

Article

Sustainable Preservation Strategies for Prunes—The Influence of Biopolymer Coatings on the Quality and Sustainability of Prunes

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Abstract

The aim of this study was to estimate the influence of biopolymer coatings based on chitosan and zein on the quality and storage stability of prunes (*Prunus domestica* L., cv. Stanley) over a one-year period coupled with modified atmosphere conditions (5% CO₂ + 95% N₂). Samples were analyzed at defined intervals (every 3 months) regarding physicochemical properties, antioxidative capacity, vitamin C content, phenolic profile, headspace gas composition, microbiological status and sensory characteristics. Biopolymer coatings, modified atmosphere, and temperature play key roles in controlling oxygen availability, which consequently affects all tested properties of prunes. Application of both types of coatings significantly improves product stability compared to uncoated samples, slows moisture loss, stabilizes pH, reduces degradation of vitamin C, phenolic compounds, and antioxidant activity, and improves microbiological safety. Chitosan exhibits more pronounced effects due to its antimicrobial and antioxidant properties, while zein primarily contributes to barrier characteristics. Gradual decline in quality, significantly slowed in coated samples, is additionally mitigated at low temperature (4 °C), which further inhibits chemical, oxidative, and microbiological changes compared to storage at 23 °C. Despite zein coating providing superior preservation of several physicochemical quality parameters, chitosan-coated prunes achieved higher sensory acceptance, demonstrating that improved physicochemical stability does not necessarily correspond to better consumer acceptability.

Keywords: prunes; coatings; chitosan; zein; quality; shelf-life

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1. Introduction

The plum belongs to the *Rosaceae* family and genus *Prunus* sp. L. Its fruit has more variation in terms of shape, size, aroma and flavor, texture, and color than any other crop [1]. Plum has a wide range of potential uses, including both direct consumption and

processing [2]. Genus *Prunus* sp. L. contains more than 200 species, of which the European plum (*Prunus domestica* L., *Prunus cerasifera*, *Prunus spinosa* L., *Prunus insititia*), Japanese plum (*Prunus salicina* Lindl. and *Prunus simonii* Carr.), and American plum (*Prunus americana* Marsh.) are the most significant contributors to global production [3,4]. According to Giuggioli et al. [5] and Taiti et al. [6], plums are prized by consumers for their esthetic appeal, contrasted taste and juiciness, pleasant aroma and texture, color and size. However, they have also been recognized for their high antioxidant content and overall nutraceutical qualities [2]. Plum fruit is abundant in organic acid, dietary fiber (pectin), minerals (K, P, Ca), vitamins (C, A, B), and carbohydrates (saccharose, glucose, and fructose) [7,8]. According to Treutter et al. [9], the most common and bioactively significant components found in plums include anthocyanins like cyanidin and peonidin, flavonol glycosides like quercetin-3-glucoside and quercetin-3-galactoside, and phenolic acids like chlorogenic and neochlorogenic acids due to which plums offer numerous health advantages. Prunes may also be regarded as a functional food because of their high antioxidant content, even if drying fresh plums causes chemical alterations [10].

The advancement of consumer-safe food preservation methods that enhance product quality and safety without losing nutrients or sensory qualities has received increased attention in recent years [11,12]. As one of the first techniques for preserving plant products, especially fruit, the food industry has concentrated on optimizing the drying process in order to meet the increasing demands of consumers for a variety of processed plant products [13,14]. One of the most crucial methods for preserving fruits and vegetables is drying [15], where the resulting reduced water activity protects the dried products from enzymatic and microbiological activity that could consequently alter their physical and chemical properties [16,17]. There have been a lot of studies done on plum drying and the changes that occur during the process, broadly categorized into three areas: treatments or pre-treatments applied prior to drying; drying process mathematical modeling and simulation; and kinetics research [18,19]. New drying methods have made it possible to produce dried products with excellent nutritional content that may be added to various food products to enhance their properties [8,20]. Convective drying is the most widely used drying technique. Despite many benefits, such as the equipment's simple design and the well-understood manufacturing process, this process has some drawbacks, including long processing time, inconsistent quality of the dehydrated product, and substantial energy consumption [21].

Research is focused on finding innovative materials that can preserve food quality and be safe for customers by preventing or reducing postharvest losses and addressing rising consumer concerns about environmental issues [22]. Natural biopolymers are used for the production of edible films and coatings, forming a protective layer around the food surface [23,24]. It is expected that the production of biopolymers will increase by 2.41 million tons by 2030 [25]. Edible biopolymer films/coatings are materials no thicker than 300 μm that can be consumed simultaneously with food, either with or without subsequent removal [26]. Typically, edible coatings are applied directly to the food's surface using spraying or immersion in liquid form, creating micro-layers of film on the food's surface [27]. Due to their edible and degradable properties, which can minimize packaging waste and remarkable resistance to moisture and aroma, solvent transfer, and oxidation, biopolymer edible films and coatings are of tremendous interest to the food packaging sector [28–30]. They improve food safety by extending the shelf life of fruits by inhibiting deterioration, such as moisture loss, which leads to fruit shrinkage, weight loss, microbial invasion, chemical degradation, etc. Edible coatings applied to minimally processed vegetables preserve their phytochemical (antioxidant, phenolic, color) and physicochemical (weight loss, respiration rate, pH, and TSS) characteristics for extended periods [31]. Fruit coating with biopolymers limits gas transfer and shields the fruit from unwanted odors

[32,33]. Coating solutions, made from renewable resources, are applied to the fruit's surface in a thin layer to extend its shelf life by reducing moisture loss and serving as a barrier against light, gases, and microbes, thereby delaying the fruit's natural decomposition. Natural substances like hydrocolloids (polysaccharides and proteins) and lipids are used to prepare the coating solutions [34]. The characteristics of these biopolymers primarily determine their function and further application [35,36]. Bio-based packaging systems have been developed using a variety of proteins (such as collagen, gelatin, caseinates, whey proteins, corn zein, wheat gluten, soy protein, pea protein, some oilseed or grain proteins, and keratin), polysaccharides (such as starch, cellulose, chitosan, gum, pectin), and lipids (such as bees wax, oils, and fatty acids) materials [37]. Recent developments in edible coating systems indicate that protein- and polysaccharide-based matrices can be strategically tailored to enhance oxygen barrier properties and reduce moisture loss in coated fruit systems, thereby improving postharvest quality and shelf stability [36,38]. When compared to other biopolymer-based materials, protein-based materials often have superior mechanical, structural, and barrier qualities for oxygen, aroma, and oil because of chain-to-chain interactions (hydrophobic, covalent, and hydrogen bonding) [38,39]. Polysaccharide-based biopolymers have excellent structural integrity and provide a barrier that protects fruits from gases and other external factors, which helps to prolong the fruit's shelf life and maintain its freshness and quality [40]. Additionally, regulatory authorities recognize polysaccharides as safe for direct food contact, which increases their use across a range of food industry applications [36,41]. Nevertheless, their hydrophilic nature is a drawback as it makes them an inadequate barrier against fruit dehydration [31].

This work aimed to evaluate the effect of biopolymer coatings applied via the immersion method, based on polysaccharide and protein, on the quality and shelf life of prunes during 12 months of storage. Chitosan was selected as a representative of polysaccharide biopolymers, while zein is a protein biopolymer. Previous studies evaluated edible coatings during short storage periods (several weeks to a few months) and focused primarily on physicochemical or microbiological quality. Studies simultaneously evaluating long-term storage, headspace gas composition, phenolic profile, antioxidant activity, and sensory properties of coated dried plums remain scarce. The novelty of this research is reflected in the comprehensive long-term evaluation of prunes' quality changes with the combined application of edible biopolymer coatings, modified atmosphere packaging and different storage temperatures. Although numerous studies have investigated edible coatings for fresh fruit, relatively little information is available regarding their effectiveness during prolonged storage of dried fruit, particularly when physico-chemical parameters (pH, dry matter), nutritional characteristics (vitamin C), antioxidant response (ABTS, DPPH, FRAP, CUPRAC), phenolic profile (HPLC), headspace gas composition (O₂, CO₂, N₂), microbiological stability and sensory acceptability of the product were simultaneously monitored during 1-year experiment. Finally, this research indicates a difference between chemical stability and sensory acceptability of products, pointing out that applied coatings, which provide better protection of bioactive components, do not necessarily lead to better consumer acceptability during long-term storage. The present study aimed to identify possible discrepancies between physicochemical preservation and sensory quality.

2. Materials and Methods

2.1. Materials

Plums (*Prunus domestica* L., cv. Stanley) were harvested in September 2022 in the territory of the municipality of Prokuplje (43.24°N, 21.19°E), Republic of Serbia.

Chitosan powder from crab shells (middle viscous) was provided by Sigma-Aldrich Chemical Co. (Sigma-Aldrich Chemical co., St. Louis, MO, USA), while purified zein was provided by Acros Organics (Acros Organic, Geel, Belgium). Glacial acetic acid (99.5%) was purchased from Macron (Macron Fine Chemicals, Phillipsburg, NJ, USA) and ethanol (96%) from Reahem (Reahem, Belgrade, Serbia). Polyethylene glycol PEG 400 was provided by Alfa Aesar (Alfa Aesar, Karlsruhe, Germany). The chemicals used in the dried plums' quality assessment were of analytical grade.

2.2. Plum Drying

Drying was carried out in a tunnel counter-flow drying machine (Progres, Čačak, Serbia). The drying time for all samples was 18 h, and the air temperature at the tunnel exit was 80 °C. After the drying, a preliminary analytical screening was performed on a single batch of dried plum samples (Table 1) in order to evaluate the immediate effects of drying on their physicochemical and bioactive properties.

Table 1. Quality of fresh plums vs. dried plums.

	pH	Dry Matter	Vit. C	ABTS	DPPH	FRAP	CU-PRAC	TPC	TFC	Neo-chlorogenic Acid	Caffeic Acid	Chlorogenic Acid	<i>p</i> -Coumaric Acid	Rutin
		(%)	(g/100 g)		(μmol/g)			(μg/g)				(mg/kg)		
fresh plum	2.93 ± 0.06	17.97 ± 0.36	9.07 ± 0.08	0.48 ± 0.01	68.3 ± 0.78	8.5 ± 0.16	13.4 ± 0.58	889 ± 39.04	94 ± 7.93	160 ± 9.00	67.6 ± 3.29	75.3 ± 2.01	20.8 ± 0.70	12.4 ± 0.24
dried plum	3.57 ± 0.03	69.63 ± 0.38	1.10 ± 0.10	1.08 ± 0.02	68 ± 0.98	27.9 ± 0.19	49.0 ± 1.12	2162 ± 91.09	3041 ± 133.19	1917.9 ± 145.81	145.5 ± 4.78	793.5 ± 19.24	192.2 ± 3.16	67.6 ± 0.57

2.3. Biopolymer Coating Synthesis and Sample Packaging

Coating solutions of chitosan and zein were prepared as described by Šuput et al. [42]. In brief, chitosan solution was obtained by dissolving chitosan powder in 99.5% acetic acid (1% volume concentration). To completely dissolve the chitosan, the solution was left overnight on a magnetic stirrer. Zein solution was obtained by dissolving zein in 85% ethanol (10% *w/v*), after which PEG 400 (0.5 g of PEG 400/g zein) was added. The coating solution was heated to 80 °C in a water bath for around 5 min.

