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Production of Active Biodegradable Films as Eco-Friendly Packaging

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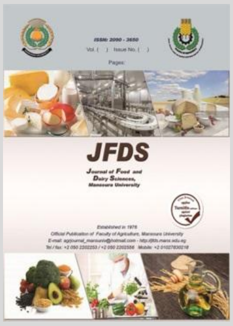

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ABSTRACT

This study investigated the potential of tomato by-products phenolic extract (TO) as a functional additive for developing biodegradable polyvinyl alcohol (POVA) films and its application in guava fruit preservation. Tomato by-products powder was found to be rich in phenolic compounds, particularly chlorogenic acid (1001.33 μg/g), rutin (688.25 μg/g), catechin (612.35 μg/g), and gallic acid (587.27 μg/g), contributing to a high antioxidant activity (87.46%). Incorporation of TO into POVA films significantly increased film thickness (0.15 mm), tensile strength (80.93 MPa), elongation at break (75.83%), water contact angle (81.56°), and biodegradability (25.61% weight loss after 30 days), while reducing solubility and water vapor permeability. In postharvest storage, guava fruits packaged with POVA/TO films showed reduced weight loss (10.27% vs. 21.58% in control), higher firmness (26.07 N vs. 10.27 N), delayed increases in total soluble solids and titratable acidity, and improved retention of vitamin C (70.11 mg/100 g) and phenolic compounds (36.02 mg GAE/100 g) after 4 weeks at 4 °C. Antioxidants activity (DPPH) was also maintained at significantly higher levels (60.53%) in POVA/TO-packaged fruits compared to control (30.05%). These findings demonstrate that TO incorporation enhances the physicochemical, mechanical, and active functionalities of POVA films, and effectively extending the shelf life and nutritional quality of guava fruits.

Keywords: Biodegradable films, Polyvinyl alcohol (POVA), Tomato by-products- , Guava preservation, Shelf-life extension

INTRODUCTION

The escalating environmental issues linked to the extensive use of non-biodegradable plastics in food packaging have intensified global efforts to identify sustainable alternatives. Biodegradable films, often referred to as bio-covers, have emerged as a promising option. These materials, derived from eco-friendly polymers and fortified with natural additives, are capable of decomposing naturally while preserving the critical barrier properties necessary for food storage. Advances in the design of bio-covers emphasize their potential as substitutes for conventional plastics, offering a practical approach to mitigating plastic pollution (Onyeaka, *et al*.,2022 and Alshehri *et al*., 2024)

Agricultural residues, a major by-product of food processing, provide an underutilized yet valuable resource for sustainable innovations. Tomato processing generates considerable amounts of by-products that are typically discarded, although they are rich in bioactive constituents such as phenolic compounds (Sorrenti *et al*., 2023). These phenolics exhibit strong antioxidant activity, making them suitable for incorporation into biodegradable packaging materials. Innovative extraction techniques, including ultrasound-assisted and enzymatic methods, have been employed to obtain phenolic compounds efficiently, turning agricultural waste into functional bioactive ingredients for food packaging applications (Alexandre Moreira *et al*., 2018).

The integration of phenolic compounds into biodegradable films enhances their functional characteristics. Besides imparting antioxidant potential, phenols contribute to improved mechanical strength and better barrier properties against oxygen and water vapor(Abdin *et al*., 2024). Such improvements are particularly beneficial for extending the shelf life of fresh produce while maintaining quality. Previous studies have confirmed the effectiveness of phenolic-loaded films in minimizing oxidative reactions and microbial spoilage, underscoring their suitability for active packaging purposes (Riaz *et al*., 2020 and Azizah A. Alshehri *et al*., 2024).

Current research has also highlighted the use of plant- and fruit-derived extracts in reinforcing biodegradable films. For instance, the incorporation of pomegranate peel extracts into chitosan-based films has demonstrated remarkable antioxidant and antimicrobial properties, thereby prolonging the storage stability of food products(Kumar *et al*., 2021). Likewise, hop plant extracts have been applied to chitosan–gelatin films, yielding notable improvements in both antioxidant activity and mechanical strength (Xu, Chen, and Liu, 2021).

Guava (*Psidium guajava* L.) is a tropical fruit highly valued for its nutritional richness, including vitamin C, dietary fiber, and various bioactive molecules. Despite its health benefits, guava is characterized by high perishability, experiencing rapid postharvest deterioration due to water loss, microbial contamination, and enzymatic reactions(Yadav *et al*., 2022). Developing effective packaging strategies to prolong guava's shelf life is crucial to reduce postharvest losses and deliver quality fruit to consumers. The application of phenolic-enriched biodegradable films represents a sustainable packaging solution for preserving guava quality during storage.

The objectives are to improve the physical, mechanical, and functional features of POVA films and to investigate their

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capacity to extend the shelf life and preserve the quality of fresh produce, using guava as a representative model.

MATERIALS AND METHODS

Materials:

Fresh and ripe guava fruits (*Psidium guajava L.*) of uniform size and maturity were purchased from a local market in Kafr El-Sheikh City, Egypt.

Tomato by-products (skins, seeds, and pulp) obtained were collected from Al-Salah Food Industries, located in the industrial area of Baltim, Kafr El-Sheikh Governorate, Egypt.

