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Antioxidant-Rich Biodegradable Films: Incorporating Date Phenolic Extracts into Polyvinyl Alcohol Biofilms for Strawberry Preservation

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ABSTRACT

This study evaluates the development and characterization of polyvinyl alcohol (POVA) films incorporated with phenolic extracts from two varieties of dates, Barhi, Medjool, and their potential application in strawberry packaging. Total phenolic content (TPC) and antioxidant activity (DPPH) were assessed for aqueous and ethanolic extracts of Barhi and Medjool dates. Barhi exhibited higher TPC and DPPH than Medjool, with 10.53 mg/g and 65.83%, respectively, in its ethanolic extract, compared to Medjool's 7.39 mg/g and 50.63%, respectively. POVA films incorporating Barhi ethanolic extract (POVA/BE) demonstrated the highest TPC (3.58 mg GAE/g) and antioxidant activity (53.68%) compared to other films. The physical properties of the films, including thickness and water vapor permeability (WVP), were evaluated, POVA/BE showing improved barrier properties with a WVP of 88.75 $\times10^{-10}$ g H_2O/m s p.a. Compared to pure POVA, POVA/BE films also showed superior mechanical properties, with a tensile strength of 69.69 MPa and elongation at break of 66.72%. Additionally, strawberry storage trials demonstrated that POVA/BE films minimized weight loss, maintained higher firmness, TSS, TTA, and vitamin C content over 14 days of storage, with weight loss of 8.00%, TSS of 4.84%, and vitamin C retention at 111.77 mg/100g. These results suggest that POVA films containing Barhi extracts offer enhanced antioxidant activity, mechanical strength, and barrier properties, making them a promising biodegradable packaging solution for extending the shelf life of perishable foods like strawberries.

Keywords: Strawberry shelf life, Date palm fruit, Biodegradable films Packaging, quality properties

INTRODUCTION

Synthesized polymeric films are widely used in food packaging due to their low cost, ease processing, and extensive utility (Shen *et al*., 2010). However, increased and indiscriminate use of petroleum-based packaging films has caused serious environmental problems. Therefore, the development of the environmental, biodegradable, biocompatible, abundant, available and reproducible plastic with light-blocking supplies a novel approach to solve the photo-oxidative degradation and ecological problems for the disposal of petroleum-based wastes (Yang *et al*., 2020).

In recent years, the pursuit of sustainable and eco-friendly packaging materials has become a paramount concern within the food industry. As consumer awareness of environmental issues continues to grow, there is a pressing need to develop innovative solutions that address both functional and ecological aspects of packaging (Oliveira Filho *et al*., 2019).

Recent studies have explored the incorporation of various fruit and plant extracts into biodegradable films to enhance their functionality. For instance, pomegranate peel extracts have been integrated into chitosan-based films, imparting significant antioxidant and antimicrobial properties, which effectively extend the shelf life of food products (de Almeida Soares and de Aquino Santana, 2024). Similarly, hop plant extracts, known for their bioactive compounds, have been used to develop chitosan–gelatin edible films with improved antioxidant activity and mechanical properties (Xu *et al*., 2021). Additionally, Aloe vera gel has been utilized to reinforce chitosan-based edible films, enhancing their barrier properties while providing bioactive compounds (Kaur *et al*., 2024). These studies highlight the growing interest in leveraging natural extracts for biodegradable film applications.

Packaging materials have a significant role in preventing the deterioration of foods because of adverse environmental factors such as microbial contamination, oxygen and moisture and provide longer shelf life for the product (Gaikwad *et a*l., 2018). To address this issue, researchers have focused on developing multifunctional, eco-friendly bio-composite films that can protect packaged food products while also degrading easily in the soil to minimize their impact on the environment. These films have the potential to extend the shelf life of food products. The produced edible films for food products have been defined as a thin layer of bio-materials that are designed to either replace or enhance natural layers in food products and it can either be applied as part of the food product or discarded (Nieto, 2009). The nature biopolymers were exploited for this purpose due to their edibility, biocompatibility, non-toxicity, biodegradability, antioxidant and antimicrobial activities (Deshmukh *et al*., 2021).

Polyvinyl alcohol (POVA), a synthetic polymer derived from petrochemical sources, is renowned for its film-forming properties, biodegradability, and compatibility with a diverse range of additives (Oun *et al*., 2022; Liu *et al*., 2022).

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POVA is a highly hydrophilic, biocompatible and non-toxic polymer with good gas barrier property and excellent flexibility. Therefore, it is widely used to improve the toughness of materials (Prakash *et al*., 2019 ; Alshehri *et al*., 2024).

The date palm (*Phoenix dactylifera* L.) is a tropical and subtropical tree which belongs the family Palmae. Date fruit contains high levels of essential nutrients including carbohydrate, mineral, fiber and vitamins (Solangi *et al*., 2024).

To enhance the functionality of POVA-based films, recent research has focused on incorporating bioactive compounds, particularly phenolic materials, known for their antioxidant and antimicrobial properties. Dates, particularly varieties such as Barhi and Medjool, are rich sources of phenolic compounds with significant antioxidant activity (Ghnimi *et al*., 2017). Phenolic compounds, such as flavonoids, phenolic acids, and tannins, can protect food from oxidative deterioration and microbial spoilage, thereby improving the effectiveness of biodegradable films (Benmeddour *et al*., 2013).

The present study focuses on developing biofilms composed of polyvinyl alcohol (POVA) enriched with phenolic extracts from Barhi and Medjool date, aiming to enhance their application in packaging strawberries. The phenolic extracts, known for their antioxidant and antimicrobial properties, are expected to improve the bioactivity of POVA films, extending the shelf life of strawberries while providing a sustainable method for utilizing agricultural waste. This research will investigate the structural and functional properties of these phenolic-enriched biofilms and evaluate their effectiveness in preserving the freshness and quality of strawberries during storage. By integrating biodegradable polymers with natural antioxidants, the study aims to contribute to environmentally friendly, functional packaging solutions for the food industry.

MATERIALS AND METHODS

Materials

Two selected varieties of Date Palm fruit, Barhi and Medjool has been attained from Al-Tahhan Golden Dates Farms at Kharga city, El Wadi ElGedid, Egypt. Strawberry fruit was purchased from local market at Tanta city, El-Gharbia, Egypt. Polyvinyl alcohol (POVA) CAS No: 9002-89-5 with purity of 94 %, viscosity 22–30 cp, hydrolysis 99–99.9 (mole %) was utilized used in the study, along with DPPH, ABTS radicals and were obtained from Sigma Aldrich Co., Ltd. (St. Louis, MO, USA). All other reagents used were of analytical grade.

Methods

Extraction of phenolic compounds from palm date (Barhi and Medjool)

Ultrasonic-assisted extraction was carried out using sample approximately (30 g) and two solvents: 300 ml of ethanol (70%) and 300 ml of distilled water. The solution was extracted for 30 min using ultrasound equipment (VCX 750, USA). After extraction, the solution was cooled to room temperature and filtered with Whatman No.1 filter paper. The filtrate was concentrated using a rotary evaporator (RV 10 C S93, Germany). Subsequently, lyophilization was performed by Laboratory Freeze Dryer (Benchtop, LYO60B-1PT, China) at −40 °C for 48 h. This lyophilization material was stored at −20 °C until it was ready for use (Owon *et al*., 2021).

Determination of phenolic compounds from Date Palm Extract

HPLC analysis was carried out using an Agilent 1260 series. The separation was carried out using Zorbax Eclipse Plus C8 column (4.6 mm x 250 mm i.d., 5 μm). The mobile phase consisted of water (A) and 0.05% trifluoroacetic acid in acetonitrile (B) at a flow rate 0.9 ml/min. The mobile phase was programmed consecutively in a linear gradient as follows: 0 min (82% A); 0–1 min (82% A); 1-11 min (75% A); 11-18 min (60% A); 18-22 min (82% A); 22-24 min (82% A). The multi-wavelength detector was monitored at 280 nm. The injection volume was 5 μl for each of the sample solutions. The column temperature was maintained at 40 °C (Pyrzynska and Sentkowska, 2019).

Film preparation:

POVA (4 g) was stirred in 100 mL distilled water at 95 °C, with a stirring speed of 700 rpm, for 2 h. 1.5 g of glycerol was added as a plasticizer, and stirring under the same conditions continued for another 30 min. Then, different concentrations of lyophilized date powder were incorporated. After that, all was stirred (900 rpm - 40 °C) for 30 min. 75 mL from prepared solution was dispensed into petri dishes (15 cm diameter). The solution was allowed to dry for 7 h at 50 °C. After that, the resulting films were delicately detached and preserved between sheets of paper within a desiccator with saturated calcium nitrate solution with 50 % relative humidity until equilibrium for further analysis **(Alshehri *et al*., 2024 b).**

Color measurements

Films color was measured with a portable colorimeter (3NH SR-66; China). Color coordinates were recorded as L*, a*, b* and c* (Alshehri *et al*., 2024 a).