To apply the coating solutions, prunes were immersed in each of the biopolymer solutions for 1 min and then drained for 5 min. The immersion process was repeated three times. The control prune sample was not coated (Figure 1). Following immersion, the samples were drained for 30 min in the strainer and eventually packed.



Figure 1. Prunes before and after coating application.

The prune samples (both coated and control) were packed in PET/PE bags (20 cm × 20 cm; 70 µm thickness). Each package contained 250 g of prunes. Packaging was performed under a modified atmosphere (5% CO₂ + 95% N₂) using a Boxer 35 packaging machine (Henkelman BV, Netherlands). Samples were stored at temperatures of 23 °C and 4 °C for 12 months. The samples were examined on the 0 day, 3rd, 6th, 9th, and 12th month of storage. Taking into account all preparation steps and sampling times, the samples are labeled as:

- S—uncoated prunes (control) stored at 23 °C
- ZS—zein-coated prunes stored at 23 °C
- HS—chitosan-coated prunes stored at 23 °C
- F—uncoated prunes (control) stored at 4 °C
- ZF—zein-coated prunes stored at 4 °C
- HF—chitosan-coated prunes stored at 4 °C

Each label has a number that indicates the moment (month) of sampling, e.g.,

- 9-S: uncoated prunes stored at 23 °C sampled in the 9th month
- 3-ZF: zein-coated prunes stored at 4 °C sampled in the 3rd month
- 12HS: chitosan-coated prunes stored at 4 °C sampled at the 12th month

2.4. Dried Plums Quality Assessment

2.4.1. pH

The pH was determined according to the Rulebook on methods of taking samples and performing chemical and physical analyses for quality control of fruit and vegetable products (Official Gazette of the SFRJ, No. 29/83) [43].

Measurements were performed in triplicate.

2.4.2. Dry Matter Content

The dry matter content was determined according to the Rulebook on methods of taking samples and performing chemical and physical analyses for quality control of fruit and vegetable products (Official Gazette of the SFRJ, No. 29/83) [43]. Each sample was analyzed in triplicate.

2.4.3. Vitamin C

The vitamin C was determined according to the Rulebook on methods of taking samples and performing chemical and physical analyses for quality control of fruit and vegetable products (Official Gazette of the SFRJ, No. 29/83) [43] as a titration with 2,6-dichlorophenolindophenol, i.e., Tillman's reagent (TR). Vitamin C was determined in triplicate.

2.4.4. Total Phenols (TPC) Content

TPC content was determined spectrophotometrically (UV/VIS-Spectrometer LLG-uniSPEC 2, LLG Labware, Meckenheim, Germany) by the Folin–Ciocalteu method [44]. The absorbance was measured at 760 nm and the test was done in three replicates.

2.4.5. Total Flavonoid (TFC) Content

TFC was determined spectrophotometrically, using the colorimetric method with aluminum chloride [45]. The absorbance was measured at 510 nm and TFC measurements were performed in triplicate.

2.4.6. Antioxidative Activity—ABTS, DPPH, FRAP and CUPRAC Methods

The antioxidant/antiradical activity of the tested samples was determined by the ABTS method [46]. For this purpose, a basic solution of ABTS with a concentration of 7×10^{-3} mol/L and a fresh solution of $K_2S_2O_8$ with a concentration of 2.4×10^{-3} mol/L were made. The working solution, which was prepared by mixing standard solutions in a ratio of 1:1, was left to stand at room temperature and in the dark for 12–16 h. After that, 14.8 mL of the working solution was diluted with 240 mL of methanol and the absorbance of the solution was measured at 734 nm. Calibration curves were obtained with a series of different concentrations of Trolox solution. A blank sample, from which the absorbance of the standard series was subtracted, was prepared by measuring 1.8 mL of the ABTS working solution and 2.2 mL of methanol. Then, 0.1 mL of the sample (5 g in 25 mL) was transferred to a normal 10 mL vessel and 1.8 mL of ABTS and 2.1 mL of methanol were added and the absorbance was read at 734 nm.

The antioxidant/antiradical activity of the tested samples was determined by the DPPH method [47]. For this purpose, a basic DPPH solution with a concentration of 1×10^{-3} mol/L was prepared. The calibration curve was obtained by measuring the absorbance at 520 nm of a series of standard solutions in which the volume of Trolox was varied from 0.2 mL to 2 mL (concentration 2–20 μ M). The blank sample, from whose absorbance the absorbances of the standard series were subtracted, consisted of 5 mL of DPPH supplemented with methanol to 10 mL. Then, 0.1 mL of the diluted sample (5 g–25 mL of which 1–8 mL) was transferred to a normal vessel of 10 mL, and 5 mL of DPPH solution with a concentration of 1×10^{-4} mol/L was added and filled up with methanol. The absorbance of the solution was measured at 520 nm.

The FRAP method is based on the ability of the extract to reduce Fe^{3+} ions to Fe^{2+} ions in a solution of 2,4,6-tripyridyl-s-triazine (TPTZ) at a lower pH [48]. The reduction is monitored by measuring the change in absorbance at 595 nm. Mix 200 mL of acetate buffer, 20 mL of TPTZ reagent and 20 mL of $FeCl_3$ (ratio 10:1:1). To obtain the calibration line, the volumes of $FeSO_4 \times 7H_2O$ (0.1–1 mL) + 3 mL of FRAP + (0.9–0 mL) of water were measured so that the total volume was 4 mL. The blank was obtained by mixing 3 mL FRAP + 1 mL water. Measure 0.1 mL of the diluted sample, 0.99 mL of water and 3 mL of FRAP into a standard 10 mL dish. The samples were shaken well and thermostated for 5 min at 37 °C. Absorbance was measured at 595 nm.

The CUPRAC test for the determination of antioxidant activity is based on the ability to reduce Cu^{2+} ions to Cu^+ [49]. The resulting Cu^+ ions form a stable complex with neocuproine in a neutral and weakly acidic environment. This complex shows an absorption maximum at 450 nm. The blank was made from 1 mL Neocuproin + 1 mL buffer + 1 mL $CuCl_2$ + 1.1 mL EtOH, and the sample from 1 mL Neocuproin + 1 mL buffer + 1 mL $CuCl_2$ + 0.1 mL diluted sample + 1 mL EtOH. The mixtures were thermostated for 30 min at 25 °C in a dark place and the absorbance was measured at 450 nm.

2.4.7. HPLC Profile of Individual Phenolic Compounds

Samples were analyzed using an Agilent 1260 series HPLC (Agilent Technologies, Santa Clara, CA, USA) equipped with a diode array detector (DAD). A ZORBAX Eclipse Plus C18 column (4.6 mm × 150 mm, 3.5 mm particles) was used. The injection volume was 20 µL, the flow rate was 0.8 mL/min and the temperature was set at 30 °C. The mobile phase consisted of aqueous 5% formic acid (eluent A) and 80% acetonitrile/5% formic acid (eluent B). The elution program used was as follows: 0–28 min 0% B, 28–35 min 25% B, 35–40 min 50% B, 40–45 min 80% B, and finally, for the last 10 min, gradually decreased, 80% to 0% B. Individual compounds were identified based on the retention times and spectral data of the available standards.

2.4.8. Headspace Analysis (O₂, CO₂ and N₂)

The composition of gases in the package headspace was determined using a gas analyzer Oxybaby M+ (WITT, Witten, Germany). The oxygen (O₂) and carbon dioxide (CO₂) concentrations were determined directly from the headspace by inserting an analyzer needle through a self-adhesive septum placed on the surface of the package. The results were expressed as %. The instrument directly measures O₂ and CO₂ concentrations, whereas nitrogen is the balance gas and was calculated as:

$$\text{N}_2 (\%) = 100 - \text{O}_2 (\%) - \text{CO}_2 (\%)$$

Measurements were performed at room temperature, and each sample was analyzed in three repetitions.

2.4.9. Sensory Analysis

The samples were presented to consumers in plastic containers marked with three-digit numbers, and before testing, the samples were tempered to room temperature. Water was used between tests to rinse the oral cavity from previous samples and prepare the senses for the next set of samples. Color, smell, taste and appearance-general condition acceptability tests were carried out. Tests involved the application of numerical values so that they could be statistically processed. Smell and taste could be appreciated on a scale of 1–4, and color and general condition on a scale of 1–6. The following phrases corresponded to the grades: Grade 1 meant the unacceptability of the examined attribute, i.e., “I don’t like it”, while the maximum grades, i.e., 4 and 6, meant “I like it extremely”. The maximum number of points that one sample could have was 20.

2.4.10. Microbiological Profile

To assess the microbiological quality of uncoated/coated prunes, microbiological determinations were carried out according to the International Organization for Standardization (ISO) methods: ISO 16649-2 [50] was used to determine *Escherichia coli*; ISO 21528-1 [51] was used to determine Enterobacteriaceae; ISO 6579 [52] was used to determine *Salmonella* spp.; and ISO 11290-2 [53] was used to determine *Listeria monocytogenes*. The total number of microorganisms was determined in accordance with ISO 4833-1 [54], and the total number of yeasts and molds was determined in accordance with ISO 21527-1 [55].

2.5. Statistical Analysis

All statistical analyses were performed using R version 4.4.3. Data normality was evaluated using the Shapiro–Wilk and Anderson–Darling tests, while homogeneity of variances was assessed using Levene’s test.

Variables that deviated from normality were transformed using the Yeo–Johnson transformation to improve distributional properties while preserving the original data

structure. The adequacy of the transformed data for parametric analysis was subsequently verified by reassessing the model assumptions.

The effects of storage time, temperature, treatment, and their interactions were analyzed using linear mixed-effects analysis of variance (ANOVA), with repeated measurements specified as random effects. Because the experimental design was balanced and the assumption of homogeneity of variances was satisfied, the linear mixed-effects ANOVA was considered appropriate and robust to moderate deviations from normality.

The effects of storage conditions were assessed on each response variable; a non-parametric factorial approach based on aligned rank transformation (ART) was applied using the *ARTool* package. For each response variable, a full factorial model including main effects (Time, Temperature, Coating) and their interactions (Time $\times$ Temperature, Time $\times$ Coating, Temperature $\times$ Coating, and Time $\times$ Temperature $\times$ Coating) was fitted. The ART procedure transforms the data in a manner that allows factorial ANOVA to be performed on ranked responses while preserving interaction structure, thereby enabling robust inference under non-normal data distributions. For each fitted model, ANOVA tables were extracted to evaluate the statistical significance of main effects and interactions. In addition, estimated marginal means were calculated using the *emmeans* package on ART-fitted linear models (*artlm*), and pairwise comparisons among factor levels were performed using Tukey-adjusted tests. This allowed post hoc identification of significant differences between storage conditions within each factor.

