



OSA starch-based edible coatings for shelf-life extension of ber (*Ziziphus mauritiana* lamk.)

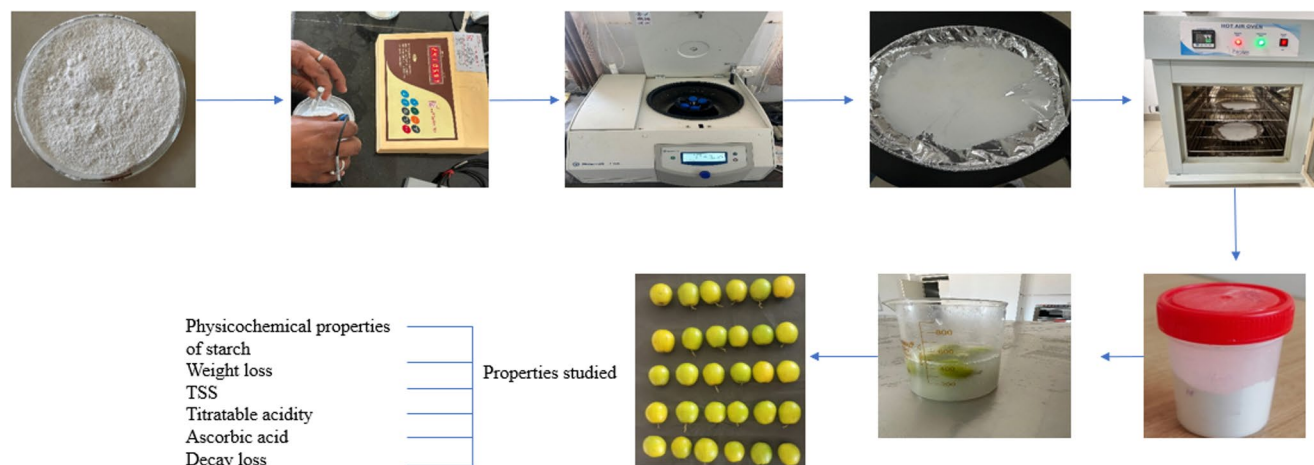
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Abstract

This study investigates the application of octenyl succinic anhydride (OSA) modified starch as an edible coating to enhance the shelf life and maintain the quality of ber fruit (*Ziziphus mauritiana* Lamk.) cv. Umran during storage. Starch was extracted from pearl millet and chemically modified with OSA under different pH conditions (4, 6, & 8) to develop coating formulations. Ber fruits were coated, and both coated and uncoated fruits (control) were stored at low temperature (10 °C) for 14 days, and changes in physiological and biochemical parameters were monitored. The results showed that OSA-starch coatings (T5) retained more total soluble solids (17.88°B), ascorbic acid (63.5 mg/100 g), and titratable acidity (0.248%) at 14 days after storage compared to the uncoated control (T1) (19.50%, 17.16 °B, 46.4 mg/100 g, and 0.229%, respectively). Among the OSA starches prepared at different pH levels, the coating prepared at pH 8 (T5) was the most effective, showing the lowest weight loss (15.18%) and decay loss (2.40%) after 14 days of storage, while preserving higher levels of soluble solids and ascorbic acid than those at other pH levels. These findings highlight OSA-starch as a safe, edible, biodegradable, and cost-effective coating that can enhance the post-harvest shelf life of ber fruits, keep them fresh for a longer period, reduce losses, and add value in the fruit supply chain.

Graphical Abstract



Keywords OSA starch · Ber (*Ziziphus mauritiana*) · Physicochemical properties · Ascorbic acid · Decay loss

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Introduction

Ber or Indian jujube (*Ziziphus mauritiana* Lamk.) is referred to as the king of arid fruits and belongs to the family *Rhamnaceae*. Known as the ‘poor man’s fruit’, wild ber species are easily available and affordable for low-income populations. Ber is cultivated across a wide range of tropical to subtropical climates and originated from the Indo-Malaysian region of South and Southeast Asia. India is the largest producer of Ber globally, with a cultivated area of approximately 52,000 hectares and an annual production of 5.31 lakh MT [1]. Ber is recognized for its excellent nutritional quality. The fruit contains protein, ash, fat, fiber, and moisture in the ranges of 4.44–6.87%, 2.67–3.45%, 1.85–2.84%, 1.29–1.92%, and 15.42–21.35%, respectively, across different cultivars [2]. Despite its nutritional and economic importance, fresh mature jujube fruits are highly perishable with a short shelf life of less than one week at ambient temperature storage conditions due to their climacteric ripening behaviour [3]. Post-harvest losses of fruits and vegetables are a major concern, with around 33% lost globally due to microbial infections and unfavourable storage conditions [4]. These challenges highlight the need for effective post-harvest technologies, including edible coatings and other preservation methods, to extend shelf life, maintain quality, and reduce losses along the supply chain.