Determination of film solubility and moisture content

The moisture content and solubility of the films were determined. In summary, ten equally sized samples measuring 20 × 20 mm were cut. Two weights were recorded, the first one was the wet weight (W0) and the second was after drying at 105 °C (W1). The dried films were carefully soaked in distilled water (50 mL) at 100 mL beakers and left for 24 hours (25 °C). The resulting films were dried in an air oven (105 °C) to obtain the final drying weight (W2) **(Eltabakh *et al*., 2021)**. The parameters were then calculated using the provided equations:

$$\textbf{Moisture amount (\%)} = \left(\frac{W0-W1}{W0}\right) \times 100$$

$$\textbf{Solubility (\%)} = \left(\frac{W1-W2}{W1}\right) \times 100$$

Determination of film thickness and water vapor permeability

For film thickness, five different places from the film were measured by digital micrometer and the mean was calculated. The film's effectiveness in blocking water vapor permeability was evaluated. Glass cups were prepared and filled with calcium chloride. The films under examination were affixed atop the cups and their weight was measured. Subsequently, the cups were moved to a regulated setting maintained at 50% relative humidity and 25 °C, establishing a variance in water vapor pressure between the interior and exterior of the flasks, which facilitates the migration of water vapor through the films. The variances in water pressure on either side of the film were measured using a digital gauge. The alterations in the cups' weight were monitored at hourly intervals over 10 hours (Abdin *et al*., 2023). By observing these weight changes, a slope was graphed and the Water Vapor Permeability (WVP) gm^{-1} s^{-1} Pa^{-1} was determined through the utilization of the subsequent formula:

$$\mathbf{WVP} = \left(\frac{Slope \times film\ length}{exposed\ area \times presusure\ difference}\right)$$

Potential biodegradability determination

The potential biodegradation ability of POVA films were performed according to method by (He *et a*l., 2021). The POVA films were put inside pot filled with clay soil at depth of 5 cm for 30 days. The spraying was carried out at a constant rate by sprinkler to moisten the soil, where the water content at the end of the experiment was 37.50 %. The POVA films were taken out every 10 days to determine the degree of degradation by calculating the rate of weight loss. The measurements were conducted in triplicate and the mean was calculated.

Characterization of mechanical properties

The mechanical characteristics of the films were evaluated by measuring their tensile strength (TS) and elongation at break (EB) through a texture analyzer (TA.XT Plus, Stable Micro Systems Ltd., located in Surrey, UK) (Rui *et al*., 2017). Rectangular samples measuring 20 × 100 mm were prepared and placed between the lower and upper grips of the machine. The upper grip was set to move (100 mm/min speed and 100 N as tensile force). The stress and strain data were obtained and analyzed using the Zwick software (Test Expert V11.02).

Scanning electron microscope (SEM) analysis

The films were cut into small square pieces. The square pieces were stabilized on metal shape grids with double-sided adhesive tape. The gold particles were sprayed to coat samples surface and cross section. The photographs were recorded by SEM (Quanta FEG 250, Netherlands) under voltage of 5 kV with power magnification of 500 µm.

Differential Scanning Calorimetry (DSC) Attributes

Differential scanning calorimetry (SETARAM Inc., DSC131, France) was used to perform the differential scanning calorimeter analysis. The instrument was calibrated using the standards (Mercury, Indium, Tin, Lead, Zinc and Aluminum). Nitrogen and Helium were used as the purging gases. The test was programed including the heating zone from 25°C to 250°C with a heating rate 10 °C / min. The samples were weighted in Aluminum crucible 30 ul and introduced to the DSC. The thermogram results were processed using CALISTO Data processing software v.149.

Fourier transform infrared spectroscopy (FT-IR)

The films pieces were cut to be suitable for detector field of machine FTIR spectrometer (Vertex 80 FTIR, Germany). The measurement of samples was performed with a cross spectral range of 400–4000 cm^{-1} and resolution of 4 cm^{-1} to detect all possible spectral curves with shoulders.

Determination of total phenolic content and the antioxidant activity of Date Palm, films and fruits

To determine the total phenolic components, the Folin-Ciocalteu procedure as described by (Attard, 2013) with some modifications was used. The procedure involved combining 10 µL of either the sample or standard with 100 µL of Folin-Ciocalteu reagent (diluted to 1:10), followed by adding 80 µL of 1M Na_2CO_3. The mixture was then incubated in the dark at 25 °C for 20 minutes. The resultant blue complex color was detected at 630 nm. Data are presented as averages ± SD. Gallic acid was prepared as a standard.

The scavenging activity 2,2-diphenyl-1-picrylhydrazyl (DPPH) of Date Palm Extract and films was measured (Zhang *et al*., 2017). In summary, a working solution of DPPH (2 mL) (concentration of 250 µM in methyl alcohol) was applied to the samples. The specimens were then left in darkness for 30 minutes before their absorbance at 517 nm was assessed using a spectrophotometer. The scavenging activity of DPPH radicals was calculated using the given formula.

$$\textbf{DPPH scavenging activity (\%)} = \left(\frac{Abs\ control - Abs\ film}{Abs\ control}\right) \times \mathbf{100}$$

where "Abs control" denotes the absorbance measurement of the DPPH working solution in the absence of any films, and "Abs films" refers to the absorbance measurement when the DPPH working solution is combined with the films.

Storage condition of strawberry after packaging

Strawberry samples were transported to laboratory and the wounded ones were discarded. After that, samples were stored in prepared films (POVA= Polyvinyl alcohol, POVA/BE = Polyvinyl alcohol with Barhi 70% ethanol extract), plastic dishes (Polyethylene) and without packaging. The packages were maintained on refrigerator at ±2 °C for 14 days. The subsequent measurements and analysis of the samples were taken at intervals of 0, 3, 7, and 14 days.

Fruit Firmness

Watkins and Harman (1981) measured firmness for strawberry fruit using a penetrometer (PCE-PTR 200, France) with a probe of 8 mm of diameter.

Total soluble solid (TSS)

Twenty grams of smashed strawberry fruit was mixed with 20 ml of distilled water and blended. The blended juice was filtered and the clear juice was utilized. The TSS was determined as degree °Brix using a digital refractometer (DR 6000, A. Kruss Optronic GmbH, Germany) (Lees, 1968).

Total titratable acidity (TTA)

According to the International Standard Organization (1998), TTA was measured in strawberry juice by titrating with 0.1N of sodium hydroxide in the presence of phenolphthalein as indicator and the results were expressed as a percentage of citric acid. Titratable acidity was measured by mixing 25 g of fruit pulp with 50 mL of boiled distilled water in a blender and filtered. Then, 25 mL of the filtrate (juice) was used for titration.

Weight loss

Weight losses of strawberries during the storage period were determined using a digital balance reading to 0.001 g. The results were expressed as percentage loss of initial weight.

Determination of Vitamin C

Estimation of ascorbic acid content of the fruit was done by following (Kumar *et al*., 2021) procedures with minor changes. Accordingly, fresh fruit (5.0 g) was macerated and added to 95 ml of 0.4% oxalic acid. 10 ml aliquot was taken from this prepared solution and titrated against 0.4% 2,6-Dichlorophenol-indophenol (DPCIP)dye till the appearance of the end point (pink color). The results were expressed in mg 100 g− 1.

Statistical analysis

To conduct multiple comparisons, the Duncan test and one-way analysis of variance (ANOVA) were employed (SPSS 16.0 package). Statistical significance was determined at a significant level of $p \leq 0.05$.

RESULTS AND DISCUSSION

Total phenolic (TPC) and antioxidant activity (DPPH) of two different types of dates (Barhi and Medjool)

The results of the study presented significant differences in TPC and DPPH of Barhi and Medjool dates, depending on the solvent used for extraction (Table. 1). Barhi dates showed higher values in both TPC and DPPH compared to Medjool dates for both aqueous and ethanolic extracts. Specifically, TPC in Barhi dates was 3.10 mg/g for the aqueous extract and 10.53 mg/g for the ethanolic extract. In contrast, Medjool dates had TPC of 1.68 mg/g for the aqueous extract and 7.39 mg/g for the ethanolic extract.

Phenolic compounds are secondary metabolites that play a crucial role in plant defense mechanisms and are known for their antioxidant properties. The presence of these compounds in higher concentrations in Barhi dates indicates a potentially greater health benefit, as phenolics are known for their ability to neutralize free radicals and reduce oxidative stress in biological systems (Awad *et al*., 2011).

Regarding antioxidant activity, Barhi dates again exhibited superior performance with 27.30% for the aqueous extract and 65.83% for the ethanolic extract. Medjool dates showed lower DPPH, with 22.34% for the aqueous extract and 50.63% for the ethanolic extract. The higher antioxidant activity in Barhi dates was consistent with their higher phenolic content, as phenolic compounds are known to contribute significantly to antioxidant activity. The results indicated that ethanol was a more effective solvent than water for extracting phenolic compounds and antioxidants from dates. This can be explained by the fact that ethanol is a polar organic solvent that can dissolve a wide range of phenolic compounds more effectively than water, which is less polar (Dorta *et al*., 2012).

