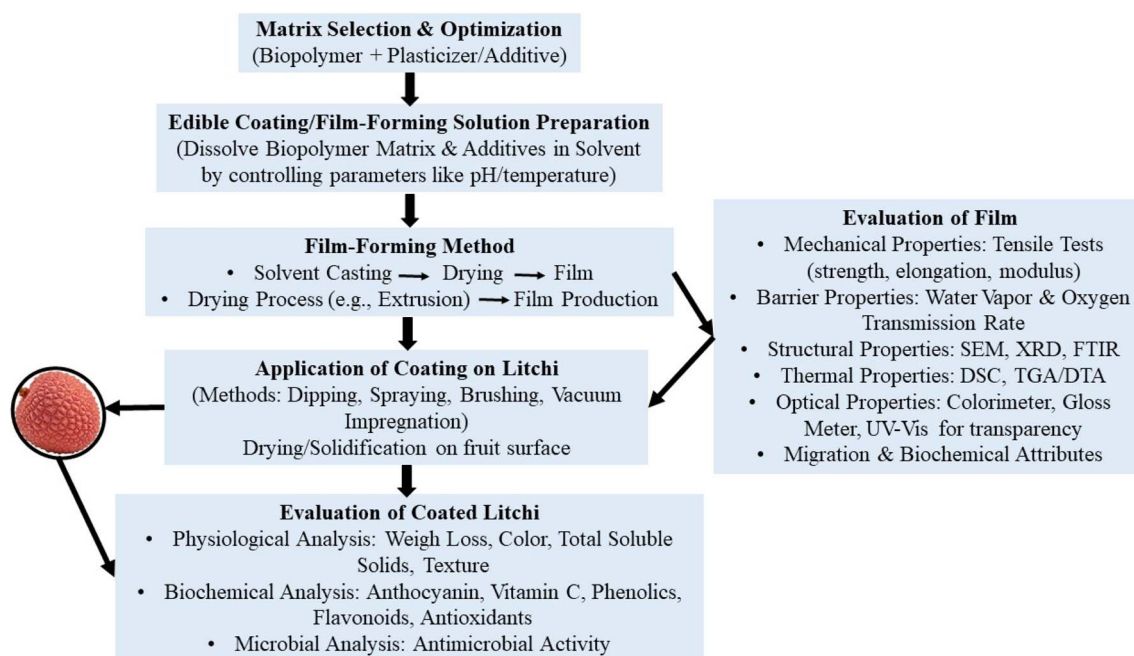


Fig. 4 Development procedure and methodology of edible films and coatings for litchi fruits.

loss (24.04% and 19.86%). In conclusion, the developed packaging can be used as a potential preservation technique for litchi fruit.

**5.1.2 Cellulose-based edible coating.** Cellulose is a widely available polymer which can be derived from plant cell walls. Its major sources are wood, cotton, agricultural residues, industrial waste, food wastes and leftovers, water plants, various grasses, rice and wheat bran, sugarcane bagasse, cereal husks,

corn kernels, cereal bran, multiple sources of bacterial cellulose, and peels from numerous fruits and vegetables.<sup>149</sup> Cellulose and its derivatives such as cellulose acetate, cellulose sulfate, cellulose nitrate, carboxymethyl cellulose, ethyl cellulose, methyl cellulose and nanocellulose can be used for food packaging due to their excellent physical and mechanical properties. Cellulose is a low cost, edible and biodegradable polymer which possess good sensory and organoleptic