Aloe vera gel coatings are widely used to improve the shelf life of fruits and vegetables. Aloe vera gel treatments, applied pre- and post-harvest, effectively reduced weight loss and enhanced antioxidant capacity in ‘Red Globe’ grapes during storage [5]. Various other techniques have also been explored to enhance the postharvest shelf life of fresh fruit and vegetables, including cold storage [6], controlled atmospheric (CA) storage [7], hot water treatment [8], and modified atmosphere packaging (MAP) [9]. These approaches help to reduce respiration rates, delay ethylene production, and limit microbial growth, thereby maintaining fruit quality [10]. In addition, several postharvest chemicals, such as edible coating or wax, CaCl_2 , and ascorbic acid, have been shown to enhance shelf life [11–13]. The choice of postharvest treatment to improve shelf life depends on the physiology of the crop.

Nowadays, the use of edible coatings ($< 300 \mu\text{m}$), safe and sustainable, has emerged as an effective strategy to extend the shelf life of fruits and vegetables. Edible coatings are based on diverse materials, including proteins, carbohydrates, lipids, and multi-component blends [14]. Among them, polysaccharide-based coatings are the most widely studied, either alone or in combination with other materials, as they help reduce postharvest losses [15]. Starch-based coatings are effective and sustainable for extending the shelf life of fruits, but the application of native starch is limited

due to its hydrophilic nature and weak barrier properties. Chemical modification with octenyl succinic anhydride (OSA) has proven to be a promising approach, enhancing the functionality of starch coatings for fruits such as grapes [16], plums [17] etc. The use of octenyl succinate as a starch modifier in edible coatings for fruits and vegetables is recognized as safe and is not restricted by the FAO or WHO [18]. The modification of starch with OSA is permitted at 3% level on the dry weight basis for use in food products in many countries [19]. Starch alkenyl succinates, including dodecenyl, octadecenyl, and OSA, are typically prepared via base-catalysed reactions with granular starch in aqueous suspension [20]. Zhou et al. [21] observed a notable decrease in both moisture absorption and surface hydrophilicity of corn starch-based films. DS of OSA modified starch significantly influenced film properties, with optimal properties observed at DS = 0.019, where elongation at break and oxygen barrier properties increased by 203.22% and 48.40%, respectively, while solubility decreased by 19.31% [22]. Although OSA-starch coatings have been widely studied for several fruits, research on their application to ber is limited. Therefore, this study was designed to evaluate the effectiveness of OSA-starch coatings in enhancing the shelf life and quality of ber fruits during storage. The novelty of this research lies in applying a cost-effective, biodegradable, and safe coating to enhance shelf life of ber fruits. OSA-modified starch has shown promising results in improving moisture resistance, gas barrier performance, and mechanical stability in other fruits, yet its application for ber fruit preservation remains insufficiently explored. OSA-starch coating specifically to ber fruit, a commercially important but under-researched arid fruit, with the potential to reduce postharvest losses and improve value addition in the supply chain.

Materials and methods

Pearl millet grains (cv.HHB-299) and Ber cv. Umran were collected from the Experimental Area, CCS Haryana Agricultural University, Regional Research Station, Bawal (Rewari), India. The mean sea height of the experimental location is 266 m with coordinates of 28°14’ North latitude and 75°70’ East longitude. The analytical grade chemicals were used during the study.

Selection of fruit

The same size, equally mature *Ziziphus* fruits were plucked from each direction of the plant. One kilogram of fruit per replication, free from signs/symptoms of insect pests and diseases, was selected. The average fruit weight was 25 g, and one replication contained about 40 fruits. These fruits

were treated in four replications; one additional replication was maintained under the same conditions for distractive methods of analysis. The data for non-distractive parameters was taken from four replications, while the analysis for the distractive method was used on the additional replication.

Starch isolation and modification

Starch was isolated from pearl millet grains using the alkaline steeping method. Pearl millet grains were steeped in 0.1% sodium metabisulfite solution for 18 to 20 h. After 20 h, grains were washed with distilled water and ground in a laboratory grinder (Sujata Powermatic Plus, Mumbai, India) with the addition of an equal amount of water. The ground slurry was passed through 0.250, 0.150, 0.100, 0.075, and 0.045 mm sieves. Starch slurry was centrifuged at 3000 rpm for 10 min, and the brown layer was scraped off with a spatula, this process was repeated 3–4 times till white starch was obtained. Collected starch was dried in a conventional oven at 40–45 °C for 12 h and stored in air air-tight container. The isolated starch was modified using OSA (octenyl succinic anhydride) @ 3% at different pH conditions (4, 6, & 8) [23, 24]. OSA (3% dwb of starch) was dissolved in 120 ml water, and starch (100 g) was dispersed in the OSA solution. pH of slurry was adjusted with 1 M NaOH or 1 M HCL solution and the reaction was continued for 1 h with stirring at room temperature. The starch was dried at 40–50 °C in a conventional oven for 24 h to a moisture content of less than 5%, ground, and then sieved. The dried OSA starch powder was heated in an electric oven at 130 °C for 2 h. After cooling the starch, it was dispersed in 150 ml water, and pH was adjusted to 6. Samples were washed twice with distilled water (450 ml), once with ethanol (150 ml), and then air dried.