When comparing these results with other studies, the findings aligned well with previous research on date varieties. For instance, a study by Biglari *et al*. (2008) found that different date varieties exhibit varying levels of phenolic content and antioxidant activity, with certain varieties showing higher levels due to their unique phytochemical profiles. Nicoli *et al*. (1999) noted that the higher phenolic content and antioxidant activity in Barhi dates suggest that they may be more beneficial for health compared to Medjool dates, particularly when extracted with ethanol. These findings have practical implications for the food industry, where date extracts can be used as natural antioxidants in food preservation and as functional ingredients in health-promoting products.

Table 1. Total phenolic content (TPC) (mg/g) and antioxidant activity (DPPH %) of two different types of dates (Barhi and Medjool) by two different solvents (70% ethanol and water)

Parameter	Total phenolic extract		Antioxidant activity	
	Aqueous extract(mg/gextract)	Ethanolic extract(mg/gextract)	Aqueous extract(%)	Ethanolic extract(%)
Barhi	3.10±0.05*	10.53±0.84*	27.30±1.40*	65.83±2.15*
Medjool	1.68±0.01	7.39±0.57	22.34±1.05	50.63±1.87

Means having * within a column are significantly different at $P \leq 0.05$.

Phenolic compounds in Barhi and Medjool extract

The analysis of phenolic compounds in Barhi and Medjool dates revealed differences in the concentration and variety of these bioactive compounds between the two types. Barhi dates contained a wider range of phenolic compounds, while Medjool dates showed higher concentrations of certain individual compounds (Table 2). This variation may be attributed to genetic, environmental, and post-harvest handling that influence the phenolic profile of each date type (Mansouri *et al*., 2005).

In this study, Barhi dates were found to have a diverse range of phenolic compounds, including chlorogenic acid, catechin, methyl gallate, rutin, and vanillin, which contribute to their antioxidant activity and health benefits. Medjool dates, on the other hand, had higher levels of specific phenolics, such as gallic acid, ferulic acid, and hesperetin, which were known for their strong antioxidant properties and potential to reduce oxidative stress. The presence of gallic acid, chlorogenic acid, caffeic acid, ferulic acid, and kaempferol in both types of dates indicated that they share some common antioxidant compounds. However, the significantly higher levels of gallic acid and ferulic acid in Medjool dates suggested a stronger antioxidant potential, which is supported by previous research (Mansouri *et al*., 2005; Biglari *et al*., 2008). The presence of unique phenolic compounds in Barhi dates, such as rutin and vanillin, may provide additional health benefits, including anti-inflammatory effects and enhanced vascular health (Al-Mssallem *et al*., 2020).

The higher phenolic content and diversity in Barhi dates might also contribute to their greater antioxidant capacity, as indicated by the higher DPPH radical scavenging activity observed in this study. However, the significant presence of gallic acid and ferulic acid in Medjool dates suggested that these dates may have stronger specific antioxidant properties, which could be particularly beneficial for health applications targeting oxidative stress-related conditions (Singh *et al*., 2020).

Previous studies have documented similar findings regarding the phenolic composition of dates, with variations depending on the date variety and environmental factors. For instance, Al-Farsi *et al*. (2005) reported that phenolic content in dates was highly variable across different varieties, impacting their antioxidant potential and health benefits. Similarly, Biglari *et al*. (2008) found that the antioxidant activity of dates is closely linked to their phenolic profile, supporting the results observed in this study.

Table 2. Phenolic compounds (µg/g) of two different types of dates (Barhi and Medjool)

Phenolic compound	Barhi	Medjool
Gallic acid	79.14	86.87
Chlorogenic acid	7.06	1.46
Catechin	3.91	0.00
Methyl gallate	0.77	0.00
Coffeic acid	7.17	9.37
Syringic acid	2.13	2.01
Pyro catechol	0.00	0.00
Rutin	2.20	0.00
Ellagic acid	2.34	1.26
Coumaric acid	5.49	1.93
Vanillin	4.91	0.56
Ferulic acid	5.23	14.14
Naringenin	5.35	3.77
Rosmarinic acid	4.31	0.00
Daidzein	0.00	0.00
Querectin	0.00	2.46
Cinnamic acid	0.24	4.72
Kaempferol	8.22	12.24
Hesperetin	0.00	8.15

Films properties

Total phenolic content and antioxidant activity (DPPH) of POVA films

Table (3) presented the total phenolic content and antioxidant activity (DPPH) of polyvinyl alcohol (POVA) films with various date extracts, revealing significant differences in their enhancement of phenolic content and antioxidant properties. The POVA films alone have a low phenolic content (0.02 mg GAE/g) and corresponding antioxidant activity (15.95%). This aligned with literature noting that pure POVA lacks antioxidant properties due to its synthetic nature. Incorporating plant extracts into POVA films had been shown to introduce beneficial phenolic compounds, enhancing the material's functional properties (Jiang *et al*., 2011).

When comparing the films with added date extracts, POVA/BE (Barhi 70% ethanol extract) showed the highest phenolic content at 3.58 mg GAE/g, which translated into superior antioxidant activity at 53.68%. Ethanol's efficacy as a solvent for phenolic extraction was well-documented, and its use here suggested that the Barhi date variety contained abundant extractable phenolics, resulting in enhanced antioxidant capabilities (Dorta *et al*., 2012).

The POVA/BW (Barhi water extract) film, while demonstrating lower phenolic content (1.05 mg GAE/g) than its ethanol counterpart, still maintains strong antioxidant activity (44.47%). This suggests that even water extracts contain potent phenolic compounds, even in lower concentrations, possibly because water, a polar solvent, extracts different phenolic compounds than ethanol. This indicates that the phenolics extracted by water may possess inherently strong antioxidant properties, which compensates for their lower overall concentration (Hamad *et al*., 2015).

Films with Medjool date extracts, POVA/ME and POVA/MW, show lower phenolic contents and antioxidant activities than those with Barhi extracts. POVA/ME (Medjool 70% ethanol extract) has a phenolic content of 0.09 mg GAE/g and antioxidant activity of 28.36%, while POVA/MW (Medjool water extract) shows even lower values at 0.05 mg GAE/g and 20.41%. These results may indicate varietal differences between Barhi and Medjool dates in terms of phenolic composition and concentration (Biglari *et al*., 2008). These findings highlight the influence of both solvent choice and date variety on the phenolic content and antioxidant activity of POVA films. Ethanol extracts generally yield higher phenolic content and antioxidant activities.

Physical properties, color and water vapor permeability of fabricated films

Table (3) provides insight into the physical properties and water vapor permeability (WVP) of different polyvinyl alcohol (POVA) films incorporated with Barhi and Medjool date extracts. The parameters include film thickness, solubility, moisture content, and WVP, which are crucial in determining the suitability of these films for packaging applications.

The POVA/BW (Barhi water extract) film exhibits the highest thickness at 0.32 mm, whereas the pure POVA film shows a lower thickness of 0.21 mm. The increase in thickness with the addition of date extracts is consistent with other studies where bioactive compounds or plant extracts are integrated into films, leading to a denser matrix and thus increasing the film's thickness. The higher thickness in the POVA/BW film might be due to the presence of more complex phenolic compounds from the Barhi water extract, which contributes to the film's structural bulk (Liu *et al*., 2021).

The POVA film demonstrates the highest solubility at 25.66%, indicating a higher rate of dissolution in water. In contrast, POVA/MW (Medjool water extract) shows the lowest solubility at 19.55%, suggesting a more hydrophobic nature. The decreased solubility in films containing date extracts can be attributed to the interaction between phenolic compounds and POVA, which reduces the film's hydrophilicity (Annu *et al*., 2021). This phenomenon is supported by similar findings in research involving other natural extracts that enhance the hydrophobic properties of POVA films, making them less soluble (Ghelejlu *et al*., 2016).

The moisture content is the highest in the pure POVA film at 17.24% and lowest in the POVA/BE (Barhi ethanol extract) film at 12.54%. The presence of bioactive compounds in the films with date extracts likely leads to a reduced affinity for water molecules, thus decreasing moisture uptake. This reduction in moisture content is favorable for applications where lower water activity is desired to extend the shelf life of packaged products (Annu *et al*., 2021).

The WVP values are crucial for assessing a film's barrier properties against moisture transmission. POVA/BE (Barhi ethanol extract) and POVA/ME (Medjool ethanol extract) films show the highest WVP at 88.75 and 87.02 g H_2O/m s p.a., respectively, while POVA/MW displays the lowest WVP at 83.44 g H_2O/m s p.a. The increased WVP in films with ethanol extracts can be explained by the plasticizing effect of ethanol, which disrupts the tight polymer network, allowing more moisture transmission (Oliveira *et al*., 2021). Conversely, the lower WVP in water extract films indicates a more compact structure due to the cross-linking effect of certain phenolic compounds, which can enhance moisture barrier properties (Liu *et al*., 2021). This phenomenon has been supported by other studies that used different extracts, showing an increase in WVP due to the presence of phenolic compounds (Yao *et al*., 2020).