Table 2 Application of edible and intelligent packaging on litchi

Edible packaging formulation	Method of application	Storage conditions	Outcome	Reference
Trehalose	Dipping	25 °C with 85 ± 5% RH for 8 days	Trehalose treatment effectively delayed browning in litchi, as evidenced by a ~15.1% higher chromaticity value on the 8th day compared to the control. It also promoted anthocyanin biosynthesis and inhibited the activities of PPO and POD	164
Glutamic acid (Glu), methionine (Met)	Dipping	25 ± 1 °C	Glu, Met and Mix (the combination of Glu and Met notably delayed pericarp browning and pulp degradation). Mix treatment increased sucrose degradation, slowed sugar oximation & cell wall breakdown	165
Cellulose, Fe-doped ZIF-8, epigallocatechin gallate	Wrapped in film	25 °C & 60–70% RH	Storage life was prolonged to 9 days with concurrent inhibition of browning reactions and mildew formation. Mass loss was curtailed by ~40%, while bioactive compounds including anthocyanins, ascorbic acid, phenolic components, and flavonoids showed enhanced stability	166
Chitosan, vanillin-based deep eutectic solvents	Dipping	Ambient conditions (25 ± 2 °C; RH 80–90%)	Shelf life was extended to 5 days. Browning and weight loss were minimized. Vitamin C & anthocyanin contents were maintained over the storage period. Antibacterial activities of the developed formulation effectively inhibited <i>E. coli</i> and <i>S. aureus</i> activity	167
Peach gum	Dipping	25 ± 1 °C with 80–85% RH for 8 days	The optimized solution reduces the browning rate, retards anthocyanin degradation, maintains weight loss, TSS and other organoleptic properties	168
Liposome, chitosan	Dipping	20 °C, 75% RH up to 9 days	Coating enhanced appearance quality (browning index ↓ ~40%), nutritional retention, moisture retention, membrane integrity, antioxidant activity, enzymatic control, disease resistance	169
Chitosan, aloe vera gel and combination with UV radiation	Dipping	Refrigerated condition storage (2 °C for 20 days)	Reduced browning, preserving phenolic compounds, flavonoids, anthocyanins, antioxidant activity, lowering physiological and biochemical degradation during refrigerated storage	170
Starch, gum, citrus peel extract		Room temperature for a 6 day storage study	Effectively reduced weight loss, microbial load, and colour degradation in litchi during 6 days of storage. The optimized formulation (starch-to-gum ratio 1 : 1, 0.4% peel extract, particle size 300 μ) preserved quality attributes more effectively than the control	171
Sodium alginate, calcium chloride, cellulose nanocrystals, nisin	Dipping	25.1 ± 1.2 °C, 30.0 ± 2.1 RH% for 11 days	Shelf life extended by 2.6 times; browning index reduced by 38.1% and decay rate by 62.5%; moisture loss minimized; firmness, pH, and quality attributes maintained	172
Chitosan, oxidized fucoidan, cinnamaldehyde	Dipping	Room temperature for 8 days	Shelf life increased to 8 days. Total phenolics content was ~72.5% higher than control; vitamin C was ~59% higher. TA, TSS, weight loss & hardness were maintained	173
Starch, selenium nanoparticles	Wrapped in edible film	25 °C, 50% RH for 15 days	The developed film showed enhanced properties in terms of UV barrier, mechanical strength, antioxidant and antimicrobial properties. Improved biodegradability (~11 days in soil) and biocompatibility was reported. The developed formulation reduces the moisture loss and decay incidence & enhances the shelf life till 15 days	174
Cellulose, methylcellulose, acacia gum		27 ± 3 °C, 82 ± 5% RH for 7 days	Optimized formulation retained TSS (~65%), TA (~42%), ascorbic acid (~24%) & phenolic acids (~40%) in treated litchi juice as compared to uncoated ones. Physiological weight loss and decay of fruits were also significantly maintained	175
Alginate oligosaccharides	Spraying	5 °C with 85% RH for 21 days	Reduced weight loss (~12%), better texture & color attributes and lower rate of decay incidence (~15%) in fruit were observed as compared to the control group	176



Table 2 (Contd.)

Edible packaging formulation	Method of application	Storage conditions	Outcome	Reference
Gluten, starch nanocrystal, montmorillonite	Edible film packaging	4 °C for 20 days	The developed biocomposite demonstrated higher tensile strength (~57 MPa) & lower WVTR characteristics. Treatment with the optimized formulation reduced the action of browning causing phenol PPO & POD. Similarly, coating treatment maintained weight loss (~7.36%), surface hardness (~19.86 N) & retained a higher level of anthocyanin and ascorbic acid	64
Egg albumin, chitosan, carbon dots	Dipping	~25 °C and ~85 RH for 6 days	The film displayed super antimicrobial, antioxidant and light hindrance quality. The developed formulation displayed constant values of vitamin C, color chromaticity & other organoleptic characteristics	156
Fisetin silver nanoparticles (AgNPs)	Dipping	~25 °C and 36% RH	The film showed greater tensile strength (~61 MPa) and lower WVP (~20 kg per m <sup>2</sup> per day). The developed coating displayed reduce rate of fruit decay & enhanced overall organoleptic properties	163
Zein, chitosan curcumin, zeolitic imidazolate framework-8	Edible film packaging	~25 °C and ~70% RH for 8 days	The developed film demonstrated enhanced tensile strength and OTR (~9.2 and 1.5-fold fruit). Freshness and overall appearance were maintained till day 8 as compared to control litchi	177
Vanillin-taurine antioxidant compound	Dipping	~25 °C and ~90% RH	Reduced level of PPO and POD enzyme & enhanced level of SOD during storage was reported. The coated fruit displayed lower weight & textural loss compared to the control. Similarly, browning was significantly reduced in the coated fruit	178
Silver nanoparticles	Dipping	Room temperature for 5 days and at 4 °C for 25 days	Minimum browning index, least decay, and least weight & firmness loss were observed	179
Chitosan, hydroxyethyl cellulose, mulberry anthocyanins, titanium dioxide nanoparticles	Edible film as sealing material	~25 °C and 4 °C	Reduced weight loss, texture degradation and browning index in coated litchi were observed. Coating retained physiological and organoleptic attributes for longer storage length	180
Silk sericin (SS), chitosan, carbon dots	Soaking	25 °C and 85% RH for 6 days	The developed biocomposite demonstrated enhanced properties such as antioxidant activity, overall flexibility and antimicrobial action. Treated fruits showed reduced water loss, firmness, TSS, TA and anthocyanins during the storage period	72
Zinc oxide nanoparticles (ZnO-NPs)	Spraying	25 ± 2 °C. After 7 days	Maximum mycelial growth inhibition (~70%) was observed for litchi fruit coated with 1 mg per ml ZnO-NPs	181
Aloe vera chitosan, corn starch, calcium chloride, salicylic acid	Dipping	Room temperature (non-refrigerated storage)	Optimized formulation reduced the weight loss & fruit hardness till day 8. The fruit cracking, skin browning, and fruit decay were reduced. Overall organoleptic attributes were maintained during the storage period	182
Calcium chloride, oxalic acid, ice treatment	Dipping	Ambient temperature	Delayed disease incidence, extended shelf life, reduced physiological weight loss, maintained firmness, lowered pericarp browning index, regulated TSS and titratable acidity, preserved vitamin C content, and stabilized pH in postharvest litchi fruit	183
Chitosan, pullulan, pomegranate peel extract	Dipping	~25 °C and RH ~ 45% and cold storage (~4 °C and RH ~ 95%)	Lower weight loss after 18 days, regulated TSS and TA, maintained pH, higher phenolics and flavonoids, and antioxidant activity, improved sensory qualities (notably on day 9 under both storage conditions)	2