Degree of substitutions (D.S.)

The D.S. gives the average amount of hydroxyl groups substituted per glucose unit. Alkali saponification was used to determine it. Whistler and Paschall's titrimetric approach evaluated the degree of octenyl succinylation in the modified starches [25]. Then, 25 mL of a 0.5 N aqueous NaOH solution was added to the OSA starch suspension (in 50 mL of distilled water with 5 g of starch added) and shaken for 24 h. Using phenolphthalein as an indicator, excess alkali was titrated with 0.5 N HCl.

Amylose content, solubility, and swelling power

The method by Williams et al. [26] was used to determine the amylose content in the starch. Starch (0.020 g) was thoroughly mixed with 10 ml of 0.5 mol/L KOH. The dispersed

sample was transferred to a volumetric flask (100 ml) and diluted to the mark with distilled water. An aliquot of test starch solution (10 ml) was pipetted into a volumetric flask (50 ml), and 5 ml of 0.1 mol/L HCl was added, followed by 0.5 ml of iodine reagent. The volume was diluted to 50 ml, and the absorbance was measured at 625 nm in a spectrophotometer (Systronics, Ahmadabad, India). The measurement of the amylose was determined in triplicate from a standard curve developed using amylose and amylopectin blends. The solubility and swelling power of starches were estimated using the method given by Leach et al. [27].

Pasting properties

The pasting parameters of starches were evaluated using a starch cell of a Modular Compact Rheometer (Model-52, Anton Paar, Austria). Starch slurries (1.2 g starch in 13.8 g distilled water) were heated at 50 °C for 1 min, then heated to 95 °C at the rate of 6 °C/min. After holding for 2.7 min, the sample was cooled to 50 °C at the same rate and held at 50 °C for 2 min. Each sample was analysed three times. Peak viscosity (PV), breakdown (BV), setback (SV), final viscosity (FV), and pasting temperature (PT) were all determined using the pasting graph.

Edible coatings preparation

Coating solutions were prepared by dissolving 2% starch in distilled water, with glycerol added at a starch-to-glycerol ratio of 2:1. After mixing, the content was heated at 85 °C for 25 min with continuous stirring. After cooling the solution at room temperature, the solution was filtered through muslin cloth. To dip one-kilogram fruits, 10 g starch mixed with 5 g glycerol, and the final volume was made to 500 ml, and the ber fruits were dipped in the solution for 30 s at room temperature. The fruits were air-dried for 30 min. and stored at low temperature (10 °C) and relative humidity (RH) 85% for further investigation. Measurements for storage studies were recorded on alternate days up to 14 days. Five samples were used in the study: the T1 control (water-dipped sample), T2 Native starch-coated sample, T3 Coated with starch modified at pH 4, T4 Coated with starch modified at pH 6, and T5 Coated with starch modified at pH 8.

Physiological loss in weight (%)

The loss in fruit weight during storage under low temperature conditions (10 °C) was estimated using a formula suggested for determining the cumulative weight loss or PLW (physiological loss in weight), which is based on the fruit weight at the start of the experiment, just after the application of treatments, and the loss in weight during storage.

$$PLW = \frac{\text{Initial wt. (g)} - \text{Final wt. (g)}}{\text{Initial wt. (g)}} \times 100$$

Total soluble solids (°Brix)

The Erma made hand refractometer ranged from 0 to 32 °Brix, set to 20 °C, used to determine total soluble solids (TSS). One to two drops of juice from a fruit selected randomly were put on the refractometer's prism, and it was adjusted according to eyesight. The reflected value was noted as TSS in degrees Brix. Before taking the next reading, the refractometer was adjusted to zero with distilled water.

