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Original Research

Shelf life and quality evaluation of Ber (*Ziziphus mauritiana* Lamk.) fruits packed in biodegradable bags made from all-cellulose nanocomposite films

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Abstract: Background and aim: In our laboratory, an all-cellulose nanocomposite (ACNC) film was developed from rice straw-derived cellulose and cellulose nanofibers (CNFs). The structural, mechanical, barrier, thermal, and biodegradability properties of the developed ACNC film have already been characterized. However, its application and comparative evaluation as an alternative packaging material to low-density polyethylene (LDPE) films for enhancing the shelf life of fruits have not yet been explored. Therefore, the present study was undertaken to investigate the potential of ACNC film as an eco-friendly alternative to LDPE films for packaging and extending the shelf life of Ber (*Ziziphus mauritiana* Lamk.) fruits stored under ambient and refrigerated conditions. **Methods:** Ber fruits (*Ziziphus mauritiana* Lamk.) cv. Gola at the green mature stage were packed in Corrugated Fiber Board (CFB) boxes, Low-Density Polyethylene (LDPE) of 300 gauge, and all-cellulose nanocomposite (ACNC) films of equal size, and stored at room temperature (RT, 25±3 ^{o}C) and low temperature (LT, 7±1 ^{o}C) conditions. The CFB-packed fruits served as the control. The fruits were analysed at regular intervals for various parameters until they became over-ripened and unacceptable. **Results:** In this investigation, based on PLW, ripening percentage, and overall acceptability, the shelf life of fruits for control, LDPE, and ACNC packed fruits was 4, 6, and 8 days for RT, and 12, 20, and 24 days, respectively, for LT stored fruits. The total plate count throughout these storage periods remained below 6 $\log_{10}$ CFU/g, thus indicating that the fruits were microbiologically safe for consumption. During storage, ACNC-packed fruits exhibited a slower decline in firmness, total soluble solids, acidity, and ascorbic acid. **Conclusion:** The study revealed that in this case the ACNC film developed from rice straw, an abundantly available agricultural waste, is biodegradable and possesses good tensile strength. It could be a promising, economical, sustainable, and environmentally friendly alternative to LDPE for packaging and extending the shelf life of Ber fruits.

Keywords: All-cellulose nanocomposite film (ACNC), Ber, Low-density polyethylene (LDPE), Packaging, Shelf life, Storage temperature, Surface microflora

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1. Introduction

Post-harvest losses of fresh horticultural produce remain a significant challenge to maintaining efficient supply chains and economic growth in horticulture. It is estimated that nearly 30-40% of fruits and vegetables are lost during the post-harvest stage, before reaching consumers [1]. After harvest, fresh produce remains metabolically active, leading to biochemical changes driven by respiration, transpiration, oxidation, and enzymatic reactions. The resulting alterations cause a decline in texture, color, and nutritional content, which severely impacts the shelf life and marketing value [2].

Indian jujube (*Ziziphus mauritiana* Lamk.), commonly referred to as Ber, has high nutritional value due to its high content of phenolics, antioxidants, vitamins A and C, and minerals such as iron, calcium, and phosphorus. It is a climacteric fruit and exhibits a marked increase in respiration rate during ripening, which exacerbates its vulnerability to post-harvest losses [3]. Despite its high resistance while on the tree, it becomes susceptible to post-harvest loss, such as browning, softening, shrivelling, and microbial decay after harvesting [4]. The post-harvest management of Ber is challenging because it has a short life cycle of 4-5 days under ambient conditions [5].

Appropriate packaging materials play a critical role in reducing post-harvest waste of fresh produce by maintaining a modified atmosphere, preventing the food from contamination from external sources, and preserving quality and safety during transportation and storage [6]. Over the years, plastic bags made from low-density polyethylene (LDPE) have been widely used due to their low cost and convenience [7]. However, the utilization of plastic packaging raises environmental concerns, with the likely risk of a potential health hazard to the public, including the amount of waste generated, and its non-biodegradability. With significant advantages over traditional packaging materials, biopolymeric packaging is emerging as a promising alternative that meets consumer demand for natural, recyclable, and biodegradable packaging solutions [8]. Cellulose-based biopolymeric films, owing to their eco-friendly properties, are rapidly becoming a promising alternative to petroleum-based plastics. Adding cellulose nanofibers (CNFs) to cellulose films significantly enhances mechanical strength, thermal stability, and barrier properties, creating sustainable, high-performance all-cellulose nanocomposite (ACNC) film materials [9, 10] suitable for food packaging applications [11].