properties, supplement food nutritional content and reduce the volume of the packaging material. It also has high thermal resistance, is a good carrier of antioxidants and antibacterial agents, and can act as a barrier for gases, moisture and UV.<sup>150</sup> However, it has several disadvantages, such as significant water absorption and poor interfacial adhesion which can be

improved by incorporating it with various other biopolymers. Applications of cellulose based edible packaging are discussed below along with the effect on litchi fruit.

Litchi fruit was immersed in carboxymethyl cellulose (CMC) biopolymeric solution and stored under ambient conditions, *i.e.*, 27 °C and 82% RH for 7 days in order to extend the shelf



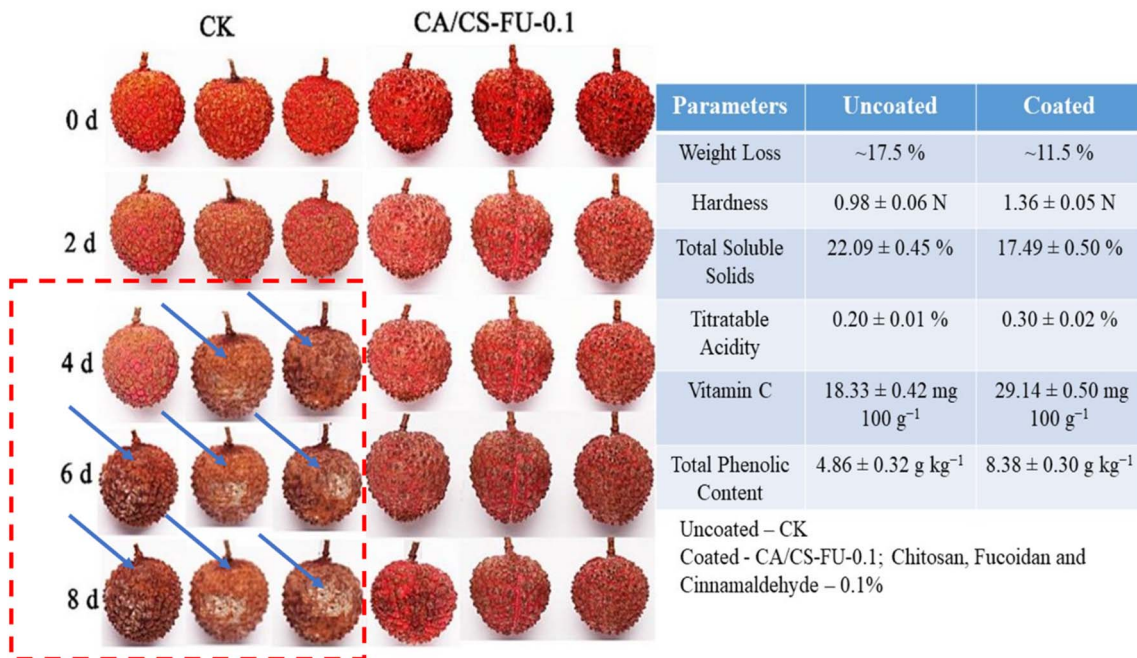
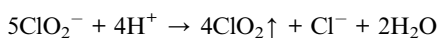


Fig. 5 Chitosan–fucoidan encapsulated cinnamaldehyde composite coating on litchi fruits and its quality parameter comparison with control ones; reproduced with permission from Liang *et al.* (2024),<sup>147</sup> Elsevier.

life.<sup>151</sup> CMC coating had a significant effect on coated litchi. CMC retained total soluble solids (~65%), and had higher titrateable acidity (~42%), ascorbic acid content (~24%), and total phenolic content (~40%) than the control fruit samples. Furthermore, enzymatic activity such as polyphenol oxidase (~25%) and peroxidase (~28%) activities were reduced. Weight loss, pericarp browning and decay incidence were lowered down in the case of treated litchi fruits as compared to uncoated ones.

Liu *et al.*<sup>152</sup> have made a novel film having a regulated release of chlorine dioxide gas on the litchi fruit surface. The idea behind the work was that a regulated amount of chlorine dioxide can control the respiration and transpiration rate as well as destroy the bacteria and fungi on the surface. Here NaClO<sub>2</sub> was encapsulated in EC (ethyl cellulose) as the shell and was finally placed in PVA (poly vinyl alcohol). Thereafter, a small amount of citric acid was introduced, which results in a regulated release of ClO<sub>2</sub> gas.