The color properties of the fabricated films as indicated by the L*, a*, and b* values demonstrate how different Barhi and Medjool date extracts affect the visual characteristics of polyvinyl alcohol (POVA) films. All the films display high L* values, indicating that they are very light or nearly white in color. The L* values for the films are quite similar, ranging from 99.27 in POVA/BW to 99.99 in POVA/ME and POVA/MW. The presence of natural extracts does not significantly affect the lightness of the films, as they all maintain a high degree of transparency or whiteness. This result aligns with other studies where POVA films with natural additives maintain their high lightness due to the inherent transparency of POVA, even when various extracts are incorporated (Ghelejlu *et al*., 2016).

The a* values vary among the films, with POVA/BW showing a significantly higher redness (2.47) compared to the other films. This increase in redness can be attributed to specific phenolic compounds or pigments present in the Barhi water extract, which impart a reddish tint to the film. Other studies have also observed similar changes in color parameters with the addition of natural extracts, as the a* value is sensitive to specific pigments or compounds in the extracts (Ghelejlu *et al*., 2016).

The b* values, which indicate yellowness, vary considerably between the films, with POVA/BE showing the highest yellowness (7.79), followed by POVA/BW (6.25) and POVA/ME (5.61). The increased yellowness in POVA/BE can be attributed to the ethanol extraction of Barhi dates, which likely extracted more yellow pigments or phenolic compounds, contributing to a higher b* value. Ethanol is known to extract more phenolic compounds, which often have yellow or brown hues, resulting in higher b* values in films (Liu *et al*., 2021).

The changes in color properties observed in this study are consistent with other research where natural extracts are used in film formulations. For instance, the incorporation of green tea extract into films often leads to increase a* and b* values due to the presence of anthocyanins and other colored phenolics (Wu *et al*., 2013).

Table 3. Total phenolic content (TPC) (mg/g), antioxidant activity (DPPH %), thickness (mm), solubility (%), moisture content (%), water vapor permeability (WVP), color properties of fabricated films

Treatments	POVA	POVA/BE	POVA/BW	POVA/ME	POVA/MW
TPC (mg GAE/g sample)	0.02±0.00^{e}	3.58±0.06^{a}	1.05±0.02^{b}	0.09±0.00^{c}	0.05±0.00^{d}
DPPH %	15.95±0.11^{e}	53.68±2.68^{a}	44.47±0.18^{b}	28.36±0.56^{c}	20.41±0.87^{d}
Thickness (mm)	0.21±0.01^{b}	0.25±0.04^{ab}	0.32±0.06^{a}	0.24±0.01^{ab}	0.27±0.01^{ab}
Solubility (%)	25.66±0.23^{a}	21.31±0.35^{bc}	21.60±0.08^{a}	20.85±0.26^{c}	19.55±0.18^{d}
Moisture content (%)	17.24±0.31^{a}	12.54±0.31^{c}	13.45±0.18^{b}	13.52±0.21^{b}	13.53±0.23^{b}
WVP ($\times10^{-10}$ g H_2O/m s p.a.)	84.21±1.32^{b}	88.75±0.20^{a}	85.15±0.43^{b}	87.02±0.59^{a}	83.44±0.28^{b}
L*	99.51±0.20^{a}	99.59±0.44^{a}	99.27±0.96^{a}	99.99±0.01^{a}	99.99±0.00^{a}
a*	1.37±0.09^{b}	1.19±0.12^{b}	2.47±0.21^{a}	1.37±0.29^{b}	1.63±0.12^{b}
b*	3.45±0.22^{a}	7.79±0.40^{a}	6.25±0.78^{b}	5.61±0.35^{b}	4.40±0.19^{a}

Values are means ± SD; means having the different case letter(s) within a column are significantly different at P ≤ 0.05. POVA= Polyvinyl alcohol. POVA/BE = Polyvinyl alcohol with Barhi 70% ethanol extract. POVA/BW = Polyvinyl alcohol with Barhi water extract. POVA/ME = Polyvinyl alcohol with Medjool 70% ethanol extract. POVA/MW = Polyvinyl alcohol with Medjool water extract

Biodegradability of fabricated films

As shown in Table 4,The biodegradability of the fabricated films was assessed over 7, 14, and 30 days, with significant differences observed between the Polyvinyl Alcohol (POVA) films and those containing the Barhi 70% ethanol extract (POVA/BE). As illustrated in figure1The POVA/BE films exhibited greater biodegradability compared to the pure POVA films at all time points measured.

Table 4. Biodegradability of fabricated films of Polyvinyl alcohol with Barhi 70% ethanol extract

Sample	Biodegradability (days) (%)		
	7	14	30
POVA	6.56±0.32	13.82±0.17	15.14±0.15
POVA/BE	10.38±0.23*	20.33±0.28*	25.69±0.32*

*** Significant differences between samples at p≤0.05. POVA= Polyvinyl alcohol. POVA/BE = Polyvinyl alcohol with Barhi 70% ethanol extract.**

A= Fabricated films with Barhi phenolic extract. B= Fabricated films without Barhi phenolic extract

Fig 1. Biodegradability of fabricated films

At the 7-day, the POVA/BE films demonstrated a biodegradability of 10.38, which was significantly higher than the 6.56 observed for the POVA films. This suggests that the incorporation of Barhi ethanol extract accelerates the biodegradation process, potentially due to the presence of phenolic compounds and other bioactive components that enhance microbial activity (Gasti *et al*., 2020).

After 14 days, the difference in biodegradability between the POVA and POVA/BE films became more pronounced, with values of 13.82 and 20.33, respectively. This continued trend reinforces the idea that the Barhi extract not only supports faster degradation but also sustains this effect over time.

By 30 days, the biodegradability of the POVA/BE films reached 25.69, significantly higher than the 15.14 measured for the POVA films. The prolonged degradation of the POVA/BE films can be attributed to the sustained activity of enzymes and microbes that continue to interact with the natural extracts, breaking down the polymer chains more effectively. This extended biodegradability aligns with findings by Riyajan et al. (2013) who observed that incorporating natural extracts into biopolymer films can effectively improve their environmental sustainability by promoting biodegradation.

The overall results indicate that the Barhi 70% ethanol extract significantly enhances the biodegradability of POVA films. This enhancement is likely due to the presence of bioactive compounds within the extract that provide an additional carbon source for microbial communities, facilitating faster and more efficient degradation.

Tensile strength and elongation at break properties of POVA films

The tensile strength and elongation at break properties of Polyvinyl Alcohol (POVA) films and Polyvinyl Alcohol with Barhi 70% ethanol extract (POVA/BE) films show significant differences, reflecting the impact of incorporating natural extracts on mechanical properties as shown in Table 5

The POVA/BE films exhibited a higher tensile strength of 69.69 MPa compared to 66.03 MPa for the pure POVA films. This enhancement in tensile strength is statistically significant at $p \leq 0.05$ and suggests that the addition of Barhi 70% ethanol extract reinforces the film matrix, making it more resistant to breaking under tension. The presence of phenolic compounds and other bioactive constituents in the Barhi extract likely contribute to stronger intermolecular interactions within the polymer network, leading to increased rigidity and tensile strength (Mahardika *et al*., 2021). Similar observations have been reported in studies where natural extracts were incorporated into polymer films, resulting in improved mechanical strength due to enhanced cross-linking and network formation (Asrofi *et al*., 2019).

Table 5. Tensile strength and elongation at break properties of studied POVA films

Sample	Tensile strength (MPa)	Elongation at break (%)
POVA	66.03±0.22*	60.65±0.52
POVA/BE	69.69±0.44*	66.72±0.34*

*** Significant differences between samples at p≤0.05. POVA= Polyvinyl alcohol. POVA/BE = Polyvinyl alcohol with Barhi 70% ethanol extract.**

The elongation at break, a measure of the film's flexibility and ability to stretch before breaking, was also significantly higher in POVA/BE films, with a value of 66.72%, compared to 60.65% for the POVA films. The increased elongation at break indicates that the Barhi extract not only enhances strength but also imparts greater flexibility to the films. This dual improvement in mechanical properties could be due to the plasticizing effect of the extract, which may reduce intermolecular forces within the POVA matrix, allowing for greater movement and flexibility of the polymer chains (Naznin *et al*., 2012).

The findings align with other research where the inclusion of natural extracts or plasticizers resulted in films that are both strong and flexible (Hidayati *et al*., 2021).

In summary, the incorporation of Barhi 70% ethanol extract into POVA films leads to significant improvements in tensile strength and elongation at break, demonstrating the potential of natural extracts to enhance the mechanical properties of biopolymer films. These enhancements are likely due to the reinforcing and plasticizing effects of the bioactive compounds in the extract, which improve the film's structural flexibility. Such modifications could be beneficial for applications requiring strong yet flexible packaging materials.