Ascorbic acid (mg/100 g pulp)

For the determination of ascorbic acid, five grams of pulp were taken and mashed in a pestle and mortar with 3% meta-phosphoric acid (HPO₃). The final volume was made to 25 ml with HPO₃. Two ml of an aliquot was placed in a conical flask and titrated against 2,6 – 2,6-dichlorophenol indophenol dye. The appearance of rose-pink colour, at least for 15 s, was the endpoint of the titration. The amount of 2,6-dichlorophenol indophenol dye used was noted down. Simultaneously, 5 ml of standard ascorbic acid solution was also titrated against 2, 6-dichlorophenol indophenol dye [28]. It was calculated as mg of ascorbic acid per 100 g of fruit pulp as per the formula given below:

$$\text{Ascorbic acid} = \frac{\text{Titrate value (ml)} \times \text{Total volume (ml)} \times 100}{\text{Std. ascorbic acid used (ml)} \times \text{ml of sample} \times \text{Wt. of fruit taken (g)}}$$

Titrateable acidity (TA) (%)

TA was estimated by the titration method reported by Rangananna [29]. The pulp of the fruit was homogenised and mixed thoroughly. A 10 g homogenized pulp was mixed with 100 ml of distilled water and mixed thoroughly. The solution was allowed to stand for an hour, then filtered through Whatman No. 1 filter paper, and the filtrate was used for titration. The extract was appropriately diluted and titrated against 0.1 N sodium hydroxide using phenolphthalein as an indicator.

$$TA (\%) = \frac{\text{Titre vol. (ml)} \times 0.5N \text{ NaOH (ml)} \times \text{Volume made up (ml)} \times \text{Eq. wt.}}{\text{Sample wt. (g)} \times \text{Aliquot taken (ml)} \times 1000} \times 100$$

Decay loss (%)

Pathogenic infection in the fruit during storage or rotting or shrinkage or physical damage or foul smell is considered decayed, and decay loss is estimated as the

sum of fruits decayed on the date of observation, based on the initial fruit weight. It includes the total of fruits decayed, including discarded fruit, from the date of start to the date of observation. The per cent decay loss was calculated using the formula suggested by Srivastava and Tandon [30].

$$\text{Decay loss (\%)} = \frac{\text{Weight of decayed fruits}}{\text{Initial wt. of fruits}} \times 100$$

Statistical analysis

The replicated data were analysed to compare the level of significance between the values of different treatments. The data was analysed using a completely randomized design, analysed with the help of Excel, Python, and GRAPES software, as explained by Gopinath et al. [31]. The level of significance was estimated at a p-value of 0.05 with the help of a critical difference (CD).

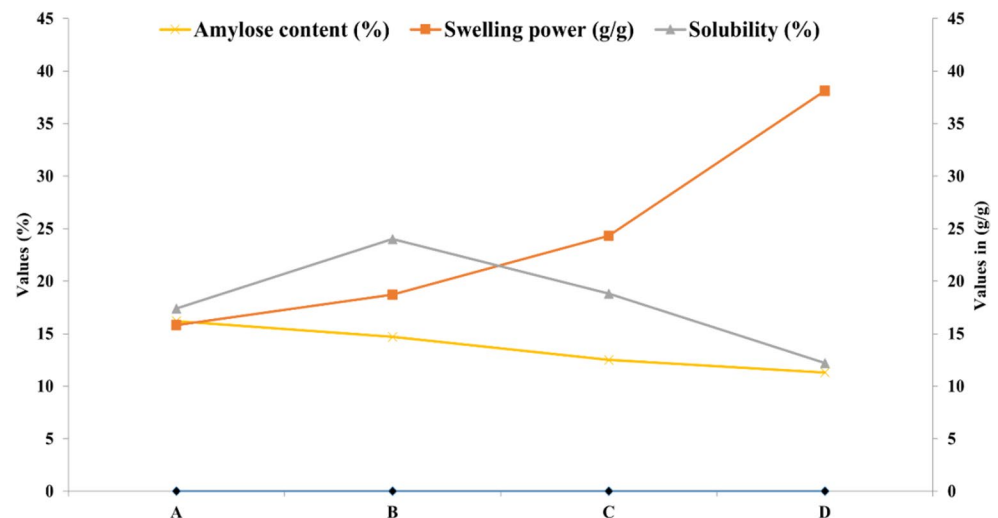
Results and discussion

Physico-chemical properties of starches

Evaluating the functional properties of starch, such as amylose content, swelling power, and solubility (Fig. 1), is essential before its application as an edible coating. These parameters determine the coating's ability to form a uniform film, its barrier properties against moisture loss, and its overall stability during storage. The amylose content of native pearl millet starch was observed to be 16.2%, while OSA-modified starch showed reduced values of 14.7, 12.5, and 11.3%, respectively, as the pH treatment was increased. In previous studies, pearl millet starch was modified with 3% OSA at pH 8, while sorghum starch was treated with 3% OSA at varying pH levels (4, 6, and 8) under dry-heat conditions. In both cases, a decrease in amylose content was observed [32, 33].