In our lab, an all-cellulose nanocomposite (ACNC) film was developed (Indian Patent application no: 202411100467) [12] by incorporating cellulose nanofibers (CNFs) at 7 % as reinforcing nanofillers within a regenerated cellulose matrix. The film was fabricated entirely from rice straw–derived cellulose and CNFs, using a lithium chloride/N, N-dimethylacetamide (LiCl/DMAc) solvent system. Although the developed ACNC film has been systematically evaluated for its mechanical, barrier, thermal, structural, and biodegradability properties (Supplementary Table 1), its application potential as a packaging material and its comparative performance with lowdensity polyethylene (LDPE) for extending the shelf life of fruits have not yet been examined. Therefore, the present study was undertaken to evaluate the potential of ACNC film as a biodegradable and eco-friendly alternative to LDPE for packaging Ber (*Ziziphus mauritiana* Lamk.) fruits and to assess its effectiveness in extending their shelf life under room and low temperature storage conditions.

2. Materials and methods

The present experiment was conducted during February-March 2025 at the Department of Life Sciences, Sharda University, Greater Noida, India. Ber fruits (*Ziziphus mauritiana* Lamk.) cv. Gola at the green mature stage were procured from the local market in Greater Noida, India. Disease-free fruits of uniform size were selected. After sorting, these fruits were thoroughly washed with tap water, air-dried, and packed in bags made from LDPE and ACNC films of approximately 150-gauge thickness. There were 15 fruits (weighing approximately 250 g) per pack, and the fruits packed in corrugated fibre board (CFB) served as the control. The packed fruits were stored at room temperature (RT, 25±3 ^{o}C) and low temperature (LT, 7±1 ^{o}C) conditions. The fruits were analysed every alternate day for various parameters until they became unmarketable.

2.1 Physicochemical analysis

2.1.1 Physiological loss in weight (PLW)

The weight was recorded at the beginning of storage and periodically, at two-day intervals. The recorded weight was then used to determine the percentage physiological loss in fruit weight according to the standard procedure [13], using the following formula:

$$\text{PLW}\ (\%) = \frac{W_i - W_o}{W_i} \times 100$$

Where w_o is the initial weight and w_i is the weight after storage.

2.1.2 Firmness

The firmness of the fruit samples was evaluated using a hand-held penetrometer (model GY-1, Acutek, India) with plunger diameters of 8 mm and 11 mm, and a firmness scale of 13 kg/ cm^2. A small section of the peel was removed, and firmness was recorded at two opposite points on the equatorial region of each unit. The values were recorded and expressed in terms of kg/cm^2.

2.1.3 Ripening and decay losses

The ripening percentage was calculated based on visual changes in colour. The fruits that turned from light yellow or yellow to brown were considered ripe. The fruits that turned dark brown and soft were considered over-ripened (OR). Ripening (%) was calculated by dividing the number of ripened fruits by the total number of fruits. Decay loss (%) was recorded by counting the number of decayed fruits out of the total number of fruits kept for storage.

2.1.4 Total soluble solids (TSS)

TSS was determined using an Abbe refractometer (Relitech RT 780, India). A drop of juice extracted from the fruit was placed on the prism of the refractometer, and the values were expressed as percent TSS. The refractometer was calibrated using distilled water prior to use and thoroughly cleaned with distilled water after each measurement.

2.1.5 Acidity

Acidity was determined by the acid-base titration method described by AOAC [14]. In brief, 5 g of fruit pulp was finely crushed and diluted with distilled water. The entire extract, including the pulp, was placed in a conical flask and titrated against 0.1N NaOH, using phenolphthalein as an indicator. The acidity was expressed in terms of percent citric acid.

2.1.6 Ascorbic acid

Ascorbic acid was determined by the titrimetric technique using 2,6-dichlorophenolindophenol reagent, following the procedure described by Ranganna [13]. In brief, 5 g of the fruit pulp was thoroughly blended with 3% metaphosphoric acid (HPO_3) and diluted to a final volume of 50 ml with 3% HPO_3, followed by filtration. An aliquot of 5 ml was then titrated with the standard ascorbic acid dye until the pink endpoint persisted for at least 15 seconds. The dye factor was calculated by titrating a solution containing 5 ml of standard ascorbic acid solution prepared in 3% HPO_3. The ascorbic acid (mg per 100 g) was calculated using the following formula:

$$\text{Ascorbic acid}\left(\frac{\text{mg}}{\text{100g}}\right) = \frac{\text{Titre} \times \text{Dye factor} \times \text{Volume made up} \times 100}{\text{Aliquote of extract taken for estmation} \times \text{Weight of fruit taken for estimation}}$$

2.2 Microbial load

To analyse the microflora load on the surface of the Ber fruits, microbiological analyses were conducted during storage using the serial dilution method. Spread plating was performed on standard nutrient agar for the enumeration of the total plate count [15, 16]. The plates were incubated in a BOD incubator at 37°C for 36 hours to determine the total plate count in terms of $\log_{10}$ CFU/g.