Scanning Electron Microscope (SEM) of fabricated films

SEM images of the POVA film and the POVA film incorporated with Barhi extract demonstrate significant differences in surface morphology, which can be attributed to the incorporation of Barhi extract into the POVA matrix. as shown in Figure 2.

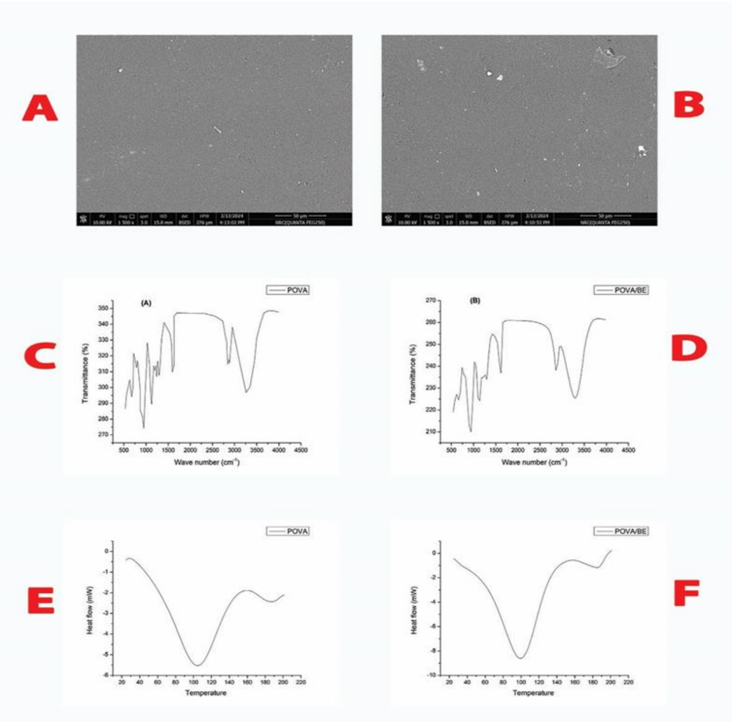


Fig. 2. SEM micrographs of (A) POVA and (B) POVA/BE films, FTIR of (C) POVA and (D) POVA/BE films and DSC of (E) POVA and (F) POVA/BE films

POVA Film (Without Barhi Extract) The surface of the POVA film appears to be relatively smooth and uniform with few irregularities. This smoothness indicates a homogenous film structure typical of pure POVA films, which is a result of the even distribution of the polymer matrix during the film-forming process. The lack of visible pores or cracks suggests good film integrity, which is crucial for applications that require barrier properties such as packaging.

POVA/BE Film (With Barhi Extract), The SEM image of the POVA film with Barhi extract shows noticeable changes in the surface texture. There are visible aggregates or clusters, indicating that the Barhi extract components may have interacted with the POVA matrix. The presence of these aggregates suggests that the phenolic compounds in the Barhi extract may not be uniformly distributed within the POVA matrix, possibly due to phase separation or incomplete solubilization. These morphological changes could influence the mechanical and barrier properties of the film, potentially enhancing antioxidant activity due to the presence of bioactive compounds from the extract (Kasai *et al*., 2018).

The incorporation of plant extracts into polymer matrices, such as POVA, is a common approach to enhance the functional properties of films. For instance, research by Kasai *et al*. (2018) reported similar morphological changes when natural extracts were added to biopolymer films, noting an increase in surface roughness and heterogeneity due to the interaction between polymer and bioactive compounds.

SEM analysis reveals that incorporating Barhi extract into POVA films significantly alters the surface morphology, potentially enhancing the film's functional properties. These changes underscore the importance of understanding the interaction between polymer matrices and bioactive compounds for developing advanced materials with tailored properties. Further research could focus on optimizing the dispersion and compatibility of such extracts to maximize the benefits for specific applications.

Fourier transform infrared spectroscopy (FTIR) of the fabricated films

FTIR spectra of both the pure POVA film and the POVA/BE film, which incorporates Barhi date extract, reveal significant insights into the structural composition and interactions within these films. The FTIR spectrum of the pure POVA film displays characteristic absorption bands typical of polyvinyl alcohol. Notably, there is a broad absorption peak around 3300 cm^{-1}, indicative of O-H stretching vibrations, highlighting the presence of hydroxyl groups, which are abundant in POVA due to its polymer structure. Additionally, peaks observed around 2900 cm^{-1} correspond to C-H stretching vibrations, typical of the polymer backbone, and a prominent peak near 1730 cm^{-1} likely arises from the C=O stretching of acetate groups. These may be present due to residual acetate groups in POVA from its partial hydrolysis during production. Furthermore, the fingerprint region (600–1500 cm^{-1}) showcases several peaks corresponding to C-O and C-C stretching, as well as C-H bending vibrations, which are crucial for understanding the material's complex molecular architecture (Kasai *et al*., 2018). When examining the FTIR spectrum of the POVA/BE film, which integrates Barhi date extract, notable changes are observed compared to the pure POVA film. There is a shift and increased intensity in the O-H stretching band around 3300 cm^{-1}, suggesting the formation of hydrogen bonds between the hydroxyl groups of POVA and phenolic compounds in the Barhi extract. This interaction is indicative of successful incorporation of the extract into the polymer matrix. Moreover, the C=O stretching band around 1730 cm^{-1} becomes more pronounced, possibly due to esterification reactions or other interactions between the POVA and phenolic acids from the extract. The appearance of new peaks and intensity variations in the fingerprint region further indicate complex interactions between POVA and the bioactive components of the Barhi extract, highlighting the introduction of new functional groups and chemical environments (Annu *et al*., 2021).

This analysis aligns with previous studies that report similar FTIR spectral changes upon incorporating natural extracts into polymer matrices. For example, Choo *et al*. (2016) discussed how the addition of plant extracts to polymers often results in new peaks and shifts in existing peaks due to interactions between the polymer and natural compounds. These changes are consistent with enhanced material properties such as improved antioxidant activity, as reported in studies where phenolic-rich extracts were added to polymers. Overall, the FTIR analysis indicates that the POVA/BE film exhibits significant structural changes due to the successful integration of Barhi date extract, which enhances its functional properties through new chemical interactions. These interactions are beneficial for applications requiring enhanced antioxidant capabilities and structural integrity, demonstrating the potential of such bio-composite films in packaging and other functional materials.

Differential Scanning Calorimetry (DSC) of fabricated films

The two DSC thermograms for the POVA film and POVA film with Barhi extract show notable differences, indicating the effect of the Barhi extract on the thermal properties of the polyvinyl alcohol (POVA) matrix.

POVA Film (First Image) The DSC thermogram of the pure POVA film displays a typical endothermic peak between 80°C and 120°C, corresponding to the melting point of POVA. This endothermic peak is likely related to the crystalline melting of POVA, which is a semi-crystalline polymer. The broad nature of the peak suggests that POVA has a complex crystallization behavior with possibly multiple phases or amorphous regions.

POVA/BE Film (Second Image) In comparison, the DSC thermogram of the POVA/BE film (POVA with Barhi extract) shows a more pronounced endothermic peak around a similar temperature range, but with greater depth and area, indicating a higher heat flow. The presence of Barhi extract appears to enhance the crystalline melting behavior of POVA, potentially due to interactions between the phenolic compounds in the extract and the POVA matrix. The extract might be acting as a nucleating agent, promoting crystallization within the POVA matrix, which could enhance thermal stability and alter the melting behavior (Sudhamani *et al*., 2003).

The presence of plant extracts can also introduce additional interactions, such as hydrogen bonding between hydroxyl groups of phenolic compounds and the polymer chains, influencing the thermal and mechanical properties of the film (Uslu *et al*., 2010).

Similar studies have shown that natural extracts can alter the thermal behavior of polymer films. For example, a study by Hikmawati *et al.* (2018) on POVA films reinforced with plant extracts showed improved thermal properties, with enhanced crystallinity and stability due to strong polymer-extract interactions.