To ensure transparency and reproducibility, all results were automatically exported. For each response variable, separate worksheets containing ANOVA results (File S1. Aligned Rank Transformation (ART) ANOVA) and post hoc comparisons (File S2. ART Post Hoc test) were generated in Excel format. A global summary table containing F-values and *p*-values for all effects across all response variables was also compiled and exported for supplementary reporting (File S3 ART Summary). The workflow included error handling to ensure that models failing to converge for any specific response variable did not interrupt the overall analysis pipeline.

Relationships among physicochemical, antioxidant, sensory, and phenolic parameters were evaluated using correlation analysis. In addition, principal component analysis (PCA) was performed using standardized variables to investigate multivariate relationships and sample discrimination patterns. Circular heatmap visualization was used to illustrate clustering trends and relative changes among samples and measured variables. The heat map and color correlation figures were generated by using <https://chip-lot.online/>.

3. Results and Discussion

3.1. Plum Drying

Drying was the initial and dominant factor that defined all subsequent processes. The increase in dry matter, the concentration of phenolic compounds and the initial changes in vitamin C indicate a strong concentration effect due to water loss, but also the initial degradation of thermolabile components (Table 1). Dry matter content increased from 17.97% in fresh fruit to 69.63% after drying as a consequence of water removal, consequently leading to the concentration of soluble constituents. A slight increase in pH was observed, consistent with compositional changes commonly occurring during fruit dehydration such as moisture removal and altering the balance between organic acids and other soluble constituents [19]. Conversely, vitamin C content decreased markedly after drying. This reduction is related to the high thermal sensitivity of ascorbic acid and its oxidative degradation during dehydration. Exposure to elevated temperatures and oxygen promotes oxidation of ascorbic acid, followed by irreversible degradation reactions, resulting in considerable losses of vitamin C [56].

Drying causes changes due to which the structure of dried plums becomes heterogeneous and subject to transformations, including the release of phenols and changes in their extractability, which is particularly important for the interpretation of TPC, TFC and HPLC results [57]. Total phenolic content (TPC) and total flavonoid content (TFC) increased substantially after drying, which could be explained by the concentration effect associated with water removal. In addition, thermal treatment may disrupt cell wall structures and improve the extractability of previously bound phenolic compounds [58]. Higher concentrations of extractable phenolic compounds may be detected after drying, even though some individual phenolics remain susceptible to thermal degradation [19]. The observed changes in antioxidant capacity reflected the complex balance between degradation of thermolabile antioxidants and increased availability of phenolic compounds. Similar conclusions have recently been highlighted in reviews of plum bioactive compounds and the effects of drying on fruit quality [56,59]. Although DPPH radical scavenging activity remained almost unchanged after drying, ABTS, FRAP and CUPRAC values increased considerably. These differences are expected because the antioxidant assays respond differently to individual antioxidant compounds, and increased phenolic extractability after drying may compensate for the loss of vitamin C [19,59]. The HPLC analysis further confirmed substantial modifications in the phenolic profile following drying. Neochlorogenic acid remained the predominant phenolic compound, while chlorogenic acid, rutin and p-coumaric acid increased markedly compared with fresh plums. Previous studies on dried plums likewise identified neochlorogenic acid as the predominant phenolic acid and demonstrated that the concentrations of individual phenolics are strongly influenced by the drying process [19].

The results obtained in this study demonstrate that both drying and long-term storage significantly influenced the physicochemical, bioactive, and sensorial properties of dried plums, while the application of biopolymer coatings and storage temperature played a decisive role in preserving product quality. The comparison between samples stored at room temperature (S, ZS, HS; 23 °C) and refrigerated conditions (F, ZF, HF; 4 °C) clearly highlights the importance of temperature control in addition to coating application.

3.2. pH

The initial pH value of fresh plums (2.9) increased after drying (3.5–3.6) (Table 1), which is attributed to the concentration of dissolved substances and partial decomposition of organic acids. In dried samples, the initial pH value of the control sample was 3.60, while the prunes coated with zein and chitosan had higher initial values, 4.27 and 4.10, respectively, which is related to the barrier properties of the coating, which affect the diffusion of organic acids and limit oxidative changes in the product (Table 2). Similar results were reported in studies investigating the application of chitosan and zein as edible fruit coatings [60,61]. During storage, an increase in pH value was recorded in all sample series, but with differences between the control and coated prunes: in the control sample, the increase in pH was the most pronounced, which indicates a more intensive consumption of organic acids and the progression of chemical changes during the aging of the product. At 23 °C, the pH of the control sample increased from 3.60 to 4.87, while at 4 °C, the increase was from 3.70 to 4.97. Even in the early stages of storage at room temperature, a growth trend was observed, which continued until the end of storage.

Conversely, the coated samples showed a stable change, which is in accordance with the available literature data [62,63]. The zein coating had the most pronounced protective effect, with the pH remaining almost unchanged during storage: at 23 °C, it ranged from 4.27 to 4.30, and at 4 °C, from 4.37 to 4.40. All the values in the intermediate stages of storage confirm this stability. Chitosan coating slowed the pH increment but less

pronounced than zein; at 23 °C, the pH increased from 4.10 to 4.53, and at 4 °C, from 4.22 to 4.65. These results point out that both coatings mitigated chemical changes during storage, with the effect being more pronounced for zein. The difference between the control and coated samples became more pronounced as storage duration increased. While the continuous increase in pH in the control samples indicated the progression of the degradation processes, in the coated samples, the changes were slower and more limited. This confirms that edible coatings act as a semi-permeable barrier for O₂/CO₂, slowing down ripening and delaying consumption of organic acids, which is coherent with literature data [64–66]. Changes in the pH of dried plums treated with edible coatings may result from the combined effects of the coating's barrier properties and alterations in the micro-environment at the fruit surface. Chitosan and zein coatings form a protective layer that limits gas exchange and moisture migration, which can slow oxidative and biochemical processes during storage [67–69]. In addition, residual components of the coating formulation, such as acetic acid and ethanol, can affect surface chemical conditions in the short term, while long-term changes in pH reflect shifts in the balance of organic acids, hydrogen ions, and the buffer system of the fruit matrix. A similar effect of chitosan coating on physicochemical characteristics, including pH, has also been reported in fresh plum fruit during storage [70].

The effect of storage temperature was noted, but less pronounced than the coating effect. Cold storage did not consistently lead to lower final pH values compared to storage at 23 °C, but contributed to a more uniform change course, especially in coated samples. This effect was most pronounced in the zein-coated samples, where changes were minimal regardless of temperature. With chitosan, the combination of lower temperature and coating additionally contributed to stability, but to a lesser extent than with zein.

The coating effect on pH retention was more effective than the effect of temperature alone, while the combination of low temperature and biopolymer coatings gave the most stable profile of changes. The lower temperature slowed down the chemical and biochemical reactions, while the coatings additionally limited the oxidative and metabolic processes, which effectively mitigated changes in the quality of the dried product. In a practical sense, the results point to the preservation of pH, and thus the chemical stability of dried plums, being primarily conditioned by the application of coating, especially zein, while the temperature had an additional stabilizing effect.

Table 2. Physico-chemical parameters (pH, dry matter) and nutritional characteristics (vitamin C) of prunes regarding different coatings and storage temperatures applied during the 12-month storage period.

Storage Temperature	Sample	pH	Dry Matter (%)	Vitamin C (g/100 g)	Storage Temperature	Samples	pH	Dry Matter (%)	Vitamin C (g/100 g)
23 °C	0-S	3.60 ± 0.04	68.30 ± 1.31	1.04 ± 0.01	4 °C	0-F	3.70 ± 0.05	68.50 ± 0.41	1.08 ± 0.02
	0-ZS	4.27 ± 0.09	69.17 ± 0.41	1.03 ± 0.01		0-ZF	4.37 ± 0.07	69.37 ± 1.41	1.04 ± 0.01
	0-HS	4.10 ± 0.06	69.60 ± 1.28	1.00 ± 0.01		0-HF	4.22 ± 0.06	69.80 ± 1.12	1.06 ± 0.03
	3-S	3.77 ± 0.03	63.23 ± 1.29	0.81 ± 0.01		3-F	3.87 ± 0.03	63.43 ± 0.71	0.93 ± 0.01
	3-ZS	4.33 ± 0.07	65.53 ± 0.48	0.94 ± 0.02		3-ZF	4.43 ± 0.09	65.73 ± 0.89	1.03 ± 0.01
	3-HS	4.23 ± 0.06	66.37 ± 0.95	0.82 ± 0.02		3-HF	4.35 ± 0.05	66.57 ± 1.02	1.02 ± 0.01
	6-S	3.86 ± 0.10	61.10 ± 1.61	0.94 ± 0.02		6-F	3.96 ± 0.09	61.30 ± 0.71	0.91 ± 0.02
	6-ZS	4.30 ± 0.07	64.33 ± 1.07	0.81 ± 0.01		6-ZF	4.40 ± 0.07	64.53 ± 0.90	0.97 ± 0.01
	6-HS	4.23 ± 0.09	63.37 ± 0.91	0.72 ± 0.01		6-HF	4.35 ± 0.03	63.57 ± 1.05	0.90 ± 0.03
	9-S	4.03 ± 0.07	59.90 ± 0.73	0.50 ± 0.01		9-F	4.13 ± 0.07	60.10 ± 0.98	0.57 ± 0.02
	9-ZS	4.33 ± 0.14	62.30 ± 1.41	0.71 ± 0.01		9-ZF	4.43 ± 0.11	62.50 ± 0.61	0.85 ± 0.01
	9-HS	4.40 ± 0.07	61.17 ± 0.51	0.61 ± 0.01		9-HF	4.52 ± 0.05	61.37 ± 1.00	0.76 ± 0.02

	12-S	4.87 ± 0.08	58.03 ± 1.12	0.41 ± 0.00		12-F	4.97 ± 0.11	58.23 ± 1.11	0.47 ± 0.01
	12-ZS	4.30 ± 0.03	60.07 ± 0.93	0.61 ± 0.01		12-ZF	4.40 ± 0.07	60.27 ± 0.47	0.73 ± 0.01
	12-HS	4.53 ± 0.12	59.57 ± 1.10	0.53 ± 0.01		12-HF	4.65 ± 0.06	59.77 ± 0.60	0.66 ± 0.00
F		50.911	39.891	628.261					
p		0.000	0.000	0.000					

F—F test, *p*—*p* value.

3.3. Dry Matter Content

After drying, there was an expected increase in dry matter content due to water removal, while the initial value for the dried samples was 68.3% for the control sample, 69.17% for the zein-coated sample and 69.6% for the chitosan-coated sample. Slightly higher initial values for coated samples indicate the contribution of the coating in limiting the migration of moisture and preserving the stability of the product immediately after coating. During storage, the dry matter content decreased in all prune samples, indicating water redistribution. The most pronounced decrease was recorded in the control samples, where at 23 °C, the content of dry matter decreased from 68.30% to 58.03%, while at 4 °C, the decrease was from 68.50% to 58.23%. This trend was noticeable in all stages of the storage, confirming a continuous change over time (Table 2).