Polyvinyl alcohol (POVA; ≥98% hydrolyzed, MW 89,000–98,000 Da) All chemicals used in this study for analysis were obtained from El Gomhouria Pharmacentical Company, EL-Mansoura city, EL-Dakahlia Governorate, Egypt

Methods:

Extraction of Phenolic Compounds from Tomato by-products

The samples of tomato by-products (skins, seeds, and pulp) were immediately transported to the laboratory and visually inspected to remove any foreign materials. The Tomato by- Products were dried in a hot air oven at 55°C, ground, sieved (<250 µm), and stored at 4 ± °C until further use according to the method descripted by Calvo *et al*., (2021)

Phenolic compounds were extracted by ultrasound-assisted extraction (UAE). Approximately 30 g of tomato powder was mixed with 300 mL of 70% ethanol or distilled water and subjected to ultrasonication (VCX 750, USA) for 30 min. The extracts were filtered (Whatman No.1), concentrated using a rotary evaporator (RV 10 C S93, Germany), and freeze-dried (LYO60B-1PT, China) at −40 °C for 48 h. The dried extracts were stored at −20 °C until according to the method descripted by Owon *et al*., (2021)

Determination of Phenolic Profile by HPLC

Phenolic constituents were analyzed using an Agilent 1260 HPLC system equipped with a Zorbax Eclipse Plus C8 column (4.6 × 250 mm, 5 µm). The mobile phase consisted of water (A) and 0.05% trifluoroacetic acid in acetonitrile (B) at a flow rate of 0.9 mL/min. A linear gradient program was applied: 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). Detection was carried out at 280 nm with an injection volume of 5 µL. Column temperature was maintained at 40 °C according to the method descripted by Atoui, *et al*.,(2005). This was done in Agricultural Research Center and Food Technology Research Institute, Giza, Egypt

Film Preparation

Control Film (POVA)

POVA solution (4 g/100 mL distilled water) was prepared by heating at 95 °C and stirring at 700 rpm for 2 h. Glycerol (1.5 g) was added as a plasticizer, followed by an additional 30 min of stirring. The mixed at 40 °C for 30 min (900 rpm). About 75 mL of the resulting solution was poured into 15 cm Petri dishes and dried at 50 °C for 7 h. Films were peeled off and conditioned in a desiccator (50% RH, saturated $Ca(NO_3)_2$ solution) until further analysis according to the method descripted by Alshehri *et al*., (2024).

Preparation of Tomato Film (POVA/TO):

For tomato film (POVA/TO), 0.25 g of lyophilized Tomato by Products powder were incorporated to the previous solution. After that, POVA and POVA/TO films were 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 according to the method descripted by Alshehri *et al*., (2024)

Color Measurements

Film color (L*, a*, b*, c*) was determined using a portable colorimeter (3NH SR-66, China) following the procedure of according to the method descripted by Alshehri *et al*., (2024).

Moisture Content and Solubility

Film samples (20 × 20 mm) were weighed fresh (W0), dried at 105 °C to obtain dry weight (W1), then immersed in 50 mL distilled water at 25 °C for 24 h. The insoluble fraction was dried again (W2) according to the method descripted by Abdin *et al*., (2024).

Results were calculated as:

$$\text{Moisture content (\%)} = ((W0 - W1)/W0) \times 100$$

$$\text{Solubility (\%)} = ((W1 - W2)/W1) \times 100$$

Thickness and Water Vapor Permeability (WVP)

Film thickness was measured at five points using a digital micrometer. WVP was determined by sealing films over glass cups containing calcium chloride and monitoring weight gain under 50% RH at 25 °C for 10 h. The slope of weight change was used to calculate WVP using the formula according to the method descripted by Younis *et al*., (2025).

Biodegradability Test in Soil

The biodegradability of the prepared films (POVA and POVA/TO) was evaluated under natural soil conditions according to the method described by Abdin *et al*. (2023) with slight modifications. Film samples (2 × 2 cm) from each formulation were buried at a depth of 5 cm in plastic pots (15 cm in diameter) containing natural clay soil collected from the Agricultural Research Center, Sakha, Kafr El-Sheikh, Egypt. The pots were kept at room temperature (25 ± 2 °C) for 30 days without any additional watering or soil moistening. To monitor the degradation process, film samples were removed every 10 days (at 10, 20, and 30 days).

At each interval, the retrieved samples were gently cleaned with a soft brush to remove soil residues, rinsed with distilled water to eliminate any remaining particles, and dried in a hot-air oven at 50 °C until constant weight. The dry weight after burial (Wt) was recorded, and the biodegradation rate was calculated using the following equation:

$$\text{Weight loss (\%)} = ((W_0 - Wt) / W_0) \times 100$$

Where W_0 is the initial dry weight and Wt is the dry weight after burial for t days. All measurements were performed in triplicate, and the results were expressed as mean ± standard deviation (SD).

Mechanical Properties

Tensile strength (TS) and elongation at break (EB) were measured using a texture analyzer (TA.XT Plus, Stable Micro Systems, UK). Rectangular strips (20 × 100 mm) were tested at 100 mm/min with a load cell of 100 N according to the method descripted by Abdin *et al*., (2024).

Total Phenolic Content

Total phenolic content (TPC) was determined using the Folin–Ciocalteu method. A 10 µL aliquot of extract was mixed with 100 µL diluted Folin reagent and 80 µL Na_2CO_3 (1M), incubated at 25 °C for 20 min, and absorbance read at

630 nm. Gallic acid was used as the standard according to the method described by Attard *et al*., (2013)

Guava Packaging Procedure

Fresh guava fruits of uniform size and maturity were selected, washed, and air-dried at room temperature. The fruits were divided into three groups: unpackaged (control), packaged with neat POVA film, and packaged with POVA/TO film containing tomato phenolic extract. Each fruit was individually wrapped with the prepared biodegradable film according to the method described by Yadav *et al*. (2022) and modified by Abdin *et al*. (2023). The edges of the films were gently pressed to ensure complete adhesion to the fruit surface. and each fruit was monitored during the 30-day storage period. All fruits were stored under refrigerated conditions at 4 ± 1 °C and 85–90 % relative humidity for 30 days. Quality evaluations of guava fruits were carried out at 0, 7, 14, 21, and 28 days of storage

Weight Loss of Fruits

Weight loss (%) was calculated from initial and final weights of fruits using a digital balance as according to the method descripted by Maria (2024)..