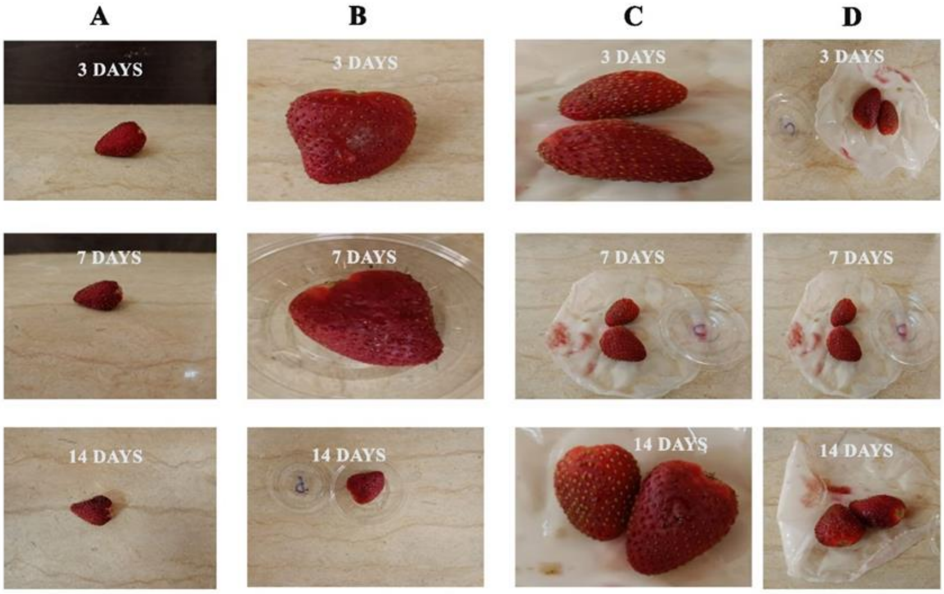
These findings collectively suggest that the addition of Barhi extract to POVA films not only alters their crystallization behavior but also potentially enhances their thermal stability, making them more suitable for various applications where higher thermal resistance is desired. The specific interactions between POVA and the phenolic compounds within Barhi extract contribute significantly to these modifications.

The incorporation of date phenolic extracts into POVA films demonstrates significant improvements in antioxidant properties and preservation effectiveness. When compared with bioactive films developed using other natural extracts, such as green tea, turmeric, or grape seed, the unique benefits of date extracts become evident. Green tea extract, rich in catechins, has been shown to significantly enhance the antioxidant activity of chitosan films, achieving DPPH scavenging activity of up to 70% (Siripatrawan and Harte, 2010). Similarly, graden cress extract has been incorporated into soduim alginate based films, yielding potent antioxidant activity, effectively preserving perishable foods like vegetable oil (Alshehri *et al.,* 2024). Compared to these, date phenolic films, particularly those utilizing Barhi ethanolic extracts, offer comparable antioxidant properties, with DPPH scavenging activity reaching 53.68%, while also providing enhanced mechanical strength and biodegradability. The use of date extracts further stands out due to their sustainability and potential utilization of agricultural waste, offering a dual benefit of waste valorization and functional packaging. These comparisons underscore the versatility of date phenolic films as an effective alternative to other bioactive films, demonstrating competitive antioxidant capabilities and superior environmental benefits.

Effect of storage of strawberry using biodegradable films

Weight loss of strawberry during cold storage

The data on weight loss of strawberries during storage using different packaging materials provides insight into the effectiveness of various films in preserving strawberry quality over time as illustrated in figure 3. The samples include strawberries stored without packaging, traditional plastic, pure Polyvinyl Alcohol (POVA), and POVA with Barhi 70% ethanol extract (POVA/BE). The measurements were taken at three intervals: 3, 7, and 14 days.



A= without packaging, B= Plastic, C= Fabricated films with Barhi phenolic extract. D= Fabricated films without Barhi phenolic extract

Fig 3. Effect of different storage condition on strawberry samples

On Day 3, strawberries stored without packaging exhibited the highest weight loss at 5.31%, followed by those in plastic at 4.66%, POVA at 4.83%, and POVA/BE at 4.68%. This initial trend suggests that both the POVA and POVA/BE films provide a better barrier against moisture loss compared to sample without packaging, with POVA/BE being slightly more effective than plastic. The reduced weight loss in POVA and POVA/BE films can be attributed to their ability to form a tighter barrier, potentially due to interactions between the film and strawberry surface, which reduces transpiration and respiration rates (Fawole *et al*., 2020).

By Day 7, the trend becomes more pronounced. The sample without packaging -stored strawberries have lost 7.94% of their weight, while those in plastic show a weight loss of 7.34%. In contrast, strawberries in POVA and POVA/BE films show significantly lower weight loss, at 6.48% and 6.59%, respectively. The superior performance of POVA-based films can be attributed to their enhanced barrier properties, which likely result from the film's hydrophilic nature that can form hydrogen bonds with water molecules, thus reducing vapor permeability. This aligns with studies that have found POVA films to exhibit good barrier properties due to their chemical structure, which restricts moisture movement (Maqbool *et al*., 2011).

By Day 14, the benefits of using POVA-based films are even more apparent. The weight loss for strawberries stored without packaging is 10.35%, and in plastic, it is 9.70%. However, strawberries stored in POVA and POVA/BE films demonstrate much lower weight losses of 7.80% and 8.00%, respectively. The POVA/BE film exhibits a slightly higher weight loss compared to pure POVA, which may be due to the extract's potential impact on film integrity or hydrophobicity, as the inclusion of natural extracts can sometimes alter the film's structural properties.

The results are significant as they highlight the potential of using biodegradable films like POVA and POVA/BE as alternatives to conventional plastic packaging. These films not only reduce the environmental impact associated with plastic use but also improve the preservation of fresh produce. The findings are particularly relevant in the context of increasing consumer demand for sustainable and effective food packaging solutions.

Comparing these results with other studies, the effectiveness of POVA films aligns with findings from Kaynarca *et al.* (2023) which demonstrated that biopolymer films, particularly those combined with natural extracts, can enhance the shelf life of fruits by reducing moisture loss.

Total Soluble Solids (TSS) of strawberry during cold storage

TSS for strawberries stored using different films presents an interesting picture of how various packaging materials influence the sugar concentration over time. The samples in this study include strawberries stored without packaging, traditional plastic, Polyvinyl Alcohol (POVA), and POVA with Barhi 70% ethanol extract (POVA/BE). Measurements were taken at intervals of 0, 3, 7, and 14 days.

At Day 0, the TSS values across all samples are quite similar, with values around 3.5%. This consistency indicates that the initial sugar content of strawberries was uniform before storage, ensuring a fair baseline for comparison.

By Day 3, differences begin to emerge. The TSS value for strawberries stored without packaging increases to 4.22%, while those in plastic, POVA, and POVA/BE films increase to 4.28%, 4.71%, and 4.82%, respectively. The significant increase in TSS for POVA and POVA/BE indicates a more pronounced conversion of starches to sugars compared to air and plastic storage. This phenomenon may be attributed to the films' ability to create a modified atmosphere around the fruit, slowing down respiration and maintaining higher metabolic activity, leading to greater sugar accumulation.

On Day 7, the trend continues, with without packaging-stored strawberries reaching a TSS of 4.83%, plastic-stored at 5.14%, POVA-stored at 5.27%, and POVA/BE-stored at 5.30%. The strawberries in POVA and POVA/BE films consistently exhibit higher TSS values, suggesting these films effectively enhance sugar retention or formation (Ding *et al.*, 2019).

By Day 14, the TSS in strawberries stored without packaging and in plastic decreases slightly to 4.68% and 4.14%, respectively. In contrast, strawberries stored in POVA and POVA/BE films maintain higher TSS levels at 4.75% and 4.84%. The decrease in TSS for sample without packaging and plastic storage can be linked to dehydration or microbial spoilage, which can consume sugars and lower their concentration. The higher retention in POVA-based films may be due to better moisture barrier properties, reducing weight loss and maintaining a stable internal environment for the fruit (Kaynarca *et al*., 2023).

Furthermore, the POVA/BE films showed a slight advantage over pure POVA, possibly due to the Barhi 70% ethanol extract providing additional antimicrobial properties or enhanced barrier performance. Studies like Kaynarca *et al*. (2023) have demonstrated that the inclusion of natural extracts in biopolymer films can improve the overall storage conditions for fruits by reducing oxidative stress and microbial activity.

The results of this study emphasize the potential of using biodegradable films, particularly those incorporating natural extracts, to enhance the storage life and quality of strawberries. The POVA and POVA/BE films show promise as alternatives to traditional plastic packaging, offering environmental benefits and improved preservation of fruit quality. The higher TSS values observed in these films indicate their effectiveness in maintaining the desired sweetness and overall acceptability of strawberries, aligning with consumer preferences for taste and quality.

Firmness of strawberry during cold storage

Firmness of strawberries stored using different films over a period of 14 days reveals notable differences in how various packaging materials influence the texture retention of the fruit. Initially, at Day 0, the firmness values for all samples are relatively uniform, indicating a consistent starting quality. This baseline allows for a meaningful analysis of how each packaging method affects the strawberries over time.

By Day 3, significant differences emerge. Strawberries stored without packaging show a marked decrease in firmness, dropping to 7.62. This decline is likely due to the lack of protection against environmental factors, leading to increased moisture loss and accelerated enzymatic activity that breaks down cell walls. In contrast, strawberries wrapped in plastic maintain better firmness, with a value of 8.81, suggesting that plastic offers a barrier that helps retain moisture and reduce the impact of oxidative processes. However, the most effective packaging appears to be the POVA-based films, with POVA and POVA/BE maintaining firmness values of 9.04 and 9.16, respectively. This superior performance could be attributed to the films' ability to create a microenvironment that limits gas exchange and moisture evaporation, preserving the fruit's structural integrity (Hernandez-Munoz *et al*., 2008).