2.3 Sensory evaluation

Sensory evaluation was carried out by a panel of 20 semi-trained panellists from the university, as per the procedure described by Khapudang & Siddiqui [15]. The panellists assessed various sensory attributes, including color and appearance, flavour and taste, texture, and overall acceptability, using a 9-point hedonic scale. The fruits scoring 9 were in the "liked extremely" category, and those scoring less than 5 were considered "unacceptable".

2.4 Statistical analysis

All experiments were conducted in triplicate, and results were expressed as mean value ± standard deviation. Statistical analysis to compare data for significance level was performed using the Opstat program (http://opstat.somee.com/opstat/). One-way analysis of variance (ANOVA) was used to evaluate the critical differences at $P \leq 0.05$.

3. Results and discussion

3.1 Physiological loss in weight (PLW)

The variation in packaging materials and storage conditions significantly influenced the PLW and ripening percentage of the fruits (Tables 1, 2). At both RT and LT storage conditions, PLW increased progressively with longer storage periods. PLW during storage was maximum in CFB, followed by ACNC, and it was minimum for LDPE-packed fruits. This trend continued throughout the storage period. A PLW of approximately 10 % is most often taken as the threshold limit for determining the end of shelf life of fresh fruits [17]. In the present investigation, under RT storage conditions, control fruits exceeded the threshold PLW value of 10% by the fourth day of storage, while the fruits packed in ACNC and LDPE continued to show PLW less than the threshold value even after 8 days of storage (Table 1). Under LT storage conditions, the PLW was lower compared to RT storage conditions. The control fruits exceeded the threshold PLW value by the twelfth day of storage, while the fruits packed in ACNC and LDPE continued to show PLW less than the threshold value even after 24 days of storage (Table 2). Reduced PLW under LT compared to RT is attributed to decreased metabolic activity and transpiration [18, 19]. Reduced PLW in ACNC and LDPE packed fruits compared to control fruits may be due to an altered internal environment that slowed the evapotranspiration of water and reduced respiration due to the creation of a modified atmosphere. The relatively higher PLW in ACNC-packed fruits compared to those packed in LDPE could be attributed to the higher water vapour transmission rate (WVTR) of the cellulose nanocomposite films, which facilitated greater evapo-transpirational water loss from the fruits during storage. The presence of CNFs decreases the WVTR of ACNC films, likely by forming a tortuous path that acts as a physical barrier to water vapour diffusion along the polymer–nanofiber interface [20, 21].

3.2 Ripening percentage and decay loss

Fruit ripening, based on changes in colour, was significantly affected by the packaging material and storage conditions (Tables 1-2; Figures 1-2). Ripening increased progressively with longer storage periods. The maximum ripening occurred in control, followed by LDPE, and it was the minimum in ACNC packed fruits. Under RT storage conditions, the fruits became fully (100%) ripe by the 6th day in the control, by the 8th day in LDPE, and reached 88.9% ripeness in ACNC packed fruits by the 8th day of storage (Table 1). Under LT storage conditions, fruits became fully ripe by the 12th day in control, by the 20th day

Table 1. Effect of packaging materials on PLW, ripening, and sensory acceptability of Ber fruits stored under room temperature conditions

Packaging	Period of storage (days)			
	2	4	6	8
	PLW (%)			
Control	7.8 ± 0.5^{cA}	9.9 ± 0.7^{cB}	-	-
LDPE	0.8 ± 0.4^{aA}	1.7 ± 0.7^{aB}	2.7 ± 0.5^{aC}	3.9 ± 0.7^{aD}
ACNC	1.3 ± 0.3^{bA}	2.5 ± 0.5^{bB}	3.7 ± 0.4^{bC}	5.1 ± 0.7^{bD}
	Ripening (%)			
Control	55.4 ± 3.5^{cA}	73.4 ± 4.2^{cB}	100.0 ± 0.0^{cC}	OR
LDPE	38.0 ± 2.8^{bA}	82.2 ± 3.8^{bB}	93.3 ± 6.7^{bC}	100.0 ± 0.0^{bD}
ACNC	22.6 ± 3.2^{aA}	42.2 ± 3.9^{aB}	66.7 ± 6.5^{aC}	88.9 ± 3.9^{aD}
	Overall sensory score (9-point hedonic scale)			
Control	7.2 ± 0.4^{aA}	5.1 ± 0.5^{aB}	< 5.0	< 5.0
LDPE	8.2 ± 0.5^{bA}	7.1 ± 0.6^{bB}	5.7 ± 0.5^{aC}	< 5.0
ACNC	8.6 ± 0.4^{cA}	8.1 ± 0.5^{cB}	7.3 ± 0.5^{bC}	5.9 ± 0.6^{D}

-: not recorded as exceeded 10% threshold limit. Means ± SD with different small superscripts within the column and capital superscripts within the row of a parameter are significantly different ($p \leq 0.05$). OR-over ripened. Sensory score at 0-day =8.9.