On the other hand, the coated samples demonstrated a slower decline and greater stability of dry matter content. The zein coating provided the most pronounced protective effect, with the highest final dry matter values in both temperature regimes, 60.07% at 23 °C and 60.27% at 4 °C. Chitosan coating also slowed down the decrease in dry matter content, but to a slightly lesser extent than zein, with final values of 59.57% at 23 °C and 59.77% at 4 °C, while intermediate values indicated high stability during most of the storage. These results confirm that the biopolymer coatings effectively reduced the exchange of moisture between the product and the packaging micro atmosphere.

Comparing the results of the dry matter content during 12 months of storage, a difference between the control and coated samples was observed, which was more pronounced with the storage duration. Zein coating had the most pronounced effect in keeping dry matter values stable, which is caused by its relatively hydrophobic nature and well-known water vapor barrier properties, while chitosan coating contributed to stabilization through film-forming properties and structural protection of the surface. Such results are in accordance with literature data confirming that zein and chitosan coatings reduce mass and moisture changes, as well as slow down texture degradation during storage [71,72].

The effect of storage temperature was present, but less pronounced than the coating effect. Samples stored at 4 °C had slightly more stable dry matter values and less fluctuation compared to samples stored at 23 °C, which can be related to reduced water mobility and smaller water vapor pressure gradients at lower temperatures. Although some studies suggest that chitosan in combination with low temperatures can have a pronounced effect in reducing moisture transfer [71,73], the results of this work show that zein achieved the highest preservation of dry matter regardless of the temperature regime.

Changes in pH and dry matter show that parallel processes of organic acid consumption, moisture redistribution and matrix modification take place during storage. The coatings mitigated these changes, with zein acting dominantly as a moisture barrier, while chitosan showed a more pronounced stabilization of chemical processes. These results are consistent with the literature describing the combination of hydrophobic and polysaccharide films as an effective system for controlling moisture and gas migration [71,72].

3.4. Vitamin C

Vitamin C is one of the most sensitive parameters and, as expected, decreased during storage across all sample series, which is related to the oxidative degradation of ascorbic acid. The initial value in the control sample was 1.04 mg/100 g, while the coated samples had values of 1.03 mg/100 g for zein and 1.00 mg/100 g for chitosan. During storage, vitamin C content decreased across all sample series, but the intensity of the changes differed between control and coated samples. For control samples, the decline was the most pronounced (Table 2). At 23 °C, the vitamin C content decreased from 1.04 to 0.41 mg/100 g, while at 4 °C, it decreased from 1.08 to 0.47 mg/100 g. The coated samples also had a decline in vitamin C content over time, but with lower overall losses compared to the control. At 23 °C, the final values were 0.61 mg/100 g for zein-coated prunes and 0.53 mg/100 g for chitosan-coated prunes, while at 4 °C, they were 0.73 mg/100 g and 0.66 mg/100 g, respectively. Intermediate values during storage point to a slower course of degradation compared to the control samples. Over time, although the coated samples started from lower initial values, they showed a smaller relative decline in vitamin C during storage. Recent findings indicate that chitosan coatings are particularly effective at preserving vitamin C due to their oxygen barrier properties and antioxidant activity [63]. Similarly, zein-based coatings reduce oxygen permeability, further enhancing vitamin stability [74].

The differences between the control and coated samples became more pronounced with the storage duration, which means that the effect of the coating was particularly significant in the later stages of storage. This can be explained by the mechanism of ascorbic acid degradation, which is accelerated in the presence of oxygen and higher temperature. Edible coatings can mitigate these processes by reducing access to O₂, as confirmed by previous research on plum [75,76]. A similar pattern was noted in other coated fruit systems, where the combination of lower temperature and coating leads to better preservation of ascorbic acid than either measure individually [77,78].

The effect of storage temperature was evident through a better preservation of vitamin C at 4 °C in all sample series. Prune samples stored at a lower temperature retained higher final concentrations of ascorbic acid than the corresponding samples stored at 23 °C, which confirms that the lower temperature slows down the oxidative and degradation processes. This effect was present in both control and coated samples, which is in accordance with the literature stating that lower temperatures significantly reduce oxidative processes [79].

3.5. Total Phenols (TPC) and Total Flavonoid (TFC) Content

The content of total phenols (TPC) and total flavonoids (TFC) exhibited changes without a simple linear decreasing trend (Table 3). Unlike parameters such as vitamin C or pH, the changes in TPC and TFC did not exclusively reflect degradation processes, but indicated dynamic changes in the phenolic matrix during storage. The initial TPC values showed differences between the samples already at the beginning of the experiment. At 23 °C, the control sample had an initial value of 2430 µg/g, the zein-coated sample 3298 µg/g, and the chitosan-coated sample 2862 µg/g. At 4 °C, the initial values were 2608 µg/g for control, 3106 µg/g for zein and 2810 µg/g for chitosan-coated prunes. Different dynamics of changes were observed during storage. At 23 °C, TPC in the control increased from 2430 to 3525 µg/g, in the zein-coated sample, increased from 3298 to 3917 µg/g, and in the prunes with chitosan coating, from 2862 to 3911 µg/g. At 4 °C, the control sample exhibited the highest increase, from 2608 to 4166 µg/g.

Similar dynamics were observed for TFC. At 23 °C, the initial values were 2550 µg/g for control, 4080 µg/g for zein and 2642 µg/g for chitosan. During storage, the control sample displayed an increase to 3007 µg/g, the sample with zein slightly decreased to 3167

µg/g, while the chitosan content increased from 2642 to 3191 µg/g. At 4 °C, both the control and chitosan-coated samples ended up at a very similar level (3136 and 3010 µg/g, respectively), while the final value for zein-coated runes was higher (4128 µg/g).

Table 3. Antioxidative properties (ABTS, DPPH, FRAP, CUPRAC) and total phenolic (TPC) and flavonoid (TFC) content of prunes regarding different coatings and storage temperatures applied during the 12-month storage period.

Storage t°	Sample	ABTS (µmol/g)	DPPH (µmol/g)	FRAP (µmol/g)	CUPRAC (µmol/g)	Total Phenols (µg/g)	Total Flavonoids (µg/g)
23 °C	0-S	0.75 ± 0.01	68.10 ± 1.05	18.20 ± 0.14	34.20 ± 0.41	2430.00 ± 56.16	2550.00 ± 13.35
	0-ZS	1.35 ± 0.02	76.00 ± 0.66	24.60 ± 0.57	38.00 ± 0.59	3298.00 ± 80.30	4080.00 ± 25.38
	0-HS	0.89 ± 0.01	69.00 ± 0.92	16.80 ± 0.38	32.40 ± 0.92	2862.00 ± 32.44	2642.00 ± 69.58
	3-S	1.02 ± 0.01	70.00 ± 1.05	20.20 ± 0.33	45.20 ± 0.59	2742.00 ± 40.29	2466.00 ± 12.04
	3-ZS	1.05 ± 0.03	73.80 ± 1.61	18.60 ± 0.23	40.10 ± 0.89	3524.00 ± 73.21	3796.00 ± 18.75
	3-HS	0.92 ± 0.01	76.10 ± 1.05	18.00 ± 0.30	35.00 ± 1.17	3099.00 ± 11.06	2884.00 ± 22.57
	6-S	0.88 ± 0.01	73.00 ± 1.06	20.40 ± 0.11	40.00 ± 0.58	2345.00 ± 35.45	3304.00 ± 99.14
	6-ZS	0.63 ± 0.01	73.80 ± 0.28	26.30 ± 0.36	51.00 ± 0.79	4005.00 ± 44.27	3825.00 ± 49.82
	6-HS	0.81 ± 0.02	74.60 ± 1.93	21.80 ± 0.37	39.00 ± 0.57	3436.00 ± 55.51	3047.00 ± 17.66
	9-S	1.04 ± 0.01	72.90 ± 1.85	21.40 ± 0.30	51.00 ± 0.93	3329.00 ± 72.64	3296.00 ± 71.32
	9-ZS	1.05 ± 0.00	70.10 ± 0.91	22.50 ± 0.37	55.00 ± 1.31	3667.00 ± 62.00	3997.00 ± 129.83
	9-HS	0.83 ± 0.02	73.60 ± 1.16	20.60 ± 0.24	41.50 ± 1.11	3749.00 ± 67.72	2801.00 ± 27.69
4 °C	12-S	1.00 ± 0.02	73.40 ± 0.53	15.50 ± 0.31	42.00 ± 0.61	3525.00 ± 27.17	3007.00 ± 9.33
	12-ZS	0.96 ± 0.01	74.50 ± 0.06	22.60 ± 0.36	43.80 ± 1.02	3917.00 ± 68.21	3167.00 ± 85.62
	12-HS	0.53 ± 0.01	75.90 ± 1.26	13.10 ± 0.18	44.80 ± 0.88	3911.00 ± 69.89	3191.00 ± 7.00
	0-F	0.72 ± 0.01	74.70 ± 1.02	18.20 ± 0.16	36.70 ± 0.61	2608.00 ± 37.50	2680.00 ± 10.19
	0-ZF	0.93 ± 0.00	70.40 ± 1.95	22.40 ± 0.22	36.10 ± 0.97	3106.00 ± 2.52	3746.00 ± 45.84
	0-HF	0.91 ± 0.01	71.10 ± 0.60	19.30 ± 0.30	41.90 ± 0.61	2810.00 ± 70.57	2631.00 ± 28.85
	3-F	1.09 ± 0.02	69.80 ± 1.14	21.60 ± 0.23	42.50 ± 0.48	3200.00 ± 50.18	2924.00 ± 36.25
	3-ZF	1.09 ± 0.02	73.40 ± 0.36	23.80 ± 0.38	42.30 ± 0.54	2803.00 ± 82.10	3767.00 ± 126.58
	3-HF	0.54 ± 0.01	73.00 ± 1.18	16.70 ± 0.24	23.40 ± 0.33	3316.00 ± 36.68	2384.00 ± 38.95
	6-F	0.96 ± 0.02	74.30 ± 2.10	20.70 ± 0.33	27.00 ± 0.41	2987.00 ± 24.58	3061.00 ± 66.01
	6-ZF	0.65 ± 0.01	73.60 ± 1.24	20.30 ± 0.41	51.00 ± 1.38	3062.00 ± 75.89	4204.00 ± 71.55
	6-HF	0.74 ± 0.01	72.70 ± 2.07	18.30 ± 0.40	41.00 ± 0.59	3480.00 ± 38.27	2936.00 ± 45.47
	9-F	0.93 ± 0.02	71.50 ± 1.09	19.90 ± 0.20	51.30 ± 0.94	3589.00 ± 62.58	2949.00 ± 36.24
	9-ZF	0.93 ± 0.01	70.90 ± 1.81	18.60 ± 0.26	41.30 ± 0.46	3384.00 ± 20.01	4038.00 ± 113.59
	9-HF	0.77 ± 0.01	72.70 ± 1.07	17.00 ± 0.20	37.00 ± 0.20	3488.00 ± 50.66	3318.00 ± 38.49
	12-F	0.93 ± 0.01	74.70 ± 1.00	18.00 ± 0.16	43.00 ± 0.43	4166.00 ± 65.11	3136.00 ± 47.50
	12-ZF	0.90 ± 0.02	73.60 ± 0.77	19.50 ± 0.42	48.90 ± 1.43	3562.00 ± 43.05	4128.00 ± 59.53
	12-HF	0.69 ± 0.02	74.60 ± 1.05	18.60 ± 0.37	37.00 ± 1.18	3491.00 ± 53.26	3010.00 ± 40.39
F		446.731	8.658	238.106	220.345	213.544	247.949
p		0.000	0.000	0.000	0.000	0.000	0.000

F—F test, p—p value.