The trend continues on Day 7, where strawberries stored without packaging soften significantly to 5.56, underscoring the inadequate protection offered by ambient conditions. Plastic-wrapped strawberries fare better, retaining a firmness of 7.75, but again, they fall short of the results seen with POVA-based films. The POVA film achieves a firmness of 8.58, and POVA/BE matches it at 8.59, highlighting their capacity to maintain quality over a more extended period. This finding aligns with studies of Kaynarca *et al*. (2023) that emphasize the benefits of biodegradable films containing natural extracts, which not only offer physical barriers but also potentially inhibit microbial growth through antimicrobial properties.

By the end of the storage period on Day 14, the firmness of strawberries stored without packaging further decreases to 5.27, reflecting significant textural degradation. Those in plastic wrap also show continued softening, although at a slower rate, with a firmness of 6.24. However, POVA and POVA/BE films again demonstrate their effectiveness, with firmness values of 8.00 and 8.12, respectively. The sustained firmness suggests that these films are particularly effective at mitigating the factors that typically lead to fruit softening, such as moisture loss and microbial spoilage.

Comparing these results with other studies, it is clear that the use of POVA-based films, especially those enhanced with extracts like Barhi ethanol, provides significant advantages over conventional plastic and without packaging storage. Similar research has shown that incorporating natural extracts into biodegradable films can enhance their protective qualities, offering not just a physical barrier but also biochemical benefits that extend shelf life and preserve texture. For instance, studies on POVA films have reported improved firmness retention in strawberries, attributed to reduced respiration rates and enhanced antimicrobial effects (Kaynarca *et al*., 2023).

The practical implications of these findings are significant for the food packaging industry, especially in the context of increasing consumer demand for environmentally friendly packaging solutions that do not compromise on food quality. POVA-based films, particularly those with added bioactive compounds, offer a promising alternative to traditional plastic wraps, providing a sustainable solution that supports both the preservation of food quality and environmental sustainability.

TTA of strawberries during cold storage

The results of TTA (% as citric acid) measurements for strawberries stored with different films over a period of 14 days reveal how packaging materials can influence the acidity levels of stored fruit. At Day 0, the TTA values for all samples are similar, with slight variations between 1.23 and 1.30. This consistency provides a clear baseline for analyzing the changes in acidity over time.

By Day 3, significant differences begin to emerge. The strawberries stored without packaging exhibit a noticeable decrease in TTA to 0.83, indicating a rapid decline in acidity. This reduction in acidity can be attributed to the metabolic activities that continue unabated in the absence of any protective packaging, leading to an increased rate of respiration and biochemical transformations that consume organic acids. In comparison, strawberries stored in plastic maintain a slightly higher TTA of 0.92, suggesting that plastic offers some protection against these processes, albeit less effectively than other materials.

In stark contrast, the strawberries stored using POVA-based films retain much higher TTA values, with POVA at 1.12 and POVA/BE at 1.07. The superior performance of these films could be due to their ability to create a modified atmosphere that slows down respiration and conserves organic acids. The addition of bioactive components like Barhi ethanol extract in POVA/BE might further enhance this effect by introducing antioxidant and antimicrobial properties that stabilize the fruit's internal environment (Hernandez-Munoz *et al*., 2008).

By Day 7, the trend continues, where strawberries stored without packaging showing a further decline in TTA to 0.57, reflecting ongoing acid degradation. Those wrapped in plastic also see a drop to 0.75, highlighting the limitations of conventional plastic packaging in preserving fruit acidity over longer storage durations. However, strawberries stored in POVA and POVA/BE films retain much higher TTA levels at 0.95 and 1.01, respectively. This finding aligns with research demonstrating that biodegradable films with natural extracts can more effectively preserve fruit quality by maintaining acidity, flavor, and freshness (Kaynarca *et al*., 2023).

By Day 14, the acidity of strawberries stored without packaging decreases even further to 0.47, signifying substantial quality loss. Plastic-wrapped strawberries also continue to lose acidity, with a TTA of 0.63. Meanwhile, strawberries stored in POVA and POVA/BE films exhibit significantly better preservation of acidity, with TTA values of 0.86 and 0.85, respectively. This sustained acidity suggests that these films provide a more favorable storage environment by reducing oxygen exposure and inhibiting microbial growth, which can degrade organic acids.

Comparing these findings with other studies like Petriccione *et al*. (2015), it is evident that the use of POVA-based films, particularly those enriched with natural extracts, offers substantial advantages over traditional plastic wraps and air storage. These results underscore the potential of biodegradable films as effective alternatives for enhancing the shelf life and quality of perishable fruits like strawberries.

The practical implications of this study are significant, especially in the context of reducing food waste and extending the shelf life of fresh produce, by preserving acidity and other quality parameters, biodegradable films can help maintain the sensory attributes of fruits, thereby increasing consumer satisfaction and reducing economic losses. This aligns with the growing trend toward sustainable packaging solutions that prioritize environmental responsibility without compromising product quality.

Vitamin C of strawberry during cold storage (mg\100g)

The vitamin C content in strawberries stored using different films reveals important insights into the effectiveness of these packaging methods in preserving nutritional quality. At Day 0, all samples have similar vitamin C levels, around 125 mg/100g, providing a baseline for assessing changes during storage.

Over time, significant differences emerge, especially by Day 3. The strawberries stored without packaging and plastic show increases in vitamin C content, reaching 127.83 mg/100g and 128.68 mg/100g, respectively. This increase could be due to the natural variation in vitamin C concentration within the fruit as it continues to ripen post-harvest. However, strawberries stored in POVA and POVA/BE films exhibit even higher vitamin C levels, at 129.41 mg/100g and 129.30 mg/100g, respectively. This suggests that these films may help maintain or even enhance vitamin C content by providing a more controlled atmosphere that slows degradation processes (Dang *et al*., 2010).

By Day 7, the differences become more pronounced. The vitamin C content in strawberries stored without packaging drops significantly to 101.36 mg/100g, indicating substantial degradation likely due to oxidation and microbial activity. Plastic-wrapped strawberries fare better at 111.22 mg/100g, yet still show a considerable decrease. In contrast, strawberries in POVA and POVA/BE films maintain higher vitamin C levels, at 117.96 mg/100g and 118.71 mg/100g, respectively. This preservation of vitamin C aligns with studies that demonstrate the efficacy of bioactive films in extending the shelf life of fruits by reducing exposure to oxygen and light, both of which contribute to nutrient degradation (Dang *et al*., 2010).

By Day 14, strawberries stored without packaging show a drastic reduction in vitamin C to 92.79 mg/100g, reflecting continued degradation and the limitations of storing fruit without protective covering. Plastic storage also results in a further decline to 100.82 mg/100g. In contrast, strawberries in POVA and POVA/BE films retain significantly higher levels of vitamin C, at 105.80 mg/100g and 111.77 mg/100g, respectively. The effectiveness of these films in preserving vitamin C may be attributed to their ability to create a modified atmosphere that inhibits oxidative reactions and microbial spoilage, as supported by previous research on similar biodegradable films (Ding *et al*., 2019).

Comparing these findings with other studies, the results corroborate the potential of biodegradable films enhanced with natural extracts to preserve the nutritional quality of fruits more effectively than conventional plastic packaging. For instance, similar studies have shown that such films can significantly delay nutrient loss and maintain antioxidant properties, supporting the use of innovative packaging solutions to improve fruit storage (Petriccione *et al*., 2015).

Overall, the study highlights the importance of packaging in preserving vitamin C content and suggests that POVA-based films, particularly those with Barhi ethanol extract, offer a superior alternative to traditional methods. This has significant implications for extending the shelf life and nutritional quality of strawberries, aligning with consumer demands for fresher, healthier produce.

Total phenolic content of strawberry during cold storage

The total phenolic content (TPC) in strawberries stored using different films highlights significant differences in how well these packaging methods preserve bioactive compounds. Initially, all samples exhibit considerable phenolic content, ranging from 146.03 mg/g to 179.53 mg/g as illustrated in figure 4.