Table 2. Effect of packaging materials on PLW, ripening, and sensory acceptability of Ber fruits stored under low temperature conditions

Packaging	Period of storage (days)					
	4	8	12	16	20	24
	PLW (%)					
Control	5.0 ± 0.3^{cA}	8.5 ± 0.3^{cB}	10.1 ± 0.4^{cC}	-	-	-
LDPE	0.6 ± 0.2^{aA}	1.2 ± 0.2^{aB}	2.0 ± 0.3^{aC}	2.8 ± 0.2^{aD}	3.7 ± 0.3^{aE}	4.2 ± 0.3^{aF}
ACNC	1.0 ± 0.4^{bA}	1.7 ± 0.4^{bB}	2.4 ± 0.2^{bC}	3.3 ± 0.2^{bD}	4.2 ± 0.2^{bE}	5.4 ± 0.3^{bF}
	Ripening (%)					
Control	26.7 ± 6.6^{cA}	57.8 ± 7.6^{cB}	100.0 ± 0.0^{cC}	OR	OR	OR
LDPE	20.0 ± 6.6^{bA}	33.3 ± 6.7^{bB}	46.7 ± 7.6^{bC}	84.6 ± 3.8^{bD}	100.0 ± 0.0^{bE}	OR
ACNC	13.3 ± 3.8^{aA}	20.0 ± 6.6^{aB}	35.4 ± 7.7^{aC}	71.1 ± 3.8^{aD}	86.7 ± 6.7^{aE}	100.0 ± 0.0^{F}
	Overall sensory score (9-point hedonic scale)					
Control	8.2 ± 0.2^{aA}	8.0 ± 0.2^{aA}	5.1 ± 0.1^{aB}	OR	OR	OR
LDPE	8.8 ± 0.1^{bA}	8.5 ± 0.2^{bA}	7.7 ± 0.2^{bB}	7.0 ± 0.3^{aC}	6.2 ± 0.2^{aD}	5.5 ± 0.3^{aE}
ACNC	8.9 ± 0.1^{bA}	8.9 ± 0.1^{cA}	8.4 ± 0.4^{cB}	8.4 ± 0.2^{bB}	7.2 ± 0.2^{bC}	7.0 ± 0.1^{bC}

-: not recorded as exceeded 10% threshold limit. Means ± SD values with different small superscripts within the column and capital superscripts within the row of a parameter are significantly different ($p \leq 0.05$). OR-over ripened in LDPE, and by the 24th day in ACNC packing (Table 2). The fully ripe fruits turned over ripe, but did not show any decay loss during later storage periods under the different packaging and storage conditions (data not presented). The greater effectiveness of ACNC compared to LDPE packaging in slowing down the ripening and reducing decay can be attributed to the enhanced barrier and functional properties of bio-nanocomposite films [22]. The lower oxygen transmission rate (OTR) of nanocellulose-based films compared to LDPE [23, 24] limits the availability of oxygen inside the package, thereby lowering metabolic activity and delaying ripening due to decreased respiration. Incorporating CNFs into the cellulose film matrix reduces structural porosity, as CNFs act as nucleating agents and interact strongly with the polymer network, thereby lowering the OTR of the films [21]

3.3 Firmness

The firmness of the fruit, which largely determines consumer acceptability and ease of transportation, is influenced by factors affecting ripening. Loss of firmness in Ber fruits during ripening is primarily because of enzymatic degradation of cell wall polysaccharides by the action of polygalacturonase and cellulase [25]. In the present investigation, it was observed that there was a progressive decrease in firmness with increasing storage periods (Figure 3), with the decrease being significantly higher in control, followed by LDPE, and it was least in ACNC-packed fruits. The decrease in firmness was faster at RT than at LT storage conditions. The greater retention of firmness in ACNC-packed fruits may be attributed to reduced respiration and slower ripening rates during storage. The decrease in flesh firmness of ber fruits with the advancement of ripening and storage period [25], and the maintenance of firmness in fruits packed in polyfilms or nano-biocomposites, has also been reported by other