Swelling power and solubility affect the hydration behavior, viscosity, and ability to form a continuous layer on the fruit surface. The swelling power of native starch was observed as 15.8 g/g (A), while OSA-modified starch exhibited a higher value, 18.7 g/g (B), 24.3 g/g (C), and 38.1 g/g (D) at pH levels 4, 6, and 8, respectively. This increase indicates enhanced water binding capacity, which likely leads to better coating uniformity and improved adherence on the fruit surface, an important factor in minimizing weight loss and delaying ripening. The solubility of native starch was observed to be 17.4%, whereas OSA-modified starches were observed to be 24.0, 18.8, and 12.2% at pH levels 4, 6, and 8, respectively. The

Fig. 1 Physico-chemical properties of native and modified starches. **A:** Native starch; **B:** Starch modified at pH 4; **C:** Starch modified at pH 6; **D:** Starch modified at pH 8



lower solubility of the starch modified at pH 8 compared to the native starch indicates enhanced hydrophobicity and decreased sensitivity to water. This property is advantageous in edible coatings as it can enhance moisture barrier properties and extend fruit shelf life by slowing down water loss. These results are consistent with observations by Punia et al. [34] for mungbean starch, where OSA modification improved swelling but reduced the solubility. Overall, the observed changes in functional properties clearly support the suitability of OSA-modified starch as an effective and sustainable coating material for extending the postharvest life of ber fruits.

Degree of substitution (DS)

The degree of substitution (DS) of the modified starches at pH 4, 6, and 8 was found to be 0.015, 0.017, and 0.023, respectively. The DS increased with the rise in reaction medium pH, indicating enhanced substitution under more alkaline conditions. DS of OSA treated rye starch was observed at 0.014, 0.019, and 0.022 at different pH (4, 6, & 8) conditions. Samples, those plums coated with OSA starch (pH 8) were more effective in preventing the quality deterioration of plum fruit [17]. The pH of the aqueous slurry plays a crucial role in the esterification process, as NaOH acts as a catalyst by generating alcoholate ions along the starch polymer [35]. According to Hui et al. [36], both DS and reaction efficiency declined markedly when pH was below 7.5 or above 8.0. They noted that pH levels above 8.0 favoured side reactions, while at pH levels below 7.5, the hydroxyl groups on starch were insufficiently activated for nucleophilic attack on the anhydride groups. The dry-heat treatment facilitated the substitution reaction, and data analysed by XRD showed that starch after modification had no change type of crystalline pattern [23].

Pasting properties

The pasting properties of native and modified pearl millet starches are presented in Fig. 2. The peak viscosity (PV) of native starch was 1459 mPa·s., while that of the modified starches ranged from 1100 to 2152 mPa·s. A slight decrease in PV was observed for starch modified at pH 4 and 6, whereas modification at pH 8 increased PV. The increase in viscosity by OSA substitution has been previously reported for starches, which may be due to the formation of amylose-OSA inclusion complexes [37]. The breakdown viscosity (BV) of native starch was 219 mPa·s, which increased after modification. The pasting temperature (PT) of native and modified starches ranged from 72.2 °C to 76.4 °C, with the highest value recorded for the native starch. A decrease in PT was observed following the modification. Siroha et al. [33] observed an increase in PV, TV, and SV after the OSA modification of starches from various cultivars.

Physiological loss in weight (%)

The effects of coating applications using different starches on the physiological loss in weight (PLW) of ber cv. Umran was assessed under low temperature (10 °C) storage conditions (Table 1). PLW was recorded on alternate days over a 14-day storage period from the same replication of fruit. The highest PLW (19.50%) was observed in the untreated control fruits (sample T1), whereas the lowest PLW (15.18%) was recorded in OSA-coated (T5) fruits on the 14th day of storage. The weight loss was 28.4% higher in T1 in comparison to T5. PLW in T3 and T4 treatment was at par with T2 and T5 treatment. Moisture loss during storage primarily occurred through transpiration driven by the water pressure gradient between the fruit tissue and the surrounding atmosphere [13].

Fig. 2 Pasting properties of native and modified OSA starches. **A:** Native starch; **B:** Starch modified at pH 4; **C:** Starch modified at pH 6; **D:** Starch modified at pH 8