Vitamin C Content

Ascorbic acid was measured according to the method descripted by Hernández *et al*. (2006). Fresh fruit (5 g) was homogenized in 95 mL of 0.4% oxalic acid. A 10 mL aliquot was titrated against 0.4% 2,6-dichlorophenol-indophenol (DCPIP) until a pink endpoint appeared. Results were expressed as mg ascorbic acid/100 g fresh weight. This was done in Agricultural Research Center and Food Technology Research Institute, Sakha Lab, Egypt.

Statistical Analysis

Data were analyzed by one-way ANOVA using SPSS v16.0. Differences between means were assessed with Duncan's test at p ≤ 0.05.

RESULTES AND DISCUSSION

Phenolic Content and Antioxidants Activity of Tomato By-Product Powder

The tomato by-products powder exhibited a relatively high total phenolic content (TPC) of 12.64 mg/g, which was accompanied by strong antioxidants activity, as indicated by 85.50% DPPH radical scavenging activity (Table 1). The significant difference observed between TPC and antioxidant activity confirms that phenolic compounds play a major role in determining the bioactive potential of tomato by-products.

Tomato processing residues (peels and seeds) are recognized as rich sources of bioactive compounds, particularly phenolic acids (such as caffeic and ferulic acid) and flavonoids, which contribute to antioxidant potential Sánchez-Rangeletal *et al*., (2013). In addition, the presence of carotenoids (mainly lycopene and β-carotene) in tomato by-products may act synergistically with phenolics, further enhancing radical scavenging efficiency Yin *et al*., (2017).

The high DPPH inhibition value (>85%) observed in this study is consistent with previous findings, where tomato peels and seeds showed strong antioxidant activity due to the abundance of polyphenols and secondary metabolites Csupász *et al*., (2022). Such activity highlights the potential of tomato by-product powder as a functional ingredient for food fortification or as a natural antioxidant additive in active packaging applications.

The strong correlation between phenolic content and antioxidants activity supports the use of tomato by-products as sustainable sources of natural antioxidants, in line with the growing interest in valorizing agro-industrial residues for functional food applications Sánchez-Rangel *et al*., (2013).

Table 1. Total phenolic content and antioxidants activity of tomato by product powder

Sample	Total phenolics (mg/g)	Antioxidants activity (DPPH%)
Tomato by product powder	12.64±0.22	85.50±2.77

*** Significant differences were occurred between two groups.**

Phenolic compounds of tomato by product powder

The HPLC analysis of tomato by-product powder revealed a diverse profile of phenolic compounds, with chlorogenic acid (1001.33 µg/g), rutin (688.25 µg/g), catechin (612.35 µg/g), and gallic acid (587.27 µg/g) being the predominant constituents (Table 2). The presence of these compounds explains the high antioxidants potential of tomato by-products, as reported earlier Szabo *et al*., (2018) and Csupász *et al*., (2022).

Table 2. Phenolic compounds (µg/g) of tomato by products powder

Phenolic Compound (µg/g)	Tomato by products powder
Gallic acid	587.27
Chlorogenic acid	1001.33
Catechin	612.35
Methyl gallate	92.97
Coffeic acid	159.71
Syringic acid	18.54
Rutin	688.25
Ellagic acid	243.72
Coumaric acid	26.88
Vanillin	39.97
Ferulic acid	0.00
Naringenin	184.77
Rosmarinic acid	23.03
Daidzein	5.50
Querectin	2.84
Cinnamic acid	0.96
Kaempferol	15.00
Hesperetin	0.84

Chlorogenic acid, the most abundant phenolic detected, is a well-known hydroxycinnamic acid with strong antioxidants and free radical scavenging activity. Its dominance in tomato residues is consistent with previous findings, where chlorogenic acid was identified as a major phenolic in tomato peels and seeds Toor and Savage, (2005). Similarly, rutin, a flavonoid glycoside, was found in high amounts (688.25 µg/g), supporting its role in enhancing antioxidant capacity and contributing to potential health benefits such as anti-inflammatory and cardioprotective effects.

Catechin (612.35 µg/g) and gallic acid (587.27 µg/g) were also abundant in the tomato by-product powder. Both compounds are recognized for their strong radical scavenging properties and synergistic interactions with other phenolics, which may explain the high DPPH and ABTS inhibition values previously observed in the same samples Yin *et al*., (2017). Moreover, the detection of ellagic acid (243.72 µg/g) and naringenin (184.77 µg/g) further confirms the functional potential of tomato by-products, since these compounds are linked with antimicrobial, anticancer, and anti-aging activities Csupász *et al*., (2022).

Interestingly, only trace levels of quercetin (2.84 µg/g) and kaempferol (15.0 µg/g) were found, while ferulic acid was not detected. This variability may be attributed to differences in tomato cultivar, processing conditions, and extraction methods, which significantly influence phenolic Content Vallverdú-Queralt *et al*., (2011). Overall, the phenolic Content observed in the present study indicates that tomato by-products are valuable sources of hydroxycinnamic acids, flavonoids, and hydroxybenzoic acids, which contribute not only to antioxidant activity but also to potential applications in functional foods, nutraceuticals, and bioactive packaging materials.

Physical and chemical properties of fabricated biodegradable films

The physical characterizations of the produced films (Table 3) showed significant differences between the neat POVA film and the POVA/TO composite film. The incorporation of TO into the POVA matrix led to an increase in film thickness from 0.11 ± 0.01 mm to 0.15 ± 0.02 mm. Such an increase can be attributed to the structural modification of the polymer matrix and the presence of bioactive additives, which may enhance intermolecular interactions and lead to denser structures Rhim *et al*., (2013) .

Film solubility decreased from 22.23% in the control POVA film to 19.73% in the POVA/TO film, suggesting an improvement in water resistance. This reduction may be explained by the hydrophobic nature of TO components, which reduce the affinity of the film matrix to water molecules, thereby decreasing solubility. Similar findings were reported for films enriched with essential oils and natural extracts(Hajji *et al*., 2014).