Changes in TPC and TFC observed during storage did not follow a unique pattern between control and coated samples, nor can they be interpreted solely as a consequence of the loss of phenolic compounds. The increase in values in certain sample series means that during storage, there may be changes in extractability, deesterification and release of bound phenolic compounds from the plum tissue, which increases their analytical availability. In this sense, an increase in TPC or TFC may not indicate biosynthesis, but may reflect transformations of phenolic fractions in the dried and structurally altered product [80]. This explains why TPC/TFC cannot be interpreted in isolation, but only in

combination with HPLC profile and antioxidant tests to get a complete picture of changes during storage. Also, variation in TPC and TFC during storage could be linked to matrix-bound phenolic release, thermal degradation, and oxidative polymerization [14]. Furthermore, the structural changes that occurred during the drying affected the release of phenolics from the food matrix [19]. In plum fruit, it was confirmed that the phenolic profiles are heterogeneous and that the antioxidant activity depends on both free and bound fractions, with neochlorogenic acid and other phenols contributing significantly to the total activity [57]. The influence of storage temperature was noted, but it did not show a clear effect on the TPC and TFC value changes. Lower temperature in some cases was associated with greater stability or an increase in phenolic parameters, while in other sample series, it did not lead to consistently higher final values compared to 23 °C. This means that temperature alone was not the dominant factor determining the changes in TPC and TFC, but that these changes resulted from the interaction of matrix condition, coating effects and temperature.

3.6. Antioxidative Activity—ABTS, DPPH, FRAP and CUPRAC Methods

The antioxidant activity of dried plums, evaluated by ABTS, DPPH, FRAP and CUPRAC methods, showed complex changes depending on storage time, application of biopolymer coatings and storage temperature. Such methodological variability is expected in fruit matrices rich in different phenolic fractions, given that each of the applied methods measures different aspects of the antioxidant system (Table 3).

ABTS values proved the greatest variability during storage. At 23 °C, the control sample had an increase from 0.75 to 1.00 µmol/g. The sample coated with zein had a drop from 1.05 to 0.96 µmol/g at the end of storage. In chitosan-coated samples, ABTS values were the lowest and finally decreased to 0.53 µmol/g. At 4 °C, ABTS values were more stable, and the final values were 0.93 µmol/g for control, 0.90 µmol/g for zein-coated prunes and 0.69 µmol/g for chitosan-coated prunes. Such dynamics indicate that ABTS in this system may reflect short-term changes in the availability of antioxidants and changes in their extractability, and not only the total antioxidant capacity.

DPPH exhibited a significantly more stable pattern of value changes. All sample groups remained within a relatively narrow range of approximately 68 to 76 µmol/g, with minor oscillations during storage. Final values were slightly higher for all sample series—uncoated and coated. Compared to other methods, DPPH showed the least variability, indicating the relative stability of this aspect of antioxidant activity during storage.

FRAP displayed more pronounced differences in values during storage. At 23 °C, the control sample decreased from 18.20 to 15.50 µmol/g, chitosan-coated prunes from 16.80 to 13.10 µmol/g, while the samples with zein coating maintained a higher level of activity (from 24.60 to 22.60 µmol/g). At 4 °C, FRAP values were more stable and ended up at 18.00 µmol/g for control, 19.50 µmol/g for zein and 18.60 µmol/g for chitosan-coated samples.

CUPRAC results also demonstrated different value fluctuations depending on storage conditions and applied coating or not. Both at 4 °C and 23 °C, an increase was recorded in the prunes, both coated and uncoated. CUPRAC values followed a similar trend to TPC and TFC. As with the FRAP method, the changes were not linear, but pointed to the combined effect of oxidative processes, transformation of phenolic compounds and changes in their availability during storage.

The results show that the antioxidant activity cannot be interpreted through a single parameter or a single trend. While ABTS and CUPRAC had more pronounced oscillations, DPPH remained relatively stable, and FRAP indicated differences in the preservation of reducing capacity during storage. This methodological difference is expected because ABTS, DPPH, FRAP and CUPRAC do not measure the same chemical property of the

antioxidant system. Individual plum phenolics, including neochlorogenic and chlorogenic acids, are known to contribute differently to individual assays depending on the matrix, bound and free fractions, and extraction conditions [57]. The temporary increases in activity recorded in some samples during storage can be further explained by the release of bound phenolic compounds or changes in the matrix structure that increase the extractability of antioxidant active components, which is in accordance with earlier findings. Recent studies confirm that edible coatings can preserve and even enhance antioxidant properties by limiting oxygen exposure and stabilizing phenolic compounds [13,71].

The influence of storage temperature was noted as follows: lower temperature in some cases was associated with more stable values and smaller oscillations, especially in FRAP and certain CUPRAC results, but did not consistently lead to higher final values in all tests. This means that the effect of temperature depended on the nature of the antioxidant response measured and the interaction with changes in the phenolic matrix during storage.

The antioxidant activity in this study should be interpreted as: DPPH was the most stable indicator of total capacity; FRAP and CUPRAC better reflected differences in reducing power, while ABTS was the most responsive to short-term changes in antioxidant availability. The results indicate that the changes during storage were due to the complex interaction of free and bound phenols, as well as their transformations during storage, a combination of oxidative degradation, and changes in the availability of bioactive compounds, while the effects of coating and temperature depended on the type of antioxidant method applied [41,65].

3.7. HPLC Profile of Individual Phenolic Compounds (Non-Chlorogenic, Caffeic, Chlorogenic and *p*-Coumaric Acids; Rutin)

The profile of individual phenolic compounds, determined by HPLC analysis, gives a finer and more analytically valuable overview than TPC/TFC summary parameters. In the initial samples, the values of neochlorogenic and chlorogenic acids were particularly high, which is in accordance with the literature that identifies these phenolic acids as the dominant components of plums [57]. At 23 °C, neochlorogenic acid decreased in all series: in the control, from 1881.50 to 474.00 mg/kg, in the sample with zein, from 1825.60 to 394.50 mg/kg, and in the sample with chitosan, from 1286.00 to 222.40 mg/kg. At 4 °C, the pattern was the same—the control demonstrated a decrease from 1827.10 to 503.60 mg/kg, while zein and chitosan-coated samples decreased to 421.00 and 340.60 mg/kg, respectively (Table 4).

Caffeic acid demonstrated a predominantly decreasing trend, especially in the coated series at 23 °C, where the values in the sample with zein coating decreased from 96.70 to 26.10 mg/kg, and for chitosan-coated prunes, from 80.30 to 21.30 mg/kg. At 4 °C, the control sample demonstrated an increase of up to 55.10 mg/kg, which additionally confirms that the temperature regime can affect the stability of individual phenolic acids differently.

Table 4. Phenolic profile of prunes regarding different coatings and storage temperatures applied during the 12-month storage period.

Storage t°	Sample	Neochlorogenic Acid (mg/kg)	Caffeic Acid (mg/kg)	Chlorogenic Acid (mg/kg)	<i>p</i> -Coumaric Acid (mg/kg)	Rutin (mg/kg)
23 °C	0-S	1881.50 ± 38.44	92.30 ± 1.74	817.00 ± 17.73	196.40 ± 3.20	69.70 ± 0.58
	0-ZS	1825.60 ± 9.24	96.70 ± 1.00	1388.60 ± 8.68	312.30 ± 10.04	76.30 ± 1.83
	0-HS	1286.00 ± 13.05	80.30 ± 0.44	1024.60 ± 19.68	171.90 ± 2.20	46.20 ± 1.02
	3-S	1322.90 ± 22.49	94.10 ± 0.67	1362.00 ± 30.45	156.10 ± 2.97	67.40 ± 0.72
	3-ZS	830.20 ± 19.92	52.30 ± 0.32	1068.60 ± 18.99	224.60 ± 4.48	64.30 ± 0.89

	3-HS	962.50 ± 13.88	74.00 ± 0.88	894.60 ± 13.68	191.90 ± 1.27	53.10 ± 1.02
	6-S	1047.10 ± 24.25	66.30 ± 1.06	1094.30 ± 11.38	198.40 ± 4.56	69.30 ± 2.34
	6-ZS	795.10 ± 19.94	47.10 ± 0.29	1270.00 ± 20.98	388.90 ± 6.56	83.20 ± 1.25
	6-HS	682.90 ± 14.43	64.20 ± 1.01	1132.30 ± 7.41	370.40 ± 4.94	58.90 ± 0.78
	9-S	781.80 ± 8.86	67.30 ± 2.16	1183.80 ± 6.19	234.60 ± 3.45	57.70 ± 0.40
	9-ZS	667.70 ± 9.52	68.60 ± 0.98	1318.10 ± 10.61	265.70 ± 3.08	67.90 ± 1.05
	9-HS	699.00 ± 11.96	56.30 ± 1.47	947.80 ± 7.25	191.90 ± 3.04	33.00 ± 0.19
	12-S	474.00 ± 7.70	39.50 ± 0.56	1563.50 ± 23.22	303.60 ± 6.88	49.20 ± 0.55
	12-ZS	394.50 ± 6.82	26.10 ± 0.65	1206.40 ± 20.02	221.80 ± 3.54	62.50 ± 1.61
	12-HS	222.40 ± 3.52	21.30 ± 0.52	1097.30 ± 16.04	227.50 ± 1.86	30.00 ± 0.43
4 °C	0-F	1827.10 ± 17.15	108.30 ± 1.03	1367.10 ± 15.05	196.80 ± 3.73	66.50 ± 1.36
	0-ZF	1269.50 ± 24.77	78.60 ± 0.55	1189.40 ± 18.42	258.60 ± 8.09	56.40 ± 0.74
	0-HF	1675.60 ± 39.42	80.50 ± 0.46	1072.50 ± 17.57	226.80 ± 6.23	56.40 ± 0.83
	3-F	1624.30 ± 42.92	78.30 ± 1.10	1206.40 ± 26.74	175.40 ± 2.38	48.30 ± 0.88
	3-ZF	823.10 ± 12.86	55.30 ± 1.21	1042.10 ± 18.69	290.90 ± 4.12	48.10 ± 0.83
	3-HF	815.20 ± 12.81	32.90 ± 0.71	949.40 ± 10.24	116.40 ± 0.53	38.30 ± 0.35
	6-F	1042.20 ± 19.44	26.10 ± 0.15	1887.70 ± 11.48	157.60 ± 2.80	71.50 ± 1.14
	6-ZF	473.20 ± 2.66	44.20 ± 0.70	2542.80 ± 40.14	402.40 ± 5.92	60.90 ± 0.60
	6-HF	565.30 ± 8.45	37.40 ± 0.30	1212.40 ± 19.84	313.70 ± 5.17	59.60 ± 1.06
	9-F	694.50 ± 18.34	26.10 ± 0.36	2006.40 ± 32.52	221.80 ± 2.22	32.80 ± 0.30
	9-ZF	474.70 ± 9.21	32.60 ± 0.47	1423.70 ± 23.16	340.00 ± 8.64	45.40 ± 1.19
	9-HF	352.30 ± 5.18	22.60 ± 0.26	964.60 ± 22.26	168.90 ± 2.93	37.20 ± 0.41
	12-F	503.60 ± 8.38	55.10 ± 1.02	2410.60 ± 71.76	426.50 ± 5.46	57.20 ± 1.43
	12-ZF	421.00 ± 11.78	29.80 ± 0.50	1930.80 ± 33.64	495.90 ± 11.53	53.70 ± 1.12
	12-HF	340.60 ± 4.24	30.20 ± 0.36	1501.20 ± 27.98	270.30 ± 3.73	33.50 ± 0.63
F		2099.385	2406.190	932.516	928.392	541.850
<i>p</i>		0.000	0.000	0.000	0.000	0.000

F—F test, *p*—*p* value.