The mechanical strength (58.66 MPa and gas barrier (36.1% H<sub>2</sub>O & 32.3% O<sub>2</sub> migration rate reduction) characteristics of the films were highly appropriate for the manufacturing of litchi storage pouches at a microcapsule content of 6.0% (w/w). Additionally, the storage bags exhibited the highest ClO<sub>2</sub> concentration of 263.22 ± 12.34 mg m<sup>-3</sup>, effectively eradicating pathogenic bacteria (*E. coli* and *L. monocytogenes*) and impeding the development of *B. cinerea*. The authors reported that this optimized film enhanced the shelf life of litchi fruit, thus the proposed PVA/EC–NaClO<sub>2</sub> active package films have the potential to enhance the shelf life of litchi fruit.

**5.1.3 Pullulan-based edible coating.** Pullulan, (C<sub>6</sub>H<sub>10</sub>O<sub>5</sub>)<sub>n</sub>, is a water-soluble exopolysaccharide produced from the black yeast-like fungus *Aureobasidium pullulans*. The monomeric unit of pullulan contains linear and unbranched maltotriose having α-(1 → 6)-linked (1 → 4)-α-D-triglucosides.<sup>104</sup> Pullulan depicted low transparency, low viscosity, gas and lipid barrier properties, edibility, biodegradability, heat sealability, non-toxicity, and colourless, tasteless and odourless characteristics. It has varying mechanical strengths based on the molecular weight. However, there are several drawbacks associated such as hydrophilicity, brittleness, high cost and no active functions. It can be used as a prebiotic, starch replacement, maltotriose syrup *etc.* in food products. Also, it can be used as a biopolymer in food packaging application to enhance the shelf-life of fruits and vegetables.

A chitosan and pullulan edible coating enriched with pomegranate peel extract were dip-coated on litchi fruit.<sup>2</sup> The treated fruits were stored for 18 days at room temperature, *i.e.*, 23 °C and 40–45% RH and refrigerated temperature, *i.e.*, 4 °C and 90–95% RH. The results suggested that 50:50 chitosan:pullulan added with 5% extract of pomegranate peel decreased physiological weight loss, total soluble solids, acidity and browning. The weight loss was reduced to 44.5% and 55.7% at room temperature whereas 10.4% and 12.6% under refrigerated conditions for treated and control litchi on the 18th day, respectively. Edible coated litchi showed lesser increase in total soluble solids and titrateable acidity. Additionally, the pH, phenolic and flavonoid contents, and antioxidant activity were reduced to a lower extent in the coated fruits.

**5.1.4 Gum-based edible coating.** Gums are high molecular weight polysaccharides which are made up of glucmannans or galactomannans and having β-D-mannose and α-D-glucose or α-



D-galactose joined by linked  $\beta$ -1  $\rightarrow$  4 bonds as linear repeating units. Gums can be divided into four categories: (i) plant exudate-based gums which include cassia gum, tragacanth gum, karaya gum and arabic gum, (ii) seed-based for example guar gum, basil seed gum and locust bean gum, (iii) microbial-based such as xanthan gum, gellan gum and tara gum, and (iv) seaweed-based gums like carrageenan gum.<sup>153</sup> They have good water retention, gelling ability, high viscosity and film-forming properties whereas poor barrier, mechanical, and thermal characteristics. They can be used as biopolymers in edible films and coatings as well as thickeners and emulsifiers in the food additive industry.

Bham *et al.*<sup>154</sup> applied guar gum, xanthan gum and methyl cellulose (low and high viscosity) at various concentrations on litchi as an edible coating for enhancing the quality and shelf life. The treated fruits were studied for 12 days under refrigerated conditions (4 °C and 90% RH). 1.5% guar gum coated fruits which were stored in a perforated brown paper bag showed minimum weight loss and fruit shrinkage%, pericarp browning and highest overall sensory attributes.

## 5.2 Protein-based edible coatings

Proteins are made up of 20 amino acids linked by peptide bonds. Proteins such as collagen, keratin, gelatin, zein, casein, gluten, soy protein, egg protein and whey protein are employed on litchi for its storage and preservation. Proteins have good mechanical, optical and gas barrier properties, however they have poor water vapor permeability.<sup>155</sup> In the context of litchi, proteins can be used with other biopolymers including polysaccharides and lipids to compensate their weaknesses and obtain the film of required properties.

An edible coating formulated with silk-sericin, chitosan and carbon dots was applied on litchi by the immersion method and thereafter fruits were stored at 25 °C and 85% RH for 6 days.<sup>72</sup> The study reported that edible coatings decreased the browning of litchi peel, weight loss, change in total soluble solids and titratable acidity, and malondialdehyde content while maintaining a higher value of antioxidant and vitamin C content as compared to the control litchi fruit.

Su *et al.*<sup>156</sup> investigated the effect of an egg albumin, chitosan, and carbon dot based edible coating in the volume ratio of 5 : 5 : 1 on litchi fruits which were stored at 25 °C and 85–90% RH for 6 days. Coated litchi showed lower pericarp browning, weight loss% and reducing sugar whereas higher chromaticity  $a^*$ ,  $b^*$ , and  $L^*$ , vitamin C, total sugar, and sucrose content were retained (Fig. 6).

## 5.3 Lipid-based edible coatings

Lipids include phospholipids, mono-, di- and tri-glycerides, phosphatide, terpenes, cerebrosides, natural wax, fatty acids, fatty alcohol, and surfactants.<sup>155</sup> They are used in edible packaging because they provide surface gloss and water vapor barrier properties. However, they offer poor mechanical and optical properties. They are fragile, non-cohesive, and greasy, with a waxy taste and texture. These can be balanced by using

other biomaterials in combination with lipids for film formation on litchi and other agro-commodities.