Moisture content also decreased significantly in the POVA/TO film (11.14%) compared to the POVA control (14.25%). The reduction in moisture content might be due to reduced water uptake capacity caused by stronger hydrogen bonding interactions between POVA and TO phenolics, limiting the availability of hydrophilic sites Perdones *et al*., (2012).

Interestingly, the water contact angle increased from 70.73° for the neat POVA to 81.56° for the POVA/TO film, indicating enhanced hydrophobicity of the film surface. This change reflects the incorporation of TO phenolics with non-polar characteristics, which modifies surface energy and improves water repellency(Rhim *et al*.,2007).

In terms of barrier performance, the water vapor permeability (WVP) was significantly reduced in the POVA/TO films (1.457 × 10−10 g·m−1·s−1·Pa−1) compared to the control POVA films (2.115 × 10−10 g·m−1·s−1·Pa−1). This decrease in WVP suggests that the addition of TO created a more compact polymer structure, which hindered the diffusion pathways of water vapor molecules. This result is consistent with earlier reports where incorporation of natural hydrophobic additives improved barrier properties in biopolymer-based films(Chen *et al*., 2018 and Lopes *et al*., 2025).

Table 3. Physical characterizations of biodegradable films

Sample	Thickness (mm)	Solubility (%)	Moisture content (%)	Water contact angel (%)	Water vapor permeability (× 10− 10 g. m− 1 s-1 pa− 1)
POVA	0.11±0.01^{b}	22.23±0.58a	14.25±0.69a	70.73±1.83^{b}	2.115±0.005^{a}
POVA/TO	0.15±0.02^{a}	19.73±0.49^{b}	11.14±0.83^{b}	81.56±2.52^{a}	1.457±0.007^{b}

Color Properties of Biodegradable Films

The color parameters of the films were significantly influenced by the incorporation of tomato by-product phenolic extract into the POVA matrix (Table 4). The lightness (L*) value of the control POVA film (93.74) significantly decreased to 88.52 in the POVA/TO film ($p < 0.05$), indicating that the films became darker with the addition of the extract. This reduction in lightness is associated with the natural pigments and phenolic compounds present in tomato by-products, including flavonoids and phenolic acids, which typically impart darker hues to polymeric films Takeo *et al*., (2018).

The incorporation of the tomato phenolic extract also induced significant changes in the chromaticity coordinates. The a* value increased from 0.07 in the neat POVA to 0.79 in the POVA/TO film, shifting the film color toward the red region. Similarly, the b* value increased from 1.63 to 2.46, reflecting a more pronounced yellow tone. These variations can be attributed to the presence of colored bioactive compounds such as rutin, naringenin, and chlorogenic acid, which are abundant in tomato by-products and are known to modify optical properties of biopolymer films Csupász *et al*., (2022) .

The darker color and reduced lightness can act as a protective barrier against light-induced degradation of sensitive food components, such as lipids, vitamins, and pigments Rhim *et al*., (2007). Thus, the incorporation of tomato phenolic extract not only modifies the visual appearance of the films but also enhances their potential as active packaging materials with light-screening properties.

Table 4. Color properties of biodegradable films

Film samples	L*	a*	b*
POVA	93.74±0.37^{a}	0.07±0.01^{c}	1.63±0.15^{c}
POVA/TO	88.52±0.48^{b}	0.79±0.03^{a}	2.46±0.03^{a}

POVA= Polyvinyl alcohol film, POVA/TO = Polyvinyl alcohol + Tomato by product powder phenoic extract, The values are expressed as the mean plus or minus the standard deviation. The letters in the same column indicate statistically significant differences (p < 0.05) between the samples.

Mechanical Properties of Biodegradable Films

The mechanical performance of the films was significantly influenced by the incorporation of tomato by-product phenolic extract into the POVA matrix (Table 5). The tensile strength (TS) of the POVA/TO film (80.93 MPa) was significantly higher than that of the neat POVA film (77.66 MPa, $p < 0.05$). This improvement in TS can be explained by the potential interactions between the hydroxyl groups of polyvinyl alcohol and the phenolic compounds present in tomato by-products, which may enhance hydrogen bonding and strengthen the polymeric network (Rhim *et al*., (2013) and Takeo *et al*., (2018).

The elongation at break (EAB) also increased significantly in the POVA/TO film (75.83%) compared to the control (70.28%). This enhancement in flexibility may be related to the plasticizing effect of bioactive compounds and possible reorganization of the polymer chains in the presence of tomato phenolics López-Rubio *et al*., (2012). A similar trend has been observed in other biopolymer films incorporated with natural extracts or polyphenols, where secondary interactions facilitated better chain mobility and improved elasticity W. Chen *et al*., (2014).

The concurrent increase in both TS and EAB is particularly relevant since it indicates that the incorporation of tomato phenolic extract did not compromise the mechanical integrity of the films. Instead, it provided reinforcement while maintaining flexibility, which is advantageous for food packaging applications that require both strength and extensibility(Rhim and Ng, 2007).

Table 5. Mechanical properties of fabricated biodegradable films

Sample	Tensile strength	Elongation at break
POVA	77.66±1.25^{b}	70.28±0.94^{b}
POVA/TO	80.93±0.77^{a}	75.83±1.45^{a}

POVA= Polyvinyl alcohol film, POVA/TO = Polyvinyl alcohol + Tomato by product powder phenoic extract, The values are expressed as the mean plus or minus the standard deviation. The letters in the same column indicate statistically significant differences (p < 0.05) between the samples.

Biodegradability of Biodegradable Films

The biodegradability results revealed that both POVA and POVA/TO films exhibited progressive weight loss over the 30-day period, confirming their susceptibility to microbial and environmental degradation (Table 6). However, the incorporation of tomato by-product phenolic extract significantly enhanced the degradation rate of the films ($p < 0.05$). After 30 days, the POVA/TO film showed a higher weight loss (25.61%) compared to the neat POVA film (21.67%).