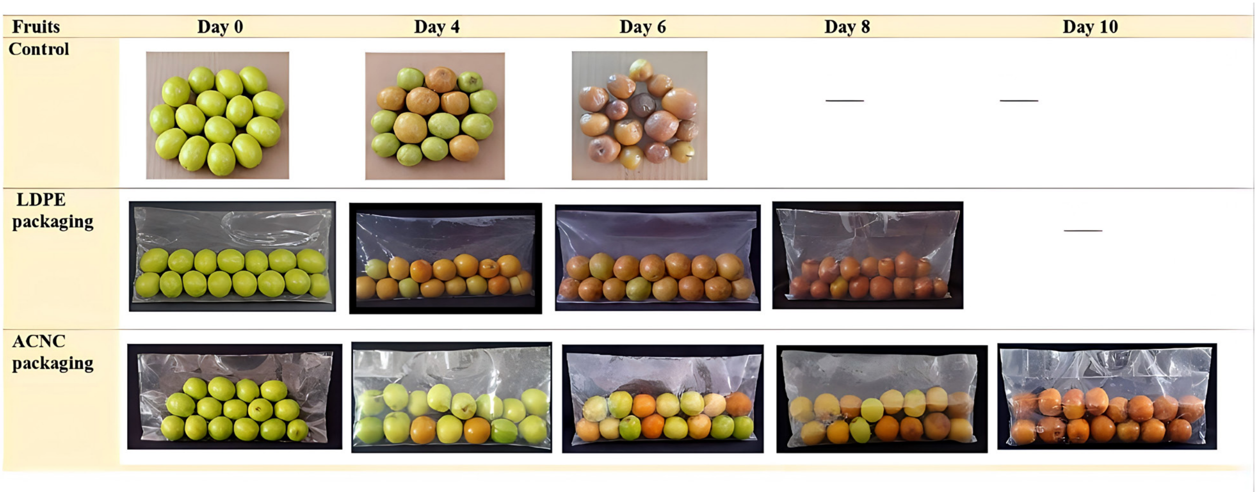

Figure 1. Effect of packaging materials on colour and appearance of Ber fruits under RT storage conditions. – means over-ripened fruits.

Figure 2. Effect of packaging materials on colour and appearance of Ber fruits under LT storage conditions. – means over-ripened fruits.

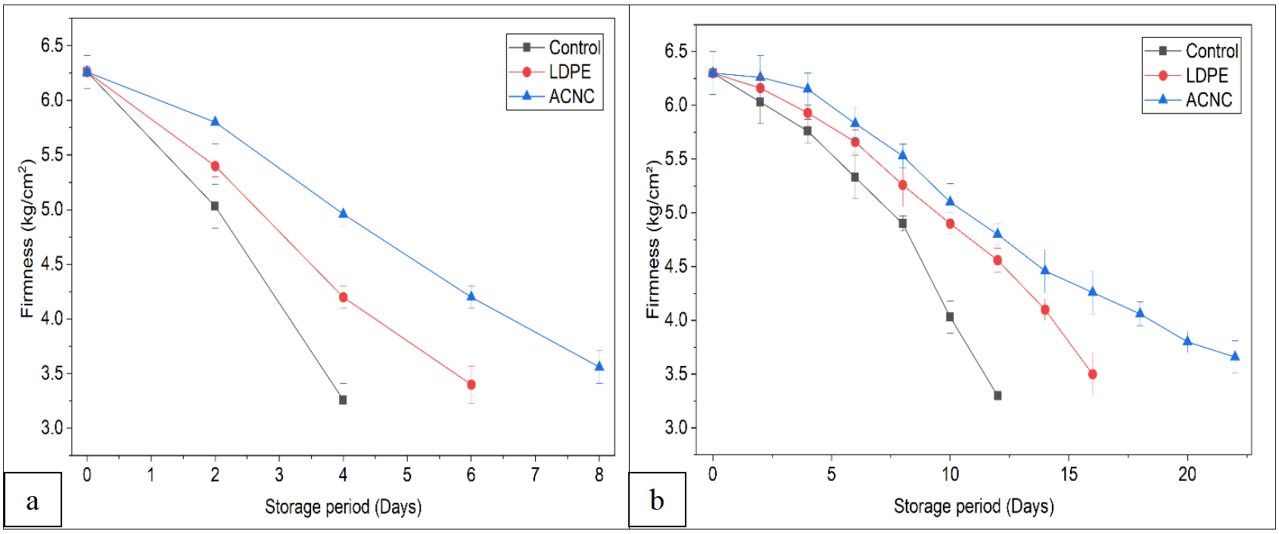

Figure 3. Effect of packaging materials on firmness (kg/cm²) of Ber fruits stored under (a) RT and (b) LT conditions. The error bars represent the SD values.

researchers [17, 26].

3.4 Growth of surface microflora

The microbiological quality and safety of packed fresh fruits during storage were determined by observing the growth of surface microflora. Sha [27] reported that approximately 80% of microorganisms isolated from the surface of Ber fruits are aerobic mesophilic bacteria, while molds tend to appear at later stages of storage as the fruits become overripe. Accordingly, in the present study, surface microflora was assessed solely based on total bacterial counts. Molds, yeasts, and the specific pathogenic microorganisms were not analyzed. It was observed that Ber fruits packed in ACNC and LDPE showed lesser growth of microbes as compared to control fruits (Table 3). At day 0, the microbial growth of 2.2±0.3 $\log_{10}$ CFU/g was observed on the fruits, which increased progressively with increasing storage periods, both at room and low temperature conditions. The total plate count, throughout the storage period, remained < 6 $\log_{10}$ CFU/g, which is within the safe range reported for fresh produce [28], thus indicating that the fruits were microbiologically safe for consumption. Throughout the storage period under both conditions, microbial growth was slower in ACNC-packed fruits than in LDPE-packed fruits, which may be attributed to reduced oxygen availability, leading to lower proliferation of aerobic bacteria on the fruit surface. The developed ACNC film exhibited a lower oxygen transmission rate (OTR) compared to LDPE (Supplementary Table 1), thereby passively establishing a modified atmosphere within the package characterized by reduced oxygen concentration. The higher water vapour transmission rates (WVTR) of ACNC compared to LDPE films may also have created an environment inside the package with relatively lower humidity, thereby further reducing the growth of microbes. Earlier also it has been reported that optimized barrier properties were likely responsible for the nano-biocomposite film's improved performance in preventing microbial metabolism [29].