Chlorogenic acid remained dominant during storage and proved an increase in all examined prune sample groups. This trend was particularly pronounced at 4 °C, where the control sample of prunes increased from 1367.10 to 2410.60 mg/kg, the zein-coated prunes from 1189.40 to 1930.80 mg/kg, and the chitosan-coated prunes from 1072.50 to 1501.20 mg/kg. At 23 °C, an increase was recorded in the control and chitosan, while a slight decrease was registered in the zein-coated prunes (from 1388.60 to 1206.40 mg/kg). Such a dynamic indicates that chlorogenic acid did not follow a simple degradation pattern, but that transformations and release of bound forms were probably present during storage.

p-coumaric acid mainly increased with storage duration, especially at 4 °C, where the final values were 426.50 mg/kg for control, 495.90 mg/kg for zein and 270.30 mg/kg for chitosan-coated prunes. This trend supports the assumption about the possible release or transformation of certain hydroxycinnamic derivatives during storage.

Rutin had a different pattern compared to phenolic acids. In the control and the sample with zein, it was relatively stable, while with chitosan, a marked decrease was recorded, especially at 4 °C, where it decreased from 56.40 to 33.50 mg/kg. This behavior confirms that temperature and coating do not affect all phenolic markers equally, but their effect depends on the chemical nature of the specific compound.

The simultaneous oxidation of some compounds and the release or transformation of others indicate interconversions among derivatives of hydroxycinnamic acids, as well as the influence of changes in the plum tissue during storage. This interpretation is coherent with the literature, where coatings can modulate which phenolic fractions will be preserved and which will be oxidized by influencing the PAL/PPO balance [75,81]. Also, it is

known that PPO acts prevalently on neochlorogenic acid, which, in fact, showed greater degradation than chlorogenic acid. Because most neochlorogenic acid is present in the flesh, oxidation takes place mainly in this substrate [82]. The increase in chlorogenic acid during the storage could be linked to coupled oxidation reactions in which chlorogenic acid is involved in the degradation of the anthocyanins, with a reaction mechanism that leads to the partial regeneration of the acid [83,84]. The fall in caffeic acid content over a period of storage is probably due to enzymatic oxidation. On the other hand, during storage, an increase in *p*-coumaric content is probably a result of degradation of the cinnamates. Furthermore, the flavonols (rutin) are not direct substrates to PPO, because the enzyme is unable to act directly on the glucosides. They are degraded by coupled oxidation reactions [83,85]. Also, recent studies have demonstrated that composite coatings based on chitosan and zein provide enhanced protection of bioactive compounds due to synergistic barrier and antioxidant effects [86]. Additionally, zein matrices have been reported to encapsulate and stabilize phenolic compounds, reducing their exposure to oxygen and light [71].

The influence of storage temperature was pronounced: lower temperature was associated with better preservation or an increase in the concentration of certain phenolic acids, especially chlorogenic and *p*-coumaric, but it did not have a universally positive effect for all compounds, which is clearly seen in the example of rutin in chitosan-coated samples.

3.8. Headspace Analysis (O_2 , CO_2 and N_2)

Control of oxygen availability leads to bioactive compounds' oxidation and, consequently, control of sensorial quality. Headspace should be considered not only as a consequence of respiration but also as an active driver of oxidative processes. So, the headspace analysis is a key that connects chemical changes (vitamin C, phenols, pH), bioactive changes (TPC, TFC, antioxidant activity), sensorial profile and microbiological stability. The reported effects should be interpreted as the outcome of a coupled system comprising edible coating properties, product respiration, and packaging film permeability (Table 5).

At 23 °C, the O_2 content in the control increased from 6.83% to 18.49%, while in the zein-coated prunes, the growth was milder (from 6.86% to 16.09%), and in the chitosan-coated prunes, the final value was the lowest (15.98%). At 4 °C, the initial values of O_2 were lower (5.93%–6.09%), but by the end of storage, they increased in all sample series, where the control had the highest final value (16.45%), and the coated samples slightly lower (15.38% for zein-coated prunes and 15.52% for chitosan-coated prunes). At the same time, CO_2 remained low, but in the coated samples, it was slightly higher than in the control, especially at 23 °C (at the end: control 0.30%, zein 0.50%, chitosan 0.70%). N_2 , as expected, decreased with slightly higher retention in chitosan.

Coatings' presence modified the availability of O_2 and the O_2/CO_2 ratio, which indirectly affected other changes: the degradation of ascorbic acid, oxidation of phenolic compounds, changes in pH and sensorial properties [74,87]. This effect is aligned with the concept that coatings act as semi-permeable barriers to gases and indirectly preserve nutritional attributes, which is literature-based [65,71,77,88]. The improved gas stability observed in chitosan-coated prunes may be related to the dense polymeric network of chitosan, which is known to exhibit low oxygen permeability and strong film-forming properties [63]. The composite systems combining protein and polysaccharide matrices have been shown to enhance barrier properties, which supports the observed behavior in zein-coated prunes [86].

Table 5. Headspace composition and sensorial score of prunes regarding different coatings and storage temperatures applied during the 12-month storage period.

Storage Temperature	Samples	Headspace O ₂	Headspace CO ₂	Headspace N ₂	Sensorial Score
23 °C	0-S	6.83 ± 0.15	1.20 ± 0.20	91.97 ± 0.26	19.30 ± 0.34
	0-ZS	6.87 ± 0.18	0.40 ± 0.00	92.73 ± 0.18	16.50 ± 0.18
	0-HS	6.52 ± 0.10	0.90 ± 0.10	92.58 ± 0.20	19.30 ± 0.35
	3-S	13.22 ± 0.24	0.80 ± 0.10	85.98 ± 0.32	17.66 ± 0.15
	3-ZS	13.03 ± 0.24	0.50 ± 0.10	86.47 ± 0.14	12.75 ± 0.12
	3-HS	14.32 ± 0.20	0.60 ± 0.10	85.08 ± 0.24	17.80 ± 0.13
	6-S	16.61 ± 0.26	0.70 ± 0.10	82.69 ± 0.17	16.41 ± 0.24
	6-ZS	17.39 ± 0.28	0.40 ± 0.10	82.21 ± 0.32	9.50 ± 0.17
	6-HS	15.71 ± 0.19	0.90 ± 0.10	83.39 ± 0.16	19.92 ± 0.46
	9-S	17.50 ± 0.22	0.70 ± 0.10	81.80 ± 0.17	17.88 ± 0.16
	9-ZS	17.58 ± 0.40	0.40 ± 0.10	82.02 ± 0.50	10.50 ± 0.19
	9-HS	15.70 ± 0.28	0.70 ± 0.10	83.60 ± 0.32	17.08 ± 0.33
	12-S	18.49 ± 0.26	0.30 ± 0.00	81.21 ± 0.26	16.98 ± 0.15
	12-ZS	16.09 ± 0.17	0.50 ± 0.00	83.41 ± 0.18	9.10 ± 0.11
	12-HS	15.94 ± 0.16	0.70 ± 0.10	83.32 ± 0.08	18.60 ± 0.28
4 °C	0-F	6.09 ± 0.11	1.07 ± 0.06	92.84 ± 0.06	19.76 ± 0.23
	0-ZF	6.39 ± 0.08	1.10 ± 0.10	92.51 ± 0.16	15.80 ± 0.21
	0-HF	5.93 ± 0.06	1.10 ± 0.10	92.97 ± 0.15	19.80 ± 0.54
	3-F	9.78 ± 0.16	0.60 ± 0.10	89.62 ± 0.24	19.32 ± 0.20
	3-ZF	8.78 ± 0.23	0.60 ± 0.10	90.62 ± 0.33	12.60 ± 0.29
	3-HF	9.42 ± 0.24	0.40 ± 0.10	90.18 ± 0.29	18.85 ± 0.49
	6-F	15.63 ± 0.21	0.20 ± 0.00	84.17 ± 0.21	18.08 ± 0.12
	6-ZF	15.23 ± 0.13	0.30 ± 0.00	84.47 ± 0.13	10.17 ± 0.14
	6-HF	14.70 ± 0.22	0.40 ± 0.00	84.90 ± 0.22	16.58 ± 0.40
	9-F	15.98 ± 0.24	0.30 ± 0.00	83.73 ± 0.24	19.05 ± 0.26
	9-ZF	15.22 ± 0.25	0.40 ± 0.00	84.38 ± 0.25	11.00 ± 0.08
	9-HF	16.52 ± 0.14	0.20 ± 0.00	83.28 ± 0.14	18.58 ± 0.21
	12-F	16.45 ± 0.23	0.20 ± 0.00	83.35 ± 0.23	17.86 ± 0.33
	12-ZF	15.38 ± 0.05	0.10 ± 0.00	84.52 ± 0.05	10.00 ± 0.04
	12-HF	15.52 ± 0.32	0.10 ± 0.00	84.38 ± 0.32	18.20 ± 0.28
F		930.565	3140.910	23.697	527.731
p		0.000	0.000	0.000	0.000

F—F test, *p*—*p* value.

The measured headspace oxygen concentration also reflects the effects of oxygen permeation through the PET/PE packaging film and oxygen consumption associated with the packaged product. Therefore, the observed differences between treatments cannot be attributed exclusively to the edible coatings. Since the empty-package controls were not included in the experiment, the individual contributions of film permeability and coating-induced modifications of respiration cannot be quantitatively separated. A limitation of this study is that oxygen transmission through the packaging material was not independently quantified, meaning that the observed changes in headspace gas composition during storage represent a combined effect of package permeability and physiological or chemical processes occurring within the prunes.