Table 6. Biodegradability of biodegradable films as weight loss (%)

Sample	Weight loss (%)		
	10 days	20 days	30 days
POVA	11.327±0.54^{b}	15.36±1.25^{b}	21.67±0.75^{b}
POVA/TO	13.33±0.64^{a}	16.77±1.09^{a}	25.61±0.32^{a}

POVA= Polyvinyl alcohol film, POVA/TO = Polyvinyl alcohol + Tomato by product powder phenoic extract, The values are expressed as the mean plus or minus the standard deviation. The letters in the same column indicate statistically significant differences (p < 0.05) between the samples.

The increased biodegradation of POVA/TO films can be attributed to the presence of phenolic compounds and other bioactive molecules from tomato by-products, which may act as natural plasticizers or weak points in the polymer matrix, facilitating microbial attack and enzymatic hydrolysis (López-Rubio *et al*., 2012 and Rhim *et al*., 2013). Phenolic compounds and associated phytochemicals could also provide nutrient sources that stimulate microbial growth in the degradation medium, thereby accelerating the breakdown of the film structure.

These findings are consistent with previous studies reporting that the addition of natural extracts or plant-derived fillers can enhance the biodegradability of biopolymer-based films. For instance Al-Tayyar *et al*., (2020) demonstrated that phenolic-rich plant powders incorporated into biopolymers promoted higher biodegradation rates due to increased hydrophilicity and microbial accessibility.

The improved biodegradability of POVA/TO films is a desirable feature for sustainable food packaging applications, as it ensures reduced environmental impact and supports circular economy goals. Importantly, the films maintained mechanical and functional integrity during use, while still being able to undergo efficient degradation after disposal.

Weight Loss of Guava Fruits

Weight loss is a critical postharvest parameter that reflects moisture loss through transpiration and respiration, directly affecting fruit texture, juiciness, and overall marketability. As shown in Table (7), guava fruits Un packaged (control) exhibited the highest cumulative weight loss during the 4-week storage period, reaching 21.58% after 4 Weeks. In contrast, fruits packaged in POVA films showed significantly reduced weight loss (13.03%), while the lowest reduction was observed in guavas packaged with POVA/TO films (10.27%) ($p < 0.05$).

The reduced weight loss in polymer-coated fruits can be explained by the **barrier properties** of POVA-based films, which act as semi-permeable membranes reducing water vapor transfer and delaying transpiration losses Thakur *et al*., (2018) and Rhim *et al*., (2013). The incorporation of tomato by-product phenolic extract further improved performance, likely due to enhanced film hydrophobicity and antioxidants activity, which not only restricted water vapor permeability but also suppressed respiration-induced moisture loss López-Rubio *et al*., (2012) .

These findings are consistent with previous reports on active packaging, where natural extracts incorporated into biopolymer films reduced weight loss in perishable fruits. For instance, Al-Tayyar *et al*., (2020) reported that PLA/chitosan films enriched with plant phenolics decreased water loss in strawberries.

Overall, the results highlight the potential of POVA/TO films as effective **active packaging systems** for guava preservation, minimizing postharvest weight loss and thereby extending shelf life under cold storage conditions.

Table 7. Weight Loss (%) of guava fruits stored at 4±C under different packaging methods

Treatment Storage Period	Control Un packaged	POVA	POVA/TO
0	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
1	4.53 ± 0.20^{a}	3.28± 0.15^{b}	2.85± 0.22^{c}
2	9.84 ± 0.30^{a}	6.53± 0.25^{b}	5.28± 0.20^{c}
3	15.22 ± 0.40^{a}	9.85± 0.30^{b}	7.54± 0.25^{c}
4	21.58 ± 0.50^{a}	13.03 ± 0.40^{b}	10.27± 0.30^{c}

POVA= Polyvinyl alcohol film, POVA/TO = Polyvinyl alcohol + Tomato by product powder phenoic extract, The values are expressed as the mean plus or minus the standard deviation. The letters in the same column indicate statistically significant differences (p < 0.05) between the samples.

Firmness of Guava Fruits

Fruit firmness is a key indicator of postharvest quality and consumer acceptability, as it is directly related to texture, juiciness, and resistance to mechanical damage. As shown in Table (8), guava fruits Un packaged (control) exhibited the fastest decline in firmness, dropping from 45.43 N at day 0 to 10.27 N after 4 weeks. In contrast, guavas stored in POVA films retained significantly higher firmness (18.56 N), while those packaged with POVA/TO films maintained the highest firmness (26.07 N) at the end of storage ($p < 0.05$).

The accelerated firmness loss in control fruits can be attributed to higher respiration and transpiration rates, which enhance enzymatic degradation of cell wall polysaccharides, including pectin, cellulose, and hemicellulose Ali, *et al*., (2010) . Packaging with POVA reduced softening due to its barrier properties that limited oxygen exposure and slowed metabolic activity. Moreover, the incorporation of tomato by-products phenolics (POVA/TO) further delayed firmness loss, likely because of the antioxidants and antimicrobial activity of phenolic compounds, which reduced oxidative stress and delayed enzymatic cell wall degradation López-Rubio *et al*., (2012).

Similar findings were reported in other fruit packaging studies. For example,

Al-Tayyar *et al*., (2020) found that chitosan–PLA films enriched with phenolic compounds slowed firmness loss in strawberries, these results confirm that active biodegradable films not only reduce moisture loss but also help preserve fruit texture and quality during storage.

Thus, POVA/TO films demonstrated superior performance in maintaining guava firmness, supporting their potential as an effective **active packaging strategy** for extending shelf life under refrigeration.