A research study depicted the effect of a 9% carnauba wax nanoemulsion (CWN) edible coating on post harvested lychee fruits which were stored at 16 °C and 70% RH.<sup>157</sup> This edible coating significantly reduced the weight loss by 4% and pericarp browning and maintained total soluble solids and pH compared to control fruits after 96 h of storage. When 9% CWN was supplemented with 1% *Mentha piperita* essential oil, the weight loss was 10.6% after 168 h while it was 18.2% for the control. The coating effectively maintained the pH, TSS, TA, firmness and color of coated litchi fruits. The incidence of disease was 20% and 60% for treated and untreated fruits.

Another study conducted by Nanglia *et al.*<sup>52</sup> analysed the effect of hydrochloric acid and shellac wax edible coating on litchi under low temperature storage (2–3 °C and 90–95% RH) for a duration of 14 days. The edible coated fruits showed lesser weight loss, browning index value and decay incidences while maintaining higher firmness and bioactive value. The coated fruits showed retarded activities of enzymes such as polyphenol oxidases, peroxidase, and phenylalanine ammonia lyase as compared to uncoated fruits.

## 5.4 Additive-based edible films and coatings

Edible packaging is fortified with additives such as antioxidants, antimicrobials, essential oils, preservatives, and browning inhibitors to maintain food quality. Plasticizers, emulsifiers, and cross-linking agents enhance structural and barrier properties. Bioactive ingredients like probiotics, plant extracts, nutrients, and nutraceuticals further improve functionality and health benefits.<sup>155</sup> These are added in permissible limits to enhance physical, chemical and functional properties of coatings or films and further, slow down deteriorative changes in food. For instance, plant oils enhance food quality and safety by providing water vapor, oxygen and UV barrier, antioxidant and antimicrobial properties in packaging.<sup>158</sup>

One such research showed that when litchi fruit was given an edible coating with 50% aloe vera gel, an active additive, and stored at 20 °C and 90% RH for 8 days, the browning was significantly delayed.<sup>159</sup> The weight loss, superoxide anion, relative electrolyte leakage, hydrogen peroxide and malondialdehyde content were also reduced as compared to untreated fruits. The enzyme activities such as peroxidase and polyphenol oxidase were decreased. Treated samples showed a higher total anthocyanin content, ascorbic acid content, total phenolic concentration, total soluble solids, titratable acidity and enzyme activities such as catalase, superoxide dismutase and ascorbate peroxidase activities.

Li *et al.*<sup>160</sup> developed an edible coating solution utilizing *Lysimachia foenum-graecum* Hance based oil, eggplant pill anthocyanin, and *Ginkgo biloba* leaf extract and utilized them for coating litchi fruit. After coating the fruit, they were stored for a period of 12 days at 25 °C. The superior preservation effect on litchi is evident with the utilization of 0.5% essential oil extract treatment, ranking above both 0.5% *Ginkgo biloba* extract and 0.05% potassium sorbate treatment. The latter