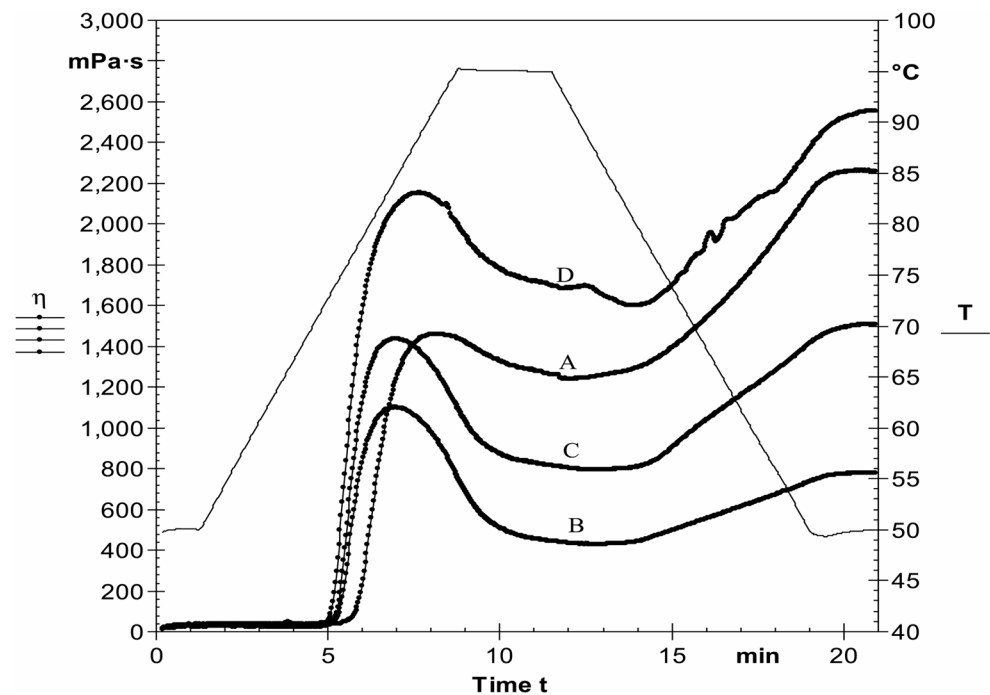


Table 1 Effect of coating on PLW (%) during low temperature storage of Ber cv. Umran

Treatments	Storage period (days)						
	2	4	6	8	10	12	14
T1	1.63±0.04a	4.33±0.12a	6.16±0.16a	9.75±0.26a	12.80±0.34a	16.72±0.44a	19.50±0.51a
T2	1.40±0.04b	4.20±0.11a	5.40±0.14b	9.40±0.25ab	12.32±0.33ab	14.92±0.40b	16.20±0.43b
T3	1.40±0.04b	3.98±0.11b	4.94±0.13c	9.00±0.24bc	12.00±0.32b	14.59±0.39b	15.92±0.42bc
T4	1.29±0.04c	3.71±0.10c	4.92±0.13 cd	8.66±0.23 cd	11.76±0.31bc	14.34±0.38bc	15.59±0.41bc
T5	1.09±0.03d	3.70±0.10c	4.67±0.12d	8.34±0.22d	11.28±0.30c	13.87±0.37c	15.18±0.40c

Mean±SD ($n=3$); the superscript letters within columns indicate the significant differences at $p<0.05$

T1: Control (water-dipped sample), T2: Native starch-coated sample, T3: Coated with starch modified at pH 4, T4: Coated with starch modified at pH 6, and T5: Coated with starch modified at pH 8

Excessive water loss negatively impacts fruit appearance, leading to the initiation of wilting, shrivelling, browning, loss in fruit texture, flavour, and saleable weight, and accelerates senescence [38]. The reduction in PLW in coated fruits may be attributed to the hydrophobic barrier formed by the OSA-starch coating, which partially blocks stomatal openings and reduces moisture diffusion, thereby minimizing transpiration losses [39]. Such findings are consistent with previous studies, where arrowroot starch coatings (4%) significantly reduced weight loss in fruits over 15 days of storage [40], and corn starch coatings on strawberries delayed weight loss and extended shelf life by 4 and 8 days at room and refrigerated temperatures, respectively [41]. These results indicate that OSA-starch coatings, particularly T5, effectively maintain fruit weight and delay physiological deterioration, highlighting their potential for commercial postharvest applications in ber fruit preservation.

Total soluble solid (°Brix)

Total Soluble Solids (TSS) is an important quality parameter that reflects fruit sweetness and overall freshness, directly influencing consumer acceptance. TSS results for coated fruits during low-temperature storage are shown in Table 2. During storage, TSS initially increased until the 8th day for most samples, except T5, and subsequently decreased. In uncoated fruits, TSS decreased 6.0% i.e. from 18.25 °Brix at harvest to 17.16 °Brix by the 14th day, whereas T5-coated fruits retained higher TSS values during storage, it decreased less from 18.21 to 17.88 °Brix ($p = 0.05$) as compared to other treatments. The starch coatings helped to maintain TSS by slowing respiration rates, which delays both the synthesis and utilization of soluble metabolites [42]. Early increases in TSS can be attributed to the breakdown of polysaccharides such as starch, cellulose, and pectic substances into simpler sugars, as well as water loss from the fruit tissue [43, 44].