3.5 Total soluble solids, acidity and ascorbic acid contents

The total soluble solids (TSS) primarily represent the sugar content of fruits. In this investigation, it was observed that the TSS progressively and significantly increased during the storage period until the fruits became fully ripe, and then showed a gradual decrease when the fruits began to over-ripen (Figure 4). The changes were significantly higher in control, followed by LDPE, and were lowest in ACNC packed fruits. The increase in TSS was faster at RT than under LT storage conditions. The progressive increase in total soluble solids (TSS) during storage may be attributed to fruit ripening and the conversion of reserve insoluble polysaccharides into soluble sugars [19]. The lower OTR of ACNC films reduced oxygen availability within the package, thereby suppressing respiration and slowing the ripening process, which resulted in a slower increase in TSS in ACNC-packed fruits during storage. Similar changes in TSS of fruits packed in polyfilms or nanocellulose-based films have also been reported by other researchers [30, 31].

The acidity of Ber fruits progressively and significantly decreased with increasing storage period (Figure 5). The decrease was faster at RT than under LT storage conditions. The decrease in acidity was significantly faster in control, followed by LDPE, and it was the least in ACNC-packed fruits. The decrease in acidity of the fruits during storage could be the result from the utilisation of organic acids in respiration and their conversion to sugars [32]. A gradual decrease in acid content in Ber fruit during storage has also been reported by other researchers [19, 25]. The retention of acidity in ACNC-packed fruits could be due to the reduced respiration, as a result of the lower OTR properties of these films [10].

The ascorbic acid (AA) content of Ber fruits progressively and significantly decreased with increasing storage period (Figure 6). The decrease in AA during storage was faster at RT than under LT storage conditions, which could be attributed to oxidation of AA by ascorbic acid oxidase and peroxidase, as higher temperatures enhanced the enzymatic activity, while reduced temperatures slowed metabolic and enzymatic mechanisms [33]. A similar decrease in AA of Ber fruits during storage has been reported previously [4, 19]. In the present investigation, the decrease in AA was significantly faster in control, followed by LDPE, and it was least in ACNC-packed fruits. The lower OTR of ACNC film reduced oxygen availability within the package. The low oxygen environment limited oxidation and resulted in enhanced retention of AA in the packed fruits during storage [4].

Table 3. Effect of packaging materials on the growth of surface microflora (log_{10} CFU/g) of Ber fruits stored under different temperature conditions

Packaging	Room temperature storage Period of storage (days)					
	2	4	6	8		
Control	3.07±0.31^{bA}	5.45±0.23^{cB}	-	-		
LDPE	3.00±0.52^{aA}	4.42±0.23^{bB}	5.12± 0.22^{bC}	-		
ACNC	3.00±0.52^{aA}	3.48±0.20^{aB}	3.74±0.20^{aB}	4.36±0.25^{C}		
	Low temperature storage Period of storage (days)					
	4	8	12	16	20	24
Control	3.00±0.30^{bA}	4.60±0.30^{cB}	5.21±0.21^{cC}	-	-	-
LDPE	2.80±0.32^{bA}	3.84±0.31^{bB}	4.71±0.25^{bC}	5.06±0.31^{bD}	-	-
ACNC	2.58±0.32^{aA}	3.35±0.25^{aB}	3.83±0.23^{aC}	4.30±0.26^{aD}	4.57±0.28^{E}	-

-: not recorded as fruits were over ripened and lost their sensorial acceptability. Means ± SD values with different small superscripts within the column and capital superscripts within the row of a parameter are significantly different ($p \leq 0.05$). At 0-day, the microflora present were 2.2±0.3 log_{10} CFU/g.