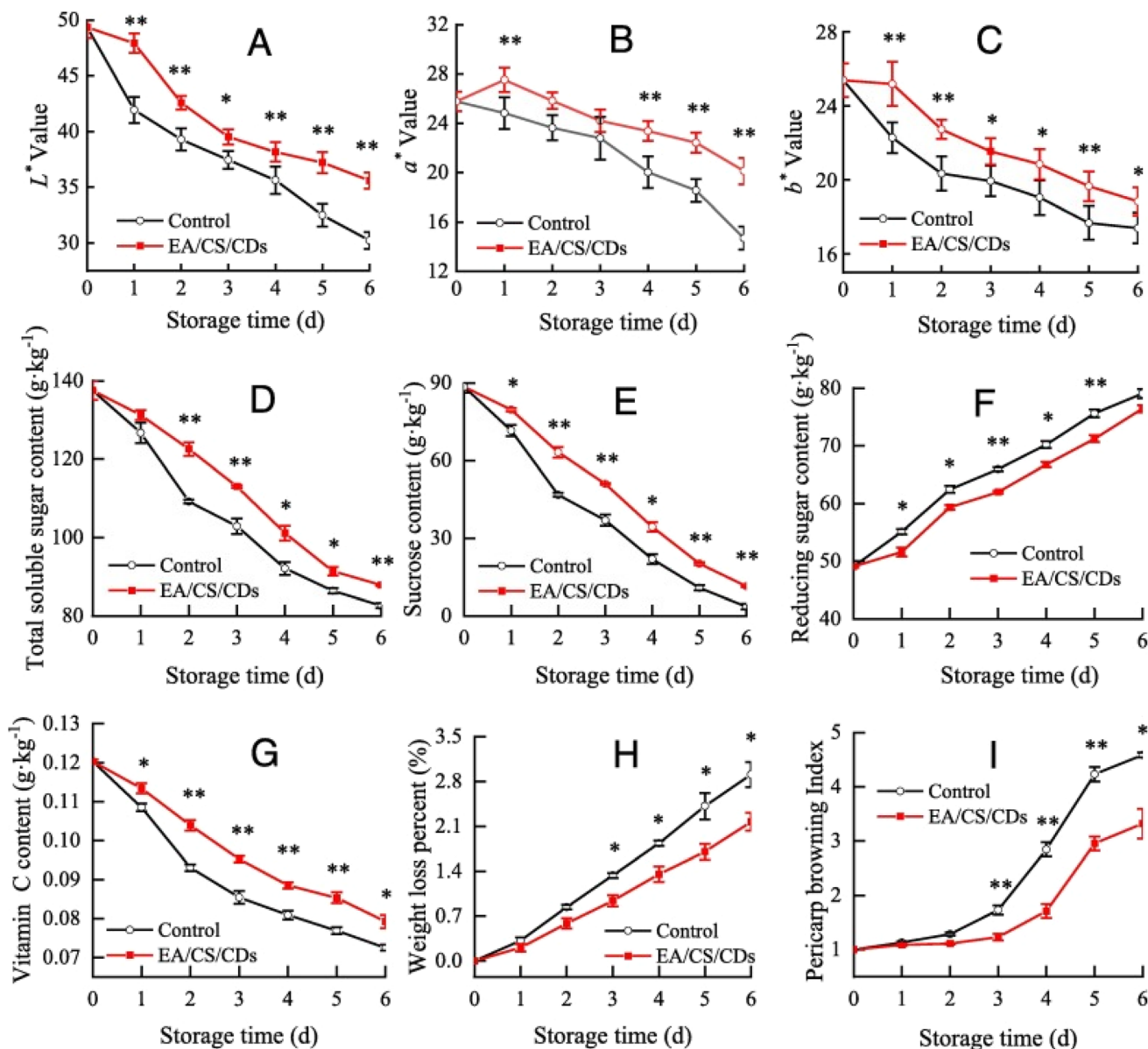


Fig. 6 Quality parameters of litchi fruit coated with the egg albumin, chitosan, and carbon dots and its comparison with the control including pericarp color attributes:  $L^*$  value (A),  $a^*$  value (B), and  $b^*$  value (C); pulp total soluble sugar content (D); sucrose content (E); reducing sugar content (F); vitamin C content (G); fruit weight loss percentage (H); and pericarp browning index (I); reproduced with permission from Su *et al.* (2023).<sup>156</sup> Elsevier.

treatments exhibit comparable effects that surpass the efficacy of 0.5% anthocyanin extract. The findings illustrated that the three types of botanical extracts exhibited a deceleration in water evaporation, suppression of enzymatic browning, mitigation of decay progression in litchi fruit to a certain degree, and exerted a specific influence on the retention of quality and vitality.

### 5.5 Nanoparticles in edible coatings

Nanomaterials are nanoscale structures that have at least one dimension in the range of 1 to 100 nm. They can be categorised as organic and inorganic. Micelles, dendrimers, liposomes, nanogels, polymeric nanoparticles, and layered biopolymers are

some examples of organic nanomaterials. Inorganic nanomaterials do not contain carbon and can be divided into metal nanoparticles (gold, silver, iron, copper, aluminium, *etc.*), metal-oxide nanoparticles (zinc oxide, titanium dioxide, iron oxide, *etc.*), ceramic nanoparticles (hydroxyapatite, alumina, silica, *etc.*), bionanomaterials (exosomes, magnetosomes, lipoproteins, viruses and ferritin) and carbon-based nanomaterials (quantum dots, graphene, carbon black, carbon nanotubes and nanofibers).<sup>161</sup> Due to their morphology and high surface area to volume distribution ratio, they provide improved physico-chemical attributes. They exhibit antibacterial and antioxidant properties and are therefore employed for food packaging applications in permitted doses and pretested conditions.



A research study was conducted in which quaternary ammonium salted chitin, epigallocatechin gallate, selenium nanoparticles, carboxymethyl cellulose and corn starch were used for formulating an edible film in order to preserve litchi stored at 25 °C and 50% RH for 15 days.<sup>162</sup> The weight loss%, decay rate%, and texture deterioration were minimum whereas soluble solid content, pH, and titratable acids were better maintained in the edible film wrapped litchi over a period of 15 days as compared to control fruits.

Using a similar approach fisetin chelated silver nanoparticles (FT-AgNPs) with a chitosan/pullulan (CS/PUL) matrix was formulated.<sup>163</sup> It was observed that the formulated novel film displayed great tensile strength (61.2 MPa) and lower WVP (below 20 kg per m<sup>2</sup> per day). The decay of litchi fruit was effectively inhibited by the 0.6% FT-AgNPs/CP treatment during storage at 25 °C, resulting in 15 days storage compared to 9 days for the control group. Furthermore, the presence of 0.024 µg kg<sup>-1</sup> of residual Ag<sup>+</sup> in litchi pulp confirmed the safety of utilizing the 0.6% FT-AgNPs/CP treatment.

## 6. Formation of edible and intelligent films and coatings

Different techniques exist for applying films and coating materials to litchi fruits and different horticulture produce on a small scale in the laboratory. These include dipping, brushing, extrusion, spraying, and solvent casting. However, transitioning to large-scale industrial production may require new processing equipment that can integrate well with existing packaging machinery. Common methods for forming films typically involve either casting solutions (wet method) or processing melted materials (dry method). The dry method includes processes like extrusion, injection molding, and thermoforming. This section briefly discusses potential edible film and coating development technology for litchi fruits with their advantages and limitations.