The effect of storage temperature was present, but less pronounced than the coating effect. Although lower temperatures contributed to a more stable gas profile, emphasizing that temperature is a critical factor in controlling gas exchange and oxidative stability in

packaged foods [62], the differences between control and coated samples were more pronounced than the differences between temperature regimes.

3.9. Sensorial Properties

Sensory analysis revealed that the chemical stability of the product does not necessarily have to be accompanied by the consumer acceptability. Initial sensory scores indicated clear differences between the samples already at the beginning of storage. At 23 °C, the control and chitosan-coated sample had the same initial score (19.30), while the zein sample had a lower initial score (16.50). A similar pattern was observed at 4 °C, where the control and chitosan had high initial scores (19.76 and 19.80, respectively), while the zein sample had an initial value of 15.80 (Table 5).

During storage, sensory scores decreased in all sample series, but with differences in the intensity of changes. At 23 °C, the control sample dropped from 19.30 to 16.98, the chitosan-coated sample from 19.30 to 18.60, while the zein sample dropped from 16.50 to 9.10. At 4 °C, a similar trend was confirmed: the control decreased from 19.76 to 17.86, the chitosan-coated sample from 19.80 to 18.20, while the sensory score value of the zein-coated sample decreased from 15.80 to 10.00. The control and chitosan-coated samples maintained relatively high scores throughout storage, with a moderate decline in acceptability. Zein-coated prunes showed lower scores from the start and further declined during storage, where out of all the tested parameters (color, smell, taste, general appearance), taste and general appearance (likeability) were rated with the lowest scores.

Although zein coating provided superior preservation of physicochemical quality, its lower sensory scores indicate that improved shelf-life does not necessarily translate into greater consumer acceptance. Sensory deterioration observed with zein coating may be explained by the nature of zein films. Zein forms compact hydrophobic protein films with excellent moisture barrier properties, but these films are also relatively dense and may modify surface texture and mouthfeel compared with polysaccharide coatings [30,89]. In addition, zein coatings are commonly prepared from aqueous ethanol solutions. Although ethanol should evaporate during drying, it cannot be completely excluded that residual solvent traces or solvent-induced changes in the volatile profile may have influenced sensory perception in terms of lower scores. This aspect was not directly evaluated and therefore requires further investigation. Based on the sensory evaluation, it could be concluded that the choice of edible coating should depend on the intended application [12,24]. Zein is more suitable when maximum moisture protection and prolonged physicochemical stability are the primary objectives, such as long-term storage or industrial distribution [30,89]. On the other hand, chitosan provides a better balance between product preservation and consumer sensory acceptance [12,90].

This pattern proved that the effect of the coating on sensory quality does not necessarily follow the effect on chemical stability, but also depends on the effect of the coating on the surface appearance, chewing texture, feel of the coating and the overall perception of the product. In fruit systems, it has been described that certain coating formulations can lead to undesirable changes in texture or surface feel despite a good preservation function, while optimized systems can preserve sensory quality [66,72,91,92].

Samples stored at 4 °C generally retained slightly higher final scores than the corresponding samples stored at 23 °C, indicating slower processes leading to loss of sensory quality. However, the differences between temperature regimes were less pronounced than the differences between coatings, indicating that the type of coating had a greater effect on the sensor response than temperature itself.

Sensory analysis confirms that the effectiveness of the coating should not be evaluated only on the basis of chemical and bioactive parameters, but also through the consumer acceptability. Although zein coating provided the greatest protection against

physicochemical deterioration, its lower sensory scores indicate that successful coating design requires balancing preservation efficiency with desirable sensory attributes. Therefore, the sensory results should be considered as a key complementary criterion when evaluating the overall efficiency of the protection system during storage. Although some chemical parameters were better preserved in the coated samples, the sensory results showed that chitosan gave the best balance between stability and acceptability. On the other hand, zein, although chemically effective, can negatively affect texture and perception. Control remains sensorially competitive despite weaker chemical protection. One of the most important findings of this work is that chemical stability does not guarantee sensory acceptability.

3.10. Microbiological Profile

The microbiological profile of prunes indicated a high degree of stability during storage, where no positive findings of pathogenic microorganisms were recorded in the analyzed samples, nor significant growth of indicator microflora (Table 6). *Salmonella* spp. and *Listeria monocytogenes* were undetectable at all tested sampling points, while Enterobacteriaceae, *E. coli*, yeasts and molds remained below the detection limit (<10 cfu/g). This result proved that the initial processing, MAP packaging and storage conditions ensured a good level of microbiological integrity of the product.

Table 6. Microbiological profile of prunes regarding different coatings and storage temperatures applied during the 12-month storage period.

Storage Temperature		<i>Salmonella</i> spp.	Enterobacteriaceae	<i>L. monocytogenes</i>	<i>E. coli</i>	Yeasts	Molds	Storage Temperature		<i>Salmonella</i> spp.	Enterobacteriaceae	<i>L. monocytogenes</i>	<i>E. coli</i>	Yeasts	Molds
23 °C	0-S	ND	<DL	ND	<DL	<DL	<DL	4 °C	0-F	ND	<DL	ND	<DL	<DL	<DL
	0-ZS	ND	<DL	ND	<DL	<DL	<DL		0-ZF	ND	<DL	ND	<DL	<DL	<DL
	0-HS	ND	<DL	ND	<DL	<DL	<DL		0-HF	ND	<DL	ND	<DL	<DL	<DL
	3-S	ND	<DL	ND	<DL	<DL	<DL		3-F	ND	<DL	ND	<DL	<DL	<DL
	3-ZS	ND	<DL	ND	<DL	<DL	<DL		3-ZF	ND	<DL	ND	<DL	<DL	<DL
	3-HS	ND	<DL	ND	<DL	<DL	<DL		3-HF	ND	<DL	ND	<DL	<DL	<DL
	6-S	ND	<DL	ND	<DL	<DL	<DL		6-F	ND	<DL	ND	<DL	<DL	<DL
	6-ZS	ND	<DL	ND	<DL	<DL	<DL		6-ZF	ND	<DL	ND	<DL	<DL	<DL
	6-HS	ND	<DL	ND	<DL	<DL	<DL		6-HF	ND	<DL	ND	<DL	<DL	<DL
	9-S	ND	<DL	ND	<DL	<DL	<DL		9-F	ND	<DL	ND	<DL	<DL	<DL
	9-ZS	ND	<DL	ND	<DL	<DL	<DL		9-ZF	ND	<DL	ND	<DL	<DL	<DL
	9-HS	ND	<DL	ND	<DL	<DL	<DL		9-HF	ND	<DL	ND	<DL	<DL	<DL
12 °C	12-S	ND	<DL	ND	<DL	<DL	<DL		12-F	ND	<DL	ND	<DL	<DL	<DL
	12-ZS	ND	<DL	ND	<DL	<DL	<DL		12-ZF	ND	<DL	ND	<DL	<DL	<DL
	12-HS	ND	<DL	ND	<DL	<DL	<DL		12-HF	ND	<DL	ND	<DL	<DL	<DL

<DL = less than detection limit = <10 cfu/10 g.

Opposite to other quality parameters, microbiological data did not show dynamics over time, nor did they enable quantitative differentiation between control and coated samples. This means that the effect of the coating on microbial growth in this experiment could not be assessed through differences in the number of microorganisms, not because the effect does not exist, but because the system conditions did not allow the microflora to develop to a level where the differences would be measurable.

Although the data did not generate differentiation among treatments, the known mechanisms of action of biopolymer coatings provide a basis for the interpretation of the

obtained results. Chitosan has well-documented antimicrobial activity against bacteria and fungi, associated with interaction with the cell membranes of microorganisms and disruption of their permeability [63,93]. Zein contributes to microbiological stability primarily through a barrier effect and limiting spoilage conditions. The literature shows that the combination of coating and low temperature can contribute to prolonging storage stability and delaying microbiological and sensory spoilage [64,66].

This outcome is expected regarding the nature of the product. Low water activity in prunes limits the growth of most microorganisms, while the previously discussed stable headspace profile, limited oxygen availability and preserved chemical stability further contribute to reducing the risk of microbiological spoilage. Consequently, the microbiological findings are coherent with previously observed changes in pH and preservation of chemical stability. It is important to emphasize that the absence of detected growth does not represent the absence of the effect of the protection system, but shows that the combination of low a_w value, coating and storage conditions kept the product in the microbiologically stable domain throughout the storage period. The microbiological profile should be seen as a confirmation of the functionality of the overall protection system, although it did not generate differentiation between treatments.

3.11. Statistical Analysis

3.11.1. Normality Test

Normality assessment using the Shapiro–Wilk and Anderson–Darling tests demonstrated that the majority of the analyzed variables significantly deviated from a normal distribution ($p < 0.05$). Specifically, pH, dry matter, vitamin C, ABTS, DPPH, CUPRAC, TFC, headspace gases (O_2 , CO_2 , and N_2), sensory properties, and individual phenolic compounds showed significant non-normality in both tests. In contrast, FRAP and TPC did not significantly differ from normal distribution according to the Shapiro–Wilk test, indicating approximate normality for these variables.

The Anderson–Darling test generally confirmed the Shapiro–Wilk results and pointed to particularly strong deviations from normality for headspace O_2 , sensory properties, chlorogenic acid, and neochlorogenic acid, as reflected by very low p -values. These deviations suggest that the replicate-level data distributions were not strictly normal.

Levene's test indicated no significant heterogeneity of variances for any analyzed variable ($p > 0.05$), indicating homogeneity of variances among groups and confirming that variance dispersion was comparable across treatments.

Given the small number of replicates ($n = 3$ per condition), normality test results should be interpreted with caution, as such low sample sizes limit statistical power and increase sensitivity to minor deviations. Nevertheless, the overall pattern suggests that parametric assumptions were not consistently met, supporting the use of non-parametric approaches for group comparisons or the confirmation of robustness using rank-based tests.

Although several variables had deviations from normal distribution according to Shapiro–Wilk and Anderson–Darling tests, Levene's test confirmed homogeneity of variances across groups. Therefore, parametric analysis based on linear mixed-effects ANOVA was considered appropriate, as ANOVA models are generally robust to moderate violations of normality in balanced experimental designs with equal replication. In addition, the experimental design included repeated measurements across storage time, temperature, and treatment conditions, which required simultaneous evaluation of main effects and their interactions. For this reason, mixed-effects ANOVA was preferred over the non-parametric Kruskal–Wallis test, since Kruskal–Wallis cannot adequately account for repeated-measures structure, factorial interactions, or random effects within the experimental design.