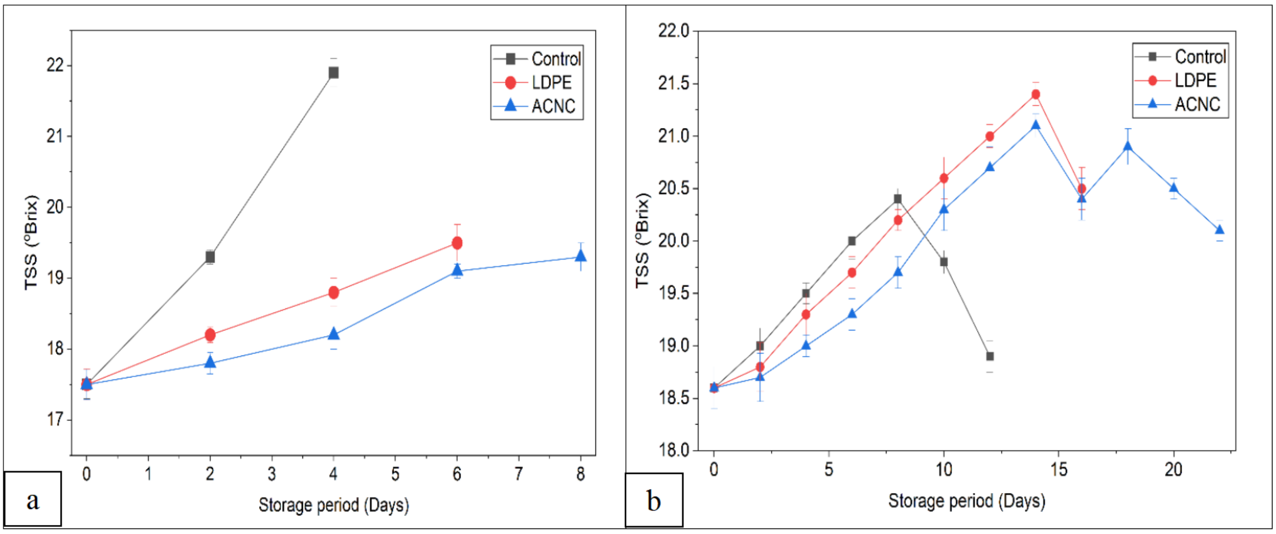

Figure 4. Effect of packaging materials on TSS (%) of Ber fruits stored under (a) RT and (b) LT conditions. The error bars represent the SD values.

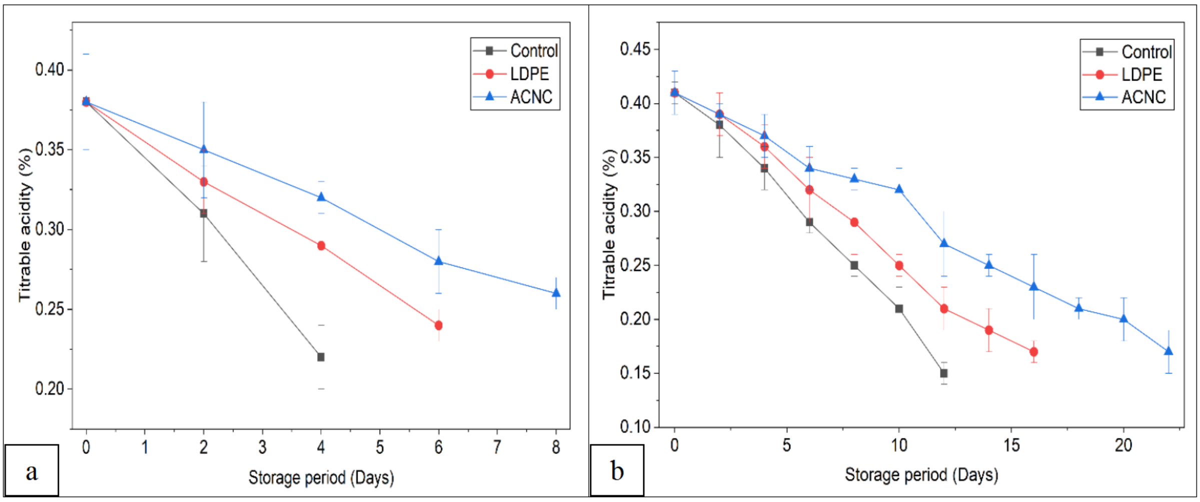

Figure 5. Effect of packaging materials on acidity (%) of Ber fruits stored under (a) RT and (b) LT conditions. The error bars represent the SD values.