### 6.1 Edible coating development technology

**6.1.1 Dipping/immersion coating.** Dipping is a widely practiced lab scale coating methodology due to its cost-effectiveness and straightforward nature on litchi fruits.<sup>9,184</sup> This process involves immersing a food sample into a dispersion to form the coating. The litchi fruit is dipped in the coating solution at a steady pace to ensure sufficient solution for wetting and interaction.<sup>185</sup> Thin layers of precursor emulsion are developed on food surfaces through deposition. Excess liquid is drained off during the deposition process. The utilization of the dipping technique proves advantageous in enabling the food item to achieve full coverage of its surface.<sup>186</sup> This method plays a crucial role in guaranteeing consistent coverage across irregular and intricate shapes found on the surfaces of food items. However, several concerns are raised by the dipping procedure, such as the potential for coating dilution, accumulation of waste or dirt, and the proliferation of microorganisms within the dipping vat.

**6.1.2 Spray coating.** Spray coating is another feasible technique for applying a protective layer to litchi fruits. The methodology involves applying a thin layer of the product across its entire surface using a coating solution that is less viscous and is applied under a pressure of ~60–80 psi. When employing the conventional spray technique, a fine mist is generated with droplets that have a size of 20 µm.<sup>187</sup> This method presents several key benefits including consistent coating, precise thickness management, and the ability to apply multiple layers, for instance, a chitosan based multilayer coating including SiO<sub>2</sub> and polyacrylate on a cotton surface was developed.<sup>188</sup> The effectiveness of spray coating relies on the rheological characteristics of the fluid, such as surface temperature, viscosity, and temperature. So, a coating mixture with the right fluid consistency is prepared and sprayed through a nozzle. After spraying, the coated sample needs some time to dry properly. During this drying stage, factors like the method used for drying, the duration, and the temperature play a crucial role in determining how well the coating adheres and performs.<sup>20</sup> Using spraying as the coating methodology, an oligo-chitosan based edible coating was developed which was further treated with irradiation (~40 kGy) to extend the shelf life of litchi fruits.<sup>189</sup>

**6.1.3 Electro spraying.** Recently, electro-spraying based edible coating has been gaining popularity for developing edible films and coatings on fruits and vegetables. Electrostatic coating, which originated in the paint industry, is a promising and effective method for coating food items. Its main advantages include reducing solvent use and waste production due to its high transfer efficiency. Additionally, it provides even and consistent coatings on the intended surfaces.<sup>190</sup> Hence electro-spraying can be a novel potential coating methodology for litchi fruit effectively. Using a similar approach water in oil-based (rice bran oil, water, and eugenol) emulsion coating was developed for strawberry fruit and was compared to the conventional dip coating methodology. The authors concluded that as compared to uncoated and dip-coated strawberry, this approach maintains the weight loss, texture, and other parameters significantly high.<sup>191</sup>

**6.1.4 Other methodologies.** Additionally, panning and fluidized bed are other coating techniques for coating horticulture produce. In the process of fluidized-bed coating, particles undergo fluidization due to a vertical airflow facilitated by a distributor plate situated at the system's base. The coating substance, typically a polymer solution or emulsion, is applied onto the fluidized particles using nozzles. The main objective of this procedure is to attain uniform distribution of droplets on an individual particle and across the entire particle population.<sup>192</sup> Fluidized bed coating is suitable for low density particles and hence it is not used for coating litchi fruit. Similarly, panning is also not a practical approach for coating fragile litchi as this process involves intense tumbling of the fruits.<sup>193</sup>

### 6.2 Edible film developing technology

**6.2.1 Solvent casting.** The casting technique is a prevalent and cost-effective method for film preparation, typically



favoured in laboratory settings. This procedure can be segmented into three distinct phases. Firstly, it involves solubilization, where the biopolymer substance is dissolved in a compatible solvent. Since it is edible in nature the solvent and other components must be nontoxic in nature. Secondly, the prepared solution is poured into the mold for solvent evaporation and drying. Thirdly, but most importantly, the edible film is removed from the surface while preserving the structural integrity of the underlying formation. Recently, solvent casting technology has been reported by different scholars for development of films for litchi preservation based on starch nanocomposites,<sup>194</sup> chitosan pullulan composite film<sup>163</sup> and silk-sericin.<sup>72</sup> The primary constraint of this method arises during the peeling phase of production, where issues like wrinkling and tearing may occur. Therefore, the moisture content of the edible film should be within the range of 5 to 8%. It is essential that the film peels off smoothly from the base during peeling to avoid wrinkling and tearing effects.<sup>80</sup> Qi *et al.*<sup>163</sup> showed that chitosan/pullulan incorporating fisetin AgNPs developed by solvent casting exhibited excellent antioxidant and antimicrobial properties (tensile strength  $\sim 61.2$  MPa). Additionally, this film possesses a significant barrier (WVTR below  $\sim 20$  kg per m per day), thermal and mechanical properties (tensile strength 61.2 MPa), which make this film a superior candidate for shelf-life enhancement of litchi fruit.

**6.2.2 Extrusion.** Extrusion is a more practical option for industrial scale film production, as it requires less solvent (dry process) and fewer evaporation stages (drying steps).<sup>187</sup> This technique depends on the glass transition, phase transition, and gelatinization capabilities of biopolymers in addition to their thermoplasticity. The extrusion procedure can be subdivided into three stages including (1) mixing and feeding of the film component, (2) increase in temperature and pressure to achieve further compression, (3) final heating in the last section of the extruder resulting in high temperature, high pressure and large shear rate.<sup>195</sup> Although these techniques are used in producing synthetic polymer films on an industrial scale, some optimization and standardization of extrusion process parameters (barrel temperature, screw speed, moisture content others) may be required for edible film formation.