Table 8. Firmness (N) of guava fruits stored at 4± C under different pack

Treatment Storage Period	Control Un packaged	POVA	POVA/TO
0	45.43 ± 1.50^{a}	45.73 ± 1.50^{a}	45.39 ± 1.50^{a}
1	35.20 ± 1.02^{c}	38.53 ± 1.20^{b}	40.03 ± 1.03^{a}
2	25.04 ± 1.23^{c}	31.07 ± 1.05^{b}	35.56 ± 0.90^{a}
3	15.52 ± 0.80^{c}	23.80 ± 1.10^{b}	30.00 ± 1.07^{a}
4	10.27 ± 0.70^{c}	18.56 ± 0.94^{b}	26.07 ± 0.80^{a}

POVA= Polyvinyl alcohol film, POVA/TO = Polyvinyl alcohol + Tomato by product powder phenoic extract, The values are expressed as the mean plus or minus the standard deviation. The letters in the same column indicate statistically significant differences ($p < 0.05$) between the samples.

Total Soluble Solids of Guava Fruits

Total soluble solids (TSS) are a key indicator of fruit ripening and sweetness, largely reflecting the concentration of sugars and soluble metabolites. As presented in Table (9), TSS values of guava fruits increased progressively during storage, with the highest accumulation observed in the control fruits (17.27 °Brix) after 4 weeks. Fruits packaged in POVA films exhibited significantly lower TSS values (15.87 °Brix), while the lowest increase was detected in guavas stored in POVA/TO films (14.53 °Brix) ($p < 0.05$).

The continuous rise in TSS during storage is attributed to metabolic processes, including the hydrolysis of starch and polysaccharides into simpler sugars during ripening Ali *et al*., (2010) and Mitra, (1997). The higher TSS accumulation in control fruits is associated with their accelerated respiration and ripening due to direct exposure to air, which enhances sugar metabolism. Conversely, the reduced TSS in packaged fruits indicates that POVA and POVA/TO films delayed ripening by modifying the internal storage atmosphere, lowering oxygen availability, and slowing respiration rates Gol *et al*., (2015) and Rhim *et al*., (2013)

The superior effect of POVA/TO films can be linked to the antioxidant and antimicrobial activities of the incorporated tomato by-product phenolics. These bioactive compounds likely helped in retarding oxidative metabolism and delaying the enzymatic breakdown of carbohydrates, thereby slowing the accumulation of soluble sugars Al-Tayyar *et al*., (2020) and López-Rubio *et al*., (2012).. Similar trends have been reported in papaya Ali *et al*., (2010) and strawberry(Olivas and Barbosa-Cánovas, (2005), where edible coatings slowed TSS accumulation during cold storage.

Therefore, the results confirm that POVA/TO films are more effective in maintaining TSS at lower levels, reflecting their role in delaying ripening and prolonging postharvest quality of guava fruits under refrigeration.

Table 9. Total Soluble Solids (TSS) (°Brix) of guava stored at 4± C under different packaging methods

Treatment Storage Period	Control Un packaged	POVA	POVA/TO
0	10.42 ± 0.30^{a}	10.00 ± 0.30^{a}	10.38 ± 0.30^{a}
1	11.58 ± 0.40^{a}	11.20 ± 0.35^{a}	11.24 ± 0.30^{a}
2	13.84 ± 0.50^{a}	12.58 ± 0.40^{b}	12.27 ± 0.35^{b}
3	15.38 ± 0.60^{a}	14.03 ± 0.50^{b}	13.58 ± 0.40^{b}
4	17.27 ± 0.70^{a}	15.87 ± 0.60^{b}	14.53 ± 0.20^{c}

POVA= Polyvinyl alcohol film, POVA/TO = Polyvinyl alcohol + Tomato by product powder phenoic extract, The values are expressed as the mean plus or minus the standard deviation. The letters in the same column indicate statistically significant differences ($p < 0.05$) between the samples.

Titratable Acidity of Guava Fruits

Titratable acidity (TA) is a key quality attribute in fruits, mainly reflecting the levels of organic acids such as citric, malic, and tartaric acids, which not only contribute to flavor but also influence postharvest metabolism and storability. As shown in Table (10), TA values of guava increased progressively during cold storage across all treatments. The control fruits Un packaged exhibited the most pronounced rise, reaching 0.82% after 4 weeks, compared with 0.70% and 0.56% for POVA and POVA/TO films, respectively ($p < 0.05$).

The increase in TA during storage may be attributed to the accumulation of organic acids as intermediates of respiratory metabolism and stress-related biochemical pathways Sharma, (2022). the higher TA values in the control fruits reflect a faster rate of ripening and senescence due to greater exposure to oxygen, leading to accelerated oxidative metabolism.

Table 10. Titratable Acidity (TA) (% Citric Acid Equivalent) of guava stored at 4± C under different packaging methods

Treatment Storage Period	Control Un packaged	POVA	POVA/TO
0	0.43 ± 0.02^{a}	0.43 ± 0.02^{a}	0.43 ± 0.02^{a}
1	0.55 ± 0.02^{a}	0.48 ± 0.02^{b}	0.45 ± 0.01^{b}
2	0.60 ± 0.03^{a}	0.55 ± 0.01^{b}	0.50 ± 0.02^{c}
3	0.77 ± 0.03^{a}	0.62 ± 0.03^{b}	0.55 ± 0.03^{c}
4	0.82 ± 0.04^{a}	0.70 ± 0.04^{b}	0.56 ± 0.03^{c}

POVA= Polyvinyl alcohol film, POVA/TO = Polyvinyl alcohol + Tomato by product powder phenoic extract, The values are expressed as the mean plus or minus the standard deviation. The letters in the same column indicate statistically significant differences ($p < 0.05$) between the samples.

Packaging with POVA films significantly reduced the rate of acidity increase, indicating their ability to modify the storage atmosphere by reducing oxygen diffusion and slowing respiratory activity (Rhim *et al*., (2013) and Gol *et al*., 2015). The most effective results were obtained with POVA/TO films, where the lowest acidity values were recorded throughout storage. This effect can be explained by the presence of tomato by-product phenolic extract, which possesses antioxidants and antimicrobial properties that may reduce oxidative stress and delay acid metabolism López-Rubio *et al*., (2012) and Al-Tayyar *et al*., (2020).