Table 2 Effect of coating on TSS (°Brix) during low temperature storage of Ber cv. Umran

Treatments	Storage period (days)						
	2	4	6	8	10	12	14
T1	18.25±0.011a	18.27±0.010b	18.37±0.008a	18.45±0.016a	17.73±0.033e	17.48±0.040e	17.16±0.048d
T2	18.23±0.011b	18.29±0.010a	18.35±0.008b	18.43±0.016ab	17.90±0.029d	17.59±0.037d	17.19±0.047d
T3	18.22±0.012b	18.27±0.010b	18.34±0.009bc	18.40±0.017bc	18.16±0.023c	17.93±0.028c	17.47±0.040c
T4	18.22±0.012b	18.26±0.011bc	18.33±0.009 cd	18.37±0.018 cd	18.25±0.020b	18.06±0.025b	17.71±0.034b
T5	18.21±0.012b	18.25±0.011c	18.32±0.009d	18.35±0.018d	18.39±0.017a	18.28±0.020a	17.88±0.029a

Mean±SD ($n=3$); the superscript letters within columns indicate the significant differences at $p<0.05$

The subsequent decline in TSS after the 10th day of storage is likely due to the consumption of soluble solids during ongoing respiration and transpiration processes [45]. Overall, T5-coated fruits demonstrated the best TSS retention, indicating that OSA-starch coatings can effectively preserve the sweetness and quality of ber fruits during storage.

Ascorbic acid (mg/100 g pulp)

The effect of postharvest OSA-starch coatings on ascorbic acid content is summarized in Table 3. Ascorbic acid is a vital antioxidant that scavenges reactive oxygen species (ROS) and prevents the accumulation of toxic ROS under stress conditions [46]. Among the different treatments, T5-coated fruits retained the highest ascorbic acid content (63.5 mg/100 g pulp), whereas uncoated control fruits (T1) showed the lowest value (46.4 mg/100 g pulp) on the 14th day at low-temperature storage. In coating treatment (T5) ascorbic acid content was found 36.9% higher in comparison to control. A gradual decline in ascorbic acid was observed over the storage period. The coatings help to preserve ascorbic acid by forming a protective barrier that limits oxidation and moisture loss, both of which contribute to

nutrient degradation. Similar effects have been reported for bananas coated with corn starch and pomelo peel essential oil, where coated fruits retained higher ascorbic acid levels than uncoated fruits [47]. The observed decline in ascorbic acid in ber fruits may also be attributed to enzymatic oxidation mediated by enzymes such as ascorbic acid oxidase, peroxidase, catalase, and polyphenol oxidase during storage [48, 49].

Titrateable acidity (%)

The titrateable acidity (TA) of ber fruits under different storage conditions is presented in Table 4. Among all treatments, the lowest titrateable acidity (0.229%) was recorded in the control (T1) samples, and T5-coated fruits retained the highest/reduced less acidity (0.248%) under low-temperature storage conditions. The TA of control samples declined more rapidly than that of coated fruits throughout the storage period, showing a continuous decrease over time. This reduction in TA, or the corresponding increase in pH, is likely due to the conversion of organic acids into sugars during respiration and the ripening process [50, 51]. Similar trends have been observed in previous studies, where

Table 3 Effect of coating on ascorbic acid (mg/100 g pulp) during low temperature storage of Ber fruit

Treatments	Storage period (days)						
	2	4	6	8	10	12	14
T1	77.2±0.8b	73.5±1.1c	70.8±1.1c	68.3±1.0c	66.6±1.0c	57.2±0.7d	46.4±0.5e
T2	78.4±0.8ab	74.8±1.2bc	73.1±1.1b	69.8±1.0bc	68.2±1.0bc	59.4±0.8c	48.5±0.5d
T3	78.9±0.9a	75.1±1.2bc	73.7±1.1b	70.5±1.1ab	69.1±1.0b	63.1±0.9b	51.8±0.6c
T4	79.3±0.9a	76.1±1.2ab	75.1±1.2ab	71.6±1.1ab	69.9±1.1ab	64.4±0.9b	58.2±0.8b
T5	79.6±0.9a	77.6±1.2a	76.2±1.2a	72.4±1.1a	71.5±1.1a	67.4±1.0a	63.5±0.9a

Mean±SD ($n=3$); the superscript letters within columns indicate the significant differences at $p<0.05$

Table 4 Effect of coating on acidity (%) during low temperature storage of Ber cv. Umran