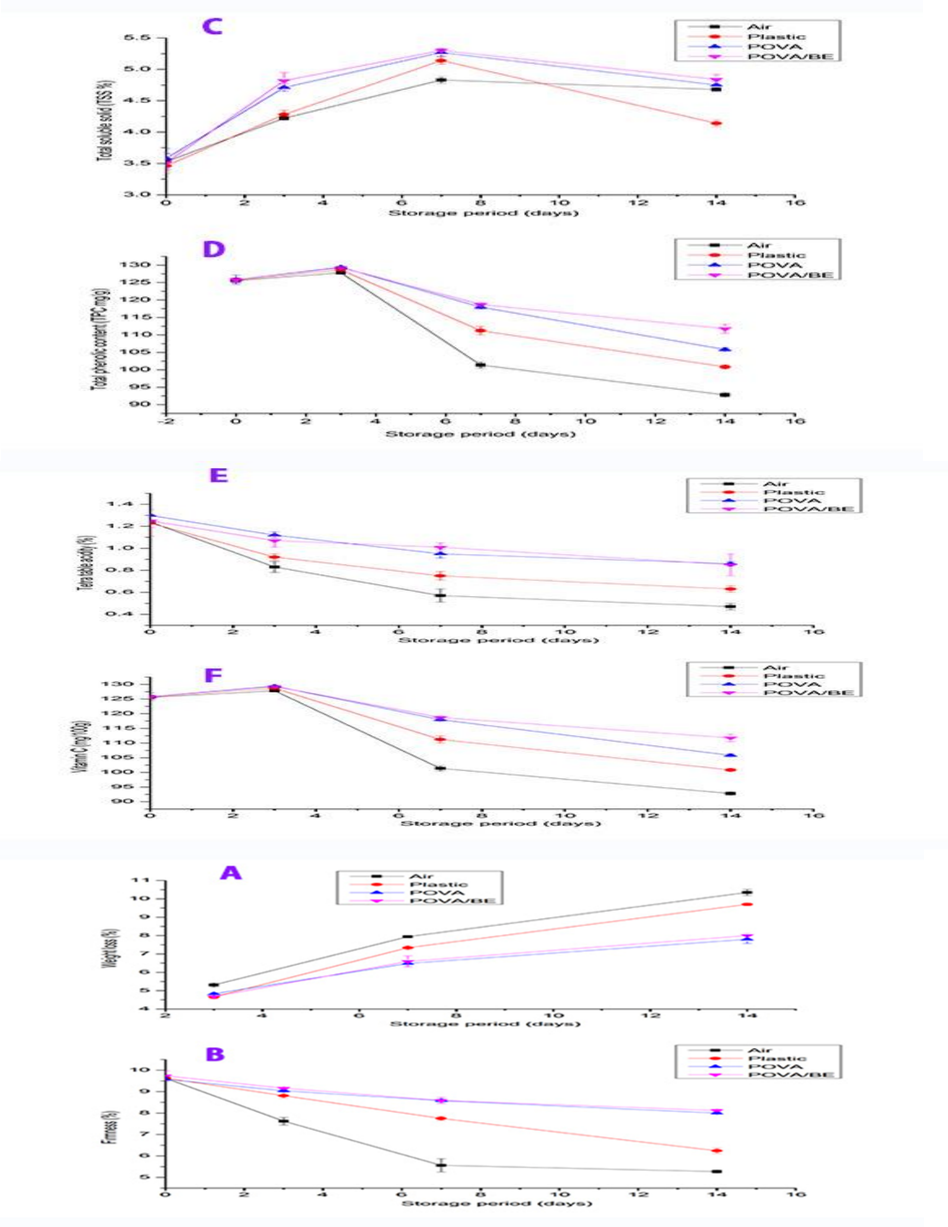


Fig. 4. Weight loss (%), total soluble solid (TSS %), firmness (%), tetra table acidity (%), vitamin C (mg/100g) and total phenolic content (mg/g) of strawberry storage at ±2 °C by using fabricated films

At Day 0, strawberries stored without packaging have the lowest TPC at 146.03 mg/g, while those in POVA show the highest at 179.53 mg/g. The initial high phenolic content across samples is consistent with previous studies indicating that strawberries are rich in phenolic compounds, which contribute to their antioxidant capacity (Van De Velde *et al*., 2013).

After 14 days, significant changes occur. The TPC in strawberries stored without packaging plummets to 72.47 mg/g, marking a substantial degradation likely due to oxidation and microbial activity. This decline is supported by Ali *et al*. (2019) who noted that exposure to air accelerates phenolic degradation in fruits.

Plastic storage yields better preservation, with TPC reducing to 102.41 mg/g. Although plastic reduces exposure to oxygen compared to strawberries stored without packaging, it still allows some oxidation, which diminishes phenolic content.

Strawberries stored in POVA films retain significantly higher TPC at 142.53 mg/g. The controlled atmosphere created by these films appears effective in limiting oxidative stress, thereby preserving phenolic compounds. This is corroborated by Kaynarca *et al*. (2023) who demonstrated that biodegradable films could enhance the shelf-life and quality of stored produce.

The POVA/BE films perform exceptionally well, with a minimal decrease in TPC, retaining 163.78 mg/g. The presence of Barhi ethanol extract may provide additional antioxidant protection, further preserving phenolic content.

Studies by Kaynarca *et al*. (2023) confirm that phenolic content is sensitive to environmental conditions, with controlled atmospheres preserving these compounds more effectively. Research by (Ding *et al*. 2019) on biodegradable films also supports these findings, emphasizing their efficacy in extending the shelf life of fruits by retaining nutritional and bioactive properties.

Overall, the data illustrates that the choice of packaging significantly impacts the preservation of phenolic content in strawberries. POVA and POVA/BE films demonstrate superior preservation capabilities, suggesting their potential as effective packaging solutions for extending the shelf life of strawberries while maintaining their nutritional quality.

CONCLUSION

This study demonstrates the potential of polyvinyl alcohol (POVA) films incorporated with date phenolic extracts, particularly from Barhi dates, as effective biodegradable packaging materials. The enhanced antioxidant activity, mechanical properties, and barrier functionality observed in the films highlight their ability to preserve perishable foods, such as strawberries, for extended periods. While the findings underscore the scientific and functional merits of these bioactive films, their scalability for commercial food packaging applications warrants further exploration. The use of agricultural by-products like date phenolic extracts aligns with sustainable practices, offering a cost-effective and eco-friendly alternative to petroleum-based plastics. Moreover, the simplicity of the film preparation process suggests feasibility for large-scale production, especially given the availability and low cost of raw materials. Future research should focus on optimizing production methods, assessing the economic viability, and conducting industrial-scale trials to validate their performance under real-world conditions. These efforts would further establish the applicability of these films in addressing the food industry's growing demand for sustainable and functional packaging solutions.

Declaration of interests: None

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أفلام قابلة للتحلل غنية بمضادات الأكسدة: دمج مستخلصات فينولية من التمر في أفلام كحول بولي فينيل لحفظ الفراولة

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الملخص

هذه الدراسة تقيم تطوير وتوصيف أفلام بولي فينيل الكحول (POVA) المدمجة مع مستخلصات فينولية من نوعين من التمر، البرحي والمجدول، وتطبيقها المحتمل في تعبئة الفراولة. تم تقييم المحتوى الفينولي الكلي (TPC) والنشاط المضاد للأكسدة (DPPH) للمستخلصات المائية والكحولية لتمور البرحي والمجدول. أظهر التمر البرحي محتوى فينولي كلي (TPC) ونشاط مضاد للأكسدة (DPPH) أعلى من التمر المجدول، حيث بلغ 10.53 ملجم/جم و65.83%، على التوالي، في مستخلصه الكحولي مقارنةً بـ 7.39 ملجم/جم و50.63% في مستخلص المجدول. أظهرت أفلام POVA المدمجة مع مستخلص البرحي الكحولي (POVA/BE) أعلى محتوى فينولي كلي 3.58 ملجم جاليك/جم وأعلى نشاط مضاد للأكسدة (53.68%) مقارنة بالأفلام الأخرى. تم تقييم الخصائص الفيزيائية للأفلام، بما في ذلك السمك ونفاذية بخار الماء(WVP) ، حيث أظهرت أفلام POVA/BE خصائص محسنة مع نفاذية بخار ماء (WVP) بلغت 88.75 × 10^{-10} غرام/H_2O م^2 ث. ضغط جوي مقارنةً بـ POVA النقي، أظهرت أفلام POVA/BE أيضًا خصائص ميكانيكية متفوقة، حيث بلغت قوة الشد 69.69 ميجا باسكال والاستطالة عند الكسر 66.72%. بالإضافة إلى ذلك، أظهرت تجارب تخزين الفراولة أن أفلام POVA/BE قللت من فقدان الوزن، وحافظت على صلابة أعلى، والمواد الصلبة الذائبة الكلية(TSS) ، والحموضة الكلية(TTA) ، ومحتوى فيتامين C على مدار 14 يومًا من التخزين، حيث بلغ فقدان الوزن 8.00%، ومحتوى المواد الصلبة الذائبة الكلية4.84% (TSS) ، واحتفاظ فيتامين C عند 111.77 ملجم/100جم. تشير هذه النتائج إلى أن أفلام POVA المحتوية على مستخلصات التمر البرحي تقدم نشاطًا مضادًا للأكسدة محسّنًا، وقوة ميكانيكية، وخصائص حاجزية، مما يجعلها حلاً قابلاً للتحلل الحيوي واعدًا لإطاله عمر الأطعمة القابلة للتلف مثل الفراولة.

الكلمات الدالة: حفظ الفراولة، فاكهه البلح، التعبئة بالأفلام الحيوية القابلة للتحلل، خواص الجودة