Comparable findings were observed in papaya coated with bioactive edible films, where a slower increase in acidity was associated with delayed senescence and extended postharvest life Ali *et al*., (2010) . Thus, the results demonstrate that POVA/TO films are more efficient than POVA films alone in maintaining balanced acidity levels, thereby contributing to flavor preservation and prolonged storage stability of guava fruits.

Vitamin C of Guava Fruits

As shown in Table (11), a continuous decline in vitamin C content was observed across all treatments during 4 weeks of cold storage. Control guavas Un packaged exhibited the most rapid reduction, decreasing from 90.11 to 30.41 mg/100 g by the end of storage. In contrast, POVA-coated fruits retained significantly higher vitamin C levels (50.24 mg/100 g), while the highest retention was recorded in POVA/TO films (70.11 mg/100 g, $p < 0.05$).

The drastic reduction in control fruits may be attributed to higher respiration and oxidative reactions in the absence of protective packaging, which accelerates ascorbic acid breakdown POVA films contributed to slowing this decline by acting as a semi-permeable barrier, reducing oxygen diffusion and thereby minimizing oxidative degradation of ascorbic acid Gol *et al*., (2015).

The superior performance of POVA/TO films is likely due to the synergistic effect of polyvinyl alcohol and tomato **by-**products phenolic extract, which not only controls gas exchange but also provides antioxidants activity from phenolic compounds. These bioactive molecules may scavenge reactive oxygen species and protect vitamin C from oxidation, thereby enhancing its stability during storage Grootaert *et al*., (2017) and Al-Tayyar *et al*., (2020).

Similar results were reported papaya, and strawberry, where edible coatings enriched with natural antioxidants significantly slowed down vitamin C degradation and extended shelf life compared to uncoated controls(Ali *et al*., (2010) andOlivas and Barbosa-Cánovas, (2005). Thus, the findings highlight the potential of POVA/TO films as an effective active packaging strategy to preserve the nutritional quality and extend the postharvest life of guava fruits.

Table 11. Vitamin C Content (mg/100g) of guava fruits stored at 4± C under different packaging methods

Treatment Storage Period	Control Un packaged	POVA	POVA/TO
0	90.11 ± 3.24^a	90.00 ± 3.11^a	91.00 ± 3.31^a
1	75.04 ± 2.32^b	80.00 ± 2.80^a	83.00 ± 2.52^a
2	60.06 ± 2.50^c	70.04 ± 2.50^b	79.43 ± 2.50^a
3	45.21 ± 2.03^c	60.06 ± 2.00^b	72.06 ± 2.05^a
4	30.41 ± 1.50^c	50.24 ± 1.80^b	70.11 ± 1.50^a

POVA= Polyvinyl alcohol film, POVA/TO = Polyvinyl alcohol + Tomato by product powder phenoic extract, The values are expressed as the mean plus or minus the standard deviation. The letters in the same column indicate statistically significant differences ($p < 0.05$) between the samples.

Total Phenolic Content of Guava Fruits

Phenolic compounds are important bioactive molecules in guava fruits, contributing not only to their antioxidants capacity but also to their sensory and nutritional quality. However, these compounds are highly sensitive to oxidative degradation, enzymatic activity, and environmental factors during postharvest storage Shahidi and Ambigaipalan, (2015).

As shown in Table (12), a progressive decline in total phenolic content (TPC) was observed across all treatments during cold storage. Control fruits stored in air exhibited the sharpest reduction, with TPC decreasing from 50.02 to 10.63 mg GAE/100 g after 4 weeks. In comparison, guavas packaged in POVA films retained significantly higher phenolic levels (28.36 mg GAE/100 g), while the highest retention was recorded in POVA/TO films (36.02 mg GAE/100 g, $p < 0.05$).

The sharp decline in control fruits can be attributed to uncontrolled oxidative stress and phenolic degradation**,** driven by higher respiration rates and enzymatic browning reactions Tomaino *et al*., (2005). The partial retention in POVA-coated fruits highlights the role of polyvinyl alcohol as a semi-permeable barrier, limiting oxygen permeability and reducing phenolic oxidation Gol *et al*., (2015).

The superior performance of POVA/TO films is likely due to the combined effect of barrier protection and phenolic enrichment from tomato by-product extracts. These phenolic-rich additives not only enhanced the film's antioxidant properties but also contributed additional bioactive compounds, effectively compensating for losses during storage Grootaert *et al*., (2017) and Al-Tayyar *et al*., (2020).

Similar findings were reported in other fruit systems such as strawberries, mangoes, and papayas, where edible coatings enriched with plant-derived phenolics or essential oils significantly delayed the decline in TPC compared to controls Ali *et al*., (2010) and Valero *et al*., (2011).

These results support the application of active packaging enriched with natural antioxidants as an effective strategy to preserve the nutritional and functional quality of guava during storage.

Table 12. Total Phenolic Content (TPC) (mg GAE/100g) of guava stored at 4± C under different packaging method

Treatment Storage Period	Control Un packaged	POVA	POVA/TO
0	50.02 ± 2.00^a	52.46 ± 2.12^a	51.00 ± 2.34^a
1	40.42 ± 1.50^b	43.04 ± 1.52^a	45.03 ± 1.20^a
2	30.14 ± 1.20^c	38.07 ± 1.30^b	42.53 ± 1.10^a
3	20.64 ± 1.00^c	33.47 ± 1.20^b	38.00 ± 1.00^a
4	10.63 ± 0.80^c	28.36 ± 1.10^b	36.02 ± 0.90^a

POVA= Polyvinyl alcohol film, POVA/TO = Polyvinyl alcohol + Tomato by product powder phenoic extract, The values are expressed as the mean plus or minus the standard deviation. The letters in the same column indicate statistically significant differences ($p < 0.05$) between the samples.