## 7. Safety and regulatory aspects of intelligent and edible films and coatings for litchi fruits

Edible films and coatings for litchi fruit are developed with different components like polysaccharides, lipids, fats independently or in combination with a plasticizer, surfactant and different bioactive components. Since edible films and coatings are applied directly onto the fruit surface (edible portion) of the produce, developing edible films and coatings for litchi involves meeting rigorous safety and regulatory standards to ensure they are safe for consumption and do not negatively impact the fruit's quality. The safety aspect mainly includes toxicological safety, microbial safety and chemical safety.<sup>196</sup>

### 7.1 Toxicological safety

Components of edible films and coatings must be examined and tested for toxicity. Ingredients should have a "Generally Recognized as Safe" (GRAS) status from the U.S. Food and Drug Administration (FDA) or an equivalent designation from other regulatory authorities. This involves thorough testing for acute and chronic toxicity, potential carcinogenic effects, and allergenicity.

### 7.2 Microbial and chemical safety

The edible films and coatings must not promote the growth of pathogenic microorganisms and should be free from toxic chemical residue. Therefore, compliance with microbial limits set by food safety authorities and residue limits for pesticides, heavy metals, and other contaminants as per *Codex Alimentarius* or regional regulations is essential. In this context, use of natural and food-grade materials, natural antioxidants and antimicrobial agents could be effective.<sup>197</sup>

One of the major components of the regulatory aspect is labelling and consumer information. Different types of coating materials applied in the development of edible coatings have the potential to induce allergic responses in certain consumers. The utilization of corn zein, soybean protein, fish components, and collagen in the formulation of edible coatings is associated with the occurrence of allergic reactions.<sup>198</sup> Similarly, natural bioactive compounds are safe to use for active properties and are approved by FDA and EU but may act as allergens in higher doses.<sup>199</sup>

Therefore, labels should include information about the coating materials, potential allergens, and any additives used. In this regard the manufacturer must follow labelling regulations such as those outlined in the FDA's Food Labeling<sup>200</sup> or EU Regulation No 1169/2011.<sup>201</sup> Another critical parameter is quality control and assurance, which requires implementing systems such as good manufacturing practices (GMP) and Hazard Analysis and Critical Control Points (HACCP). Regular monitoring and testing are required following the GMP guidelines and HACCP principles from controlling bodies like FDA, EFSA, and *Codex Alimentarius*.

## 8. Conclusions and future perspectives

Litchi is a highly perishable food commodity which becomes more susceptible to contamination after harvesting. Quantitatively, up to  $\approx 45\%$  postharvest loss is reported. The major quality deterioration includes rapid pericarp browning, fungal attack and textural loss. The major postharvest treatment used conventionally is sulfur fumigation mainly targeting the browning problem. However, the associated health related concerns limit its applicability. Therefore, in this context edible films and coatings as novel technology and its recent applications have been discussed along with the postharvest problem of litchi, conventional treatment for its preservation, properties of edible films and coatings and their manufacturing technology. At the end of the review, safety and regulatory aspects of



films and coatings are discussed. Edible films and coatings having good antioxidant, antimicrobial and barrier properties are particularly appropriate for litchi fruit controlling the browning and microbial growth. Various developed formulations have enhanced the shelf life of litchi fruit significantly under room temperature storage. Therefore, it could be a sustainable method for litchi preservation specifically targeting the farmers of this fruit. The overall discussion will be beneficial to researchers for the formulation, optimization and application of novel films and coatings for litchi fruit.

A wide volume of research has been performed on the development of intelligent and edible film and coating formulation and shelf life study of litchi fruit. But, potentially none of them have been commercialized yet. Therefore, more targeted research is required in this area for further optimization and application.

(I) Cost-benefit analysis study of the developed films and coatings is very limited; thus, more research is required in this area. In particular, machinery, material cost, manpower, infrastructure cost, *etc.*, should be considered.

(II) Integration of advance processing technology should be done during the formulation of edible films and coatings. In this context, nanotechnology in edible films and coatings is a novel and effective strategy to enhance the active properties but very few studies are done for litchi fruit. Thus, investigation in this direction needs to be done more.

(III) Scalability studies under real environment conditions for commercial viability are required to be explored for food processors to meet the market standard and consumer acceptability.

(IV) The toxicology, biocompatibility, digestibility and possible allergenic reactions need to be investigated in detail for meeting food regulatory standards delivering safer and high-quality products to consumers.

In conclusion, optimized intelligent & edible films and coatings could be a promising technology for preservation of postharvest litchi fruits which is a safer, low cost, durable, and environment-friendly alternative.

## Author contributions

Sonu Kumar: writing – review & editing, writing – original draft, visualization, investigation, formal analysis, conceptualization. Shikha Sharma: writing – review & editing, writing – original draft, visualization, investigation, formal analysis, conceptualization. Vimal Katiyar: validation, supervision, conceptualization, project administration.

## Conflicts of 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.

## Data availability

All data and information discussed in this review are drawn from the published literature and are fully presented within the

manuscript with suitable references. No additional datasets were generated in the preparation of this work.

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