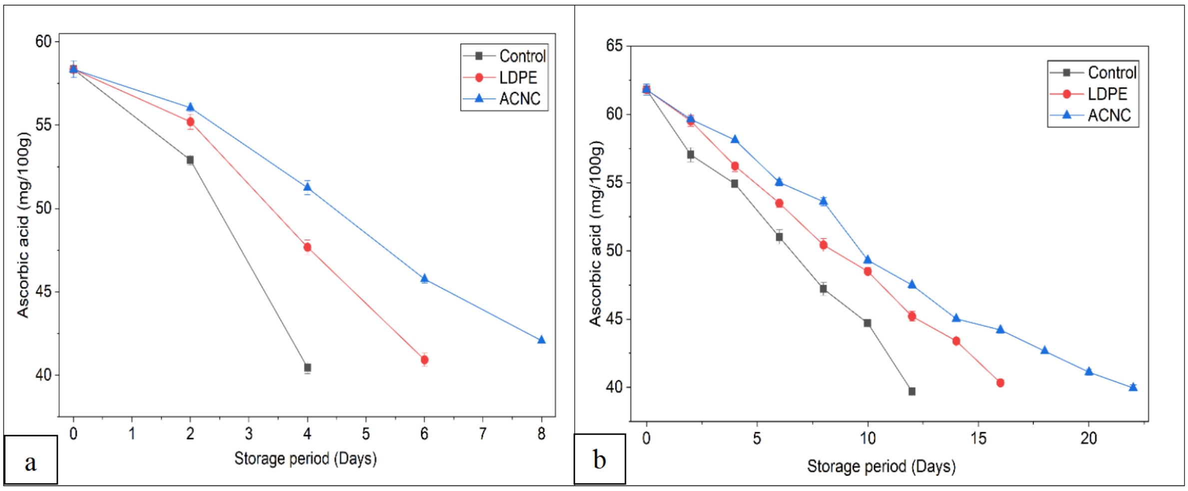

Figure 6. Effect of packaging materials on ascorbic acid content (mg/100g) of Ber fruits stored under (a) RT and (b) LT conditions. The error bars represent the SD values.

3.6 Sensory acceptability

The overall sensory acceptability scores of the fruits were influenced by the packaging material and storage conditions (Tables 1-2). These scores were the average of the scores for colour and appearance, taste and flavour, and texture (Supplementary Tables 2-3). There was a gradual and significant decrease in the overall acceptability of the fruits with increasing storage period, with the decrease being slower under LT conditions. The sensory acceptability of the fruits was maintained significantly higher in ACNC than in LDPE packaging under both storage temperature conditions. Under RT storage conditions, the fruits remained in the acceptable category up to the 4th day in control, the 6th day in LDPE, and the 8th day in ACNC packing (Table 1). Under LT storage conditions, the fruits remained in the acceptable category up to the 12th day in control, while the fruits packed in ACNC and LDPE continued to be acceptable even after 24 days of storage (Table 2). The higher acceptability of the ACNC packed fruits compared to those packed in LDPE may be due to slower ripening. Ber is a climacteric fruit, and ripening during storage has been reported to affect its firmness, taste, and overall organoleptic quality [25].

4. Conclusion

In this investigation, based on PLW, ripening percentage, and overall acceptability, the shelf life of fruits for control, LDPE, and ACNC packed fruits was 4, 6, and 8 days at RT, and 12, 20, and 24 days, respectively, for LT stored fruits. The total plate count throughout the storage period, remained within the safe range reported for fresh produce, thus indicating that the fruits were microbiologically safe for consumption. The OTR of the ACNC film reduced oxygen availability within the package, thereby creating a passive modified atmosphere. This reduced oxygen environment suppressed respiration rates, which in turn slowed ripening and resulted in a slower increase in TSS during storage. Additionally, limited oxygen availability reduced oxidative degradation, leading to enhanced retention of AA in the packed fruits. The restricted oxygen levels also inhibited the growth of aerobic microorganisms, contributing to lower microbial proliferation on the fruit surface. Collectively, these effects played a significant role in maintaining the physicochemical quality and extending the shelf life of fruits packaged in ACNC films. Thus, this study revealed that the ACNC film developed in our lab from rice straw could be a promising, economical, sustainable, and environmentally friendly alternative to LDPE for packaging and extending the shelf life of Ber fruits. However, further research is required to tailor the composition of the ACNC film to match the WVTR and OTR requirements of different other fruits packed and stored under different temperature conditions.

Supplementary materials

The supplementary tables are available at: https://file.luminescience.cn/FNDS-535%20Supplementary%20updated.pdf.

Conflict of interest

Authors declare there is no conflict of interest.

Authors' contributions

Sadhana Jadon: investigation, writing original draft; Saleem Siddiqui: conceptualization, data interpretation, manuscript reviewing.

Human ethics and consent to participate

This study did not involve a clinical trial or any research involving human participants or animals. Human ethical approval for sensory evaluation involving human participants approved by the Research Ethics Review Committee of Sharda University in accordance with relevant sensorial evaluation guidelines and regulations (ISO 4121:2003). Sensory evaluation of the product was conducted by semi-trained panelists (aged 20 years and above). They were verbally informed about the product to minimize health risks such as allergies or food intolerances. They were also briefed on the study's purpose, the nature of the information to be collected, their right to withdraw at any time, and the confidentiality of their responses. Participation was entirely voluntary, and no compensation was provided. Informed consent to participate was obtained from all panelists.

Consent for publication

Both the authors agreed to publish this research.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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