Antioxidants Activity – DPPH

Antioxidants activity is a crucial indicator of the nutritional quality of guava fruits since it reflects their ability to neutralize free radicals and prevent oxidative deterioration. As presented in Table (13), a progressive reduction in DPPH radical scavenging activity was recorded in all treatments during storage. However, the rate of decline varied significantly depending on the packaging method.

Control fruits stored in air showed the most drastic reduction in antioxidant activity, decreasing from 71.43% at day 0 to only 30.05% by the fourth week. This rapid loss may be attributed to accelerated oxidation and degradation of phenolic compounds and vitamin C, which are major contributors to guava's antioxidants potential Shahidi and Ambigaipalan, (2015) and Thaipong, Boonprakob, Crosby, Cisneros-Zevallos, and Byrne, (2006).

In contrast, guavas packaged with POVA films retained higher antioxidant activity (48.06% at week 4), demonstrating the effectiveness of polyvinyl alcohol films as a semi-barrier system that reduced oxygen permeability and delayed oxidative reactions Gol *et al*., (2015). The most pronounced preservation was achieved by POVA/TO films, where DPPH activity remained as high as 60.53% after four weeks ($p < 0.05$). This superior effect can be explained by the incorporation of tomato by-products phenolic extract**,** which enriched the films with additional antioxidants and provided a synergistic protective effect by reducing oxidative stress in stored guava(Grootaert *et al*., (2017) and Al-Tayyar *et al*., (2020) . These findings are consistent with earlier reports in other fruits such as strawberries, mangoes, and papayas, where edible coatings enriched with natural extracts significantly enhanced antioxidant retention during storage Ali *et al*., (2010) and Valero *et al*., (2011). Therefore, the use of POVA/TO films not only extended the storage life of guava but also preserved its functional bioactivity, supporting its potential as a natural and eco-friendly active packaging solution

Table 13. Antioxidants Activity Using DPPH (%) of guava Fruits stored at 4± C under different packaging method

Treatment Storage Period	Control Un packaged	POVA	POVA/ TO
0	71.43 ± 2.49^a	70.26 ± 2.62^a	72.74 ± 2.52^a
1	60.03 ± 2.20^c	63.66 ± 2.00^b	65.27 ± 1.86^a
2	50.24 ± 2.00^c	58.25 ± 1.90^b	62.26 ± 1.73^a
3	40.14 ± 1.80^c	53.42 ± 1.80^b	63.84 ± 1.66^a
4	30.05 ± 1.50^c	48.06 ± 1.60^b	60.53 ± 1.54^a

POVA= Polyvinyl alcohol film, POVA/TO = Polyvinyl alcohol + Tomato by product powder phenoic extract, The values are expressed as the mean plus or minus the standard deviation. The letters in the same column indicate statistically significant differences (p < 0.05) between the samples.

CONCLUSION

The present study demonstrated the effectiveness of tomato by-products phenolic extract in improving the functional and environmental properties of biodegradable polyvinyl alcohol films. Incorporation of TO not only enhanced the barrier, mechanical, and biodegradability characteristics of the films but also significantly improved their performance as active packaging in preserving guava fruits during cold storage. Fruits packed with POVA/TO films exhibited better retention of firmness, vitamin C, phenolic compounds, and antioxidant activity, while showing delayed ripening and reduced physiological losses. These results highlight the potential of valorizing tomato processing residues into high-value active packaging materials, offering a sustainable solution for both food preservation and waste reduction.

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انتاج افلام نشطه قابله للتحلل الحيوي كأغلفه صديقه للبيئة

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الملخص

أظهرت هذه الدراسة إمكانية استخدام المستخلص الفينولي الناتج من مخلفات الطماطم (TO) كمضاف وظيفي لتطوير أفلام قابلة للتحلل الحيوي من بولي فينيل الكحول (POVA) ، وتطبيقها في حفظ ثمار الجوافة. وُجد أن مسحوق مخلفات الطماطم غني بالمركبات الفينولية، خصوصًا حمض الكلوروجينيك (1001.33 ميكروجرام/جم)، الروتين (688.25 ميكروجرام/جم)، الكاتيشين (612.35 ميكروجرام/جم)، وحمض الجاليك (587.27 ميكروجرام/جم)، مما ساهم في ارتفاع النشاط المضاد للأكسدة (87.46%). أدى دمج TO في أفلام POVA إلى زيادة ملحوظة في سمك الفيلم (0.15 مم)، قوة الشد (80.93 ميجاباسكال)، الاستطالة عند الكسر (75.83%)، زاوية التلامس مع الماء (81.56°)، وقابلية التحلل الحيوي (فقدان وزن بنسبة 25.61% بعد 30 يومًا)، بينما يؤدي الي خفض الذوبانية ونفاذية بخار الماء. في تخزين ما بعد الحصاد، أظهرت ثمار الجوافة المعبأة بأفلام POVA/TO انخفاضًا في الفقد في الوزن (10.27% مقابل 21.58% في الكنترول)، واحتفاظًا بصلابة أعلى (26.07 نيوتن مقابل 10.27 نيوتن)، وتأخيرًا في الزيادة بمحتوى المواد الصلبة الذائبة الكلية والحموضة، وتحسنًا في الاحتفاظ بفيتامين C (70.11 ملج/100جم) والمركبات الفينولية (36.02 ملج مكافئ حمض الجاليك/100جم) بعد 4 أسابيع عند 4 °م. كما حُفظ النشاط المضاد للأكسدة (DPPH) عند مستويات أعلى بشكل ملحوظ (60.53%) في الثمار المعبأة بأفلام POVA/TO مقارنة بالكنترول (30.05%). توضح هذه النتائج أن دمج TO يعزز الخصائص الفيزوكيميائية والميكانيكية والوظائف النشطة لأفلام POVA، وزيادة مدة التخزين وتحسين الجودة الغذائية لثمار الجوافة.