Treatments	Storage period (days)						
	2	4	6	8	10	12	14
T1	0.324±0.005c	0.305±0.004c	0.286±0.004c	0.263±0.004c	0.251±0.004b	0.246±0.003d	0.229±0.004c
T2	0.332±0.005bc	0.308±0.004bc	0.293±0.004bc	0.270±0.004b	0.253±0.004b	0.249±0.003 cd	0.231±0.001c
T3	0.338±0.005ab	0.311±0.004abc	0.296±0.004b	0.272±0.004b	0.247±0.003b	0.253±0.004bc	0.238±0.003b
T4	0.342±0.005a	0.316±0.004ab	0.306±0.004a	0.283±0.004a	0.261±0.004a	0.256±0.004ab	0.242±0.003b
T5	0.345±0.005a	0.319±0.005c	0.310±0.004a	0.286±0.004a	0.265±0.004a	0.260±0.004a	0.248±0.003a

Mean±SD ($n=3$); the superscript letters within columns indicate the significant differences at $p<0.05$

ber fruits coated with chitosan (0%, 0.5% & 1%) showed lower reductions in TA (27.6% at 5 °C and 67.3% at 25 °C) compared to uncoated fruits [52]. These results indicate that OSA-starch coatings, particularly T5, help to preserve the acidity of ber fruits, contributing to their overall postharvest quality and shelf life.

Decay loss (%)

Decay defined as rotted or damaged fruits unsuitable for consumption, is a key parameter in shelf-life studies, as it indicates susceptibility to microbial growth and physical damage (Fig. 3). The visual decay assessment was intended to show decay as quantitative data by adding the decay up to

the date of observation. The mean of total decay is reflected in the results as a cumulative value. During storage, decay incidence increased due to tissue softening, which enhances vulnerability to pathogens [53]. The decay losses of ber fruits under different coating treatments are summarized on the basis of the original value in Table 5. Among all treatments, T5-coated fruits showed the lowest decay loss (4.80%), whereas the highest decay loss (8.60%) was observed in uncoated control (T1) fruits after 14 days of storage. No decay was observed in uncoated (T1) and T2 fruits up to 4 days, T3-coated fruits for up to 6 days, and in T4-coated fruits for up to 8 days, while maximum in T5 up to 10 days. Beyond these periods, decay progressively increased with storage duration, with the highest losses recorded at the end

Fig. 3 Visual representation of fruits 14 days after storage. T1: Control (water-dipped sample), T2: Native starch-coated sample, T3: Coated with starch modified at pH 4, T4: Coated with starch modified at pH 6, and T5: coated with starch modified at pH 8



Table 5 Effect of coating on decay loss (%) during low temperature storage of Ber cv. Umran

Treatments	Storage period (days)						
	2	4	6	8	10	12	14
T1	(0)*1.00	(0)*1.00	(2.50)1.87±0.02b	(4.60)2.36±0.03a	(6.10)2.66±0.03a	(7.30)2.88±0.03a	(8.60)3.09±0.04a
T2	(0)*1.00	(0)1.00	(2.60)1.89±0.02a	(4.40)2.32±0.02b	(5.80)2.60±0.03b	(7.00)2.82±0.03b	(8.20)3.03±0.04b
T3	(0)1.00	(0)1.00	(0)1.00c	(2.20)1.78±0.02c	(4.00)2.23±0.02c	(5.50)2.55±0.03c	(7.60)2.93±0.03c
T4	(0)1.00	(0)1.00	(0)1.00c	(0)1.00d	(2.30)1.81±0.02d	(4.50)2.34±0.03d	(5.80)2.60±0.03d
T5	(0)1.00	(0)1.00	(0)1.00c	(0)1.00d	(0)1.00e	(2.70)1.92±0.02e	(4.80)2.40±0.03e

*The values in parentheses are original values (square root transformation is done as $\sqrt{x+1}$ is written outside the bracket). The transformation is done to analyse the data; however, the results are explained with original values

of the experiment. Overall, coated fruits experienced lower decay losses than uncoated fruits, likely because the starch coatings delayed ripening and senescence. Ripening leads to progressive loss of tissue integrity, making fruits more susceptible to pathogenic infection [54].

Conclusion

OSA-modified starch coatings effectively improved the post-harvest shelf life and quality of ber (cv. Umran) fruits during low-temperature storage. The present study demonstrated that starch coatings effectively extended the shelf life and quality of ber (cv. Umran) fruits at low-temperature storage. Among the treatments, fruits coated with OSA starch at pH 8 (T5) exhibited the most favourable results by minimizing physiological weight loss, retaining higher total soluble solids and ascorbic acid content, maintaining titratable acidity, and reducing decay incidence compared to uncoated fruits. These improvements can be attributed to the coating's ability to act as a semi-permeable barrier, reducing transpiration, respiration, and oxidative reactions. Overall, OSA starch represents a cost-effective, biodegradable, and consumer-friendly option for prolonging the postharvest life of ber fruits. Future work should explore large-scale implementation and investigate synergistic effects of combining OSA starch with natural antimicrobials to further enhance its functionality.

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Declarations

Declaration of competing interest No.

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