The Yeo–Johnson transformation was applied to all measured variables in order to improve normality and stabilize variance prior to further statistical analysis. The transformation was successful in improving distributional properties for most variables, as evidenced by changes in Shapiro–Wilk test p -values before and after transformation. The estimated transformation parameters (λ) varied substantially across variables, indicating heterogeneous distributional characteristics of the dataset. Positive λ values were observed for variables such as vitamin C ($\lambda = 3.22$), DPPH ($\lambda \approx 5.00$), sensory properties ($\lambda = 3.53$), and pH ($\lambda = 1.28$), suggesting strong power-type transformations were required to approximate normality, whereas negative λ values for DM ($\lambda = -2.43$), TFC ($\lambda = -0.56$), headspace CO₂ ($\lambda = -0.44$), headspace N₂ ($\lambda \approx -5.00$), and p -coumaric acid ($\lambda = -0.21$) indicate inverse or strong left-skew correction. Near-zero λ values for compounds such as neochlorogenic acid ($\lambda = 0.09$) and caffeic acid ($\lambda = 0.32$) suggest minimal transformation was required, indicating these variables were already closer to normal distribution. Assessment of normality using the Shapiro–Wilk test showed that the transformation generally improved distributional properties. For several variables, including DPPH (p improved from 0.037 to 0.222), CUPRAC ($p = 0.030$ to 0.057), TPC ($p = 0.158$ to 0.289), neochlorogenic acid ($p = 4.67 \times 10^{-6}$ to 0.0168), chlorogenic acid ($p = 1.95 \times 10^{-8}$ to 0.236), and p -coumaric acid ($p = 9.75 \times 10^{-5}$ to 0.168), normality was substantially improved, with several variables achieving non-significant departures from normality after transformation ($p > 0.05$). However, for certain strongly skewed variables such as headspace gases (O₂, CO₂, N₂), sensory properties, and some antioxidant parameters, improvements were moderate and normality was not fully achieved, although skewness was reduced.

3.11.2. Aligned Rank Transformation (ART) ANOVA

The ART ANOVA results showed that storage time, temperature, and coating had highly significant effects on most evaluated responses, with very large test statistics and extremely small p -values, confirming strong factor influences across the system. For pH, significant main effects were observed for Time ($F = 84.62$, $p < 0.001$), Temperature ($F = 45.47$, $p < 0.001$), and Coating ($F = 60.94$, $p < 0.001$), with a significant Time $\times$ Coating interaction ($F = 32.99$, $p < 0.001$). Dry matter was mainly affected by Time ($F = 216.68$, $p < 0.001$) and Coating ($F = 37.64$, $p < 0.001$), whereas Temperature was not significant ($F = 0.96$, $p > 0.05$). Vitamin C showed very strong effects of Time ($F = 362.56$, $p < 0.001$), Temperature ($F = 183.70$, $p < 0.001$), and Coating ($F = 223.10$, $p < 0.001$), together with pronounced interactions, including Time $\times$ Temperature ($F = 34.97$, $p < 0.001$) and Time $\times$ Temperature $\times$ Coating ($F = 23.84$, $p < 0.001$). Similar highly significant patterns were observed for ABTS (Time $\times$ Coating $F = 244.25$, $p < 0.001$), DPPH (Time $F = 18.48$, $p < 0.001$; Coating $F = 5.56$, $p < 0.01$), FRAP (Time $F = 56.31$, $p < 0.001$; Coating $F = 242.71$, $p < 0.001$), and CUPRAC (Time $F = 287.54$, $p < 0.001$; Coating $F = 243.37$, $p < 0.001$), all showing strong interaction structures with temperature and time. Total phenolic and flavonoid contents also exhibited strong effects, including TPC (Time $F = 299.27$, $p < 0.001$; T $\times$ Coating $F = 272.28$, $p < 0.001$) and TFC (Time $F = 81.73$, $p < 0.001$; Coating $F = 110.59$, $p < 0.001$), again with significant higher-order interactions. Headspace gases were highly responsive, particularly CO₂ (Time $\times$ T $F = 645.97$, $p < 0.001$; T $\times$ Coating $F = 1007.61$, $p < 0.001$), while O₂ also showed strong effects (Time $F = 127.76$, $p < 0.001$). Phenolic acids and rutin consistently exhibited extremely strong effects across all factors and interactions, with very large F -values (often > 200 – 400) and p -values far below 10^{-30} , indicating pronounced degradation and strong protective effects of coatings depending on storage conditions.

The results confirm that product quality evolution is governed by highly significant, non-additive interactions among time, temperature, and coating, with most responses showing F -values ranging from approximately 20 up to >1000 and p -values typically $<10^{-15}$, indicating a strongly synergistic and condition-dependent system behavior.

3.11.3. Circular Heatmap

The circular heatmap (Figure 2a) revealed distinct clustering patterns according to storage time, storage temperature, and coatings applied, indicating progressive physicochemical and biochemical changes during storage. Across all treatments, prolonged storage was generally associated with increasing pH values and decreasing dry matter, vitamin C, neochlorogenic acid, and caffeic acid contents, confirming progressive oxidative and metabolic degradation processes.

Samples stored at 4 °C generally exhibited better preservation of dry matter, vitamin C, sensory quality, and phenolic stability compared with samples stored at 23 °C, indicating that refrigerated storage effectively slowed quality deterioration. In contrast, storage at 23 °C accelerated degradation of antioxidant-related compounds and promoted more pronounced physicochemical changes, particularly losses of neochlorogenic and caffeic acids.

Among antioxidant-related parameters, TPC, TFC, and CUPRAC values remained relatively stable or slightly increased during storage, whereas individual phenolic acids showed substantial declines. Chlorogenic and *p*-coumaric acids tended to accumulate during later storage stages, suggesting possible transformation and interconversion processes among phenolic compounds during storage.

The heatmap also demonstrated progressive changes in headspace gas composition throughout storage. Depletion of O₂ and corresponding increases in N₂ reflected active atmospheric modification within the packaging systems. Treatments characterized by lower oxygen levels generally indicated improved retention of vitamin C and selected phenolic compounds, indicating reduced oxidative degradation under oxygen-restricted conditions.

Sensory properties declined progressively with storage time across all treatments, with more pronounced deterioration observed at 23 °C. Refrigerated samples retained higher sensory acceptability throughout storage, confirming the beneficial effect of low-temperature storage on overall product quality preservation.

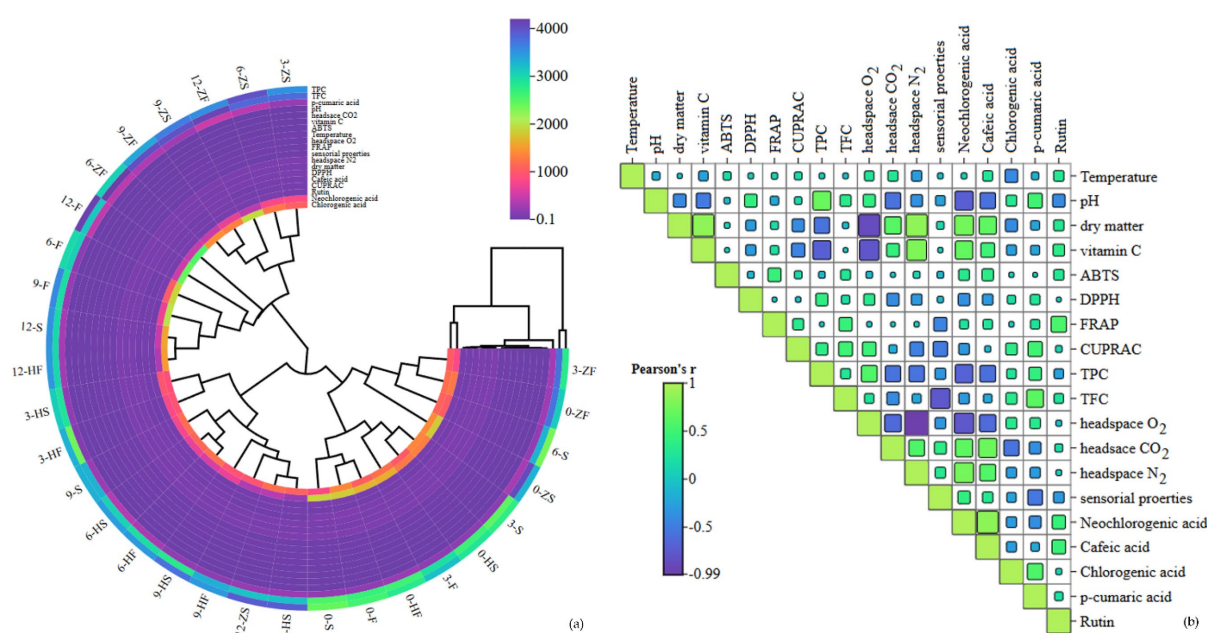


Figure 2. (a) Circular heatmap showing changes in physicochemical, antioxidant, phenolic, headspace gas, and sensory parameters during storage under different treatments and temperatures, and (b) color correlation matrix illustrating the relationships among the analyzed variables.

3.11.4. Correlation Analysis

Correlation analysis (Figure 2b) revealed several significant relationships among physicochemical, antioxidant, phenolic, headspace gas, and sensory parameters, indicating strong interactions between product composition, antioxidant capacity, and modified atmosphere conditions.

Dry matter content had a strong positive correlation with vitamin C content ($r = 0.866$, $p < 0.001$), headspace N_2 ($r = 0.863$, $p < 0.001$), neochlorogenic acid ($r = 0.748$, $p < 0.001$), and caffeic acid ($r = 0.658$, $p < 0.001$), while exhibiting strong negative correlations with headspace O_2 ($r = -0.871$, $p < 0.001$), total phenolic content ($r = -0.567$, $p < 0.001$), and chlorogenic acid ($r = -0.396$, $p < 0.05$). The samples with higher dry matter retained greater amounts of certain phenolic acids and vitamin C, whereas elevated oxygen levels were associated with lower DM values.

Vitamin C was negatively correlated with TPC ($r = -0.702$, $p < 0.001$) and headspace O_2 ($r = -0.787$, $p < 0.001$), but positively correlated with headspace N_2 ($r = 0.791$, $p < 0.001$), neochlorogenic acid ($r = 0.678$, $p < 0.001$), and caffeic acid ($r = 0.484$, $p < 0.01$). This indicates that nitrogen-rich atmospheres may contribute to better preservation of vitamin C and selected phenolic compounds, whereas oxygen exposure may promote oxidative degradation.

Among antioxidant assays, FRAP correlated positively with ABTS ($r = 0.444$, $p < 0.05$) and rutin ($r = 0.560$, $p < 0.001$), while CUPRAC was positively associated with TPC ($r = 0.378$, $p < 0.05$), TFC ($r = 0.482$, $p < 0.01$), headspace O_2 ($r = 0.467$, $p < 0.01$), chlorogenic acid ($r = 0.358$, $p < 0.05$), and *p*-coumaric acid ($r = 0.505$, $p < 0.01$). These relationships confirm that antioxidant activity was closely related to phenolic composition.

TPC exhibited strong positive correlations with headspace O_2 ($r = 0.583$, $p < 0.001$) and chlorogenic acid ($r = 0.417$, $p < 0.05$), while significant negative correlations were observed with headspace CO_2 ($r = -0.565$, $p < 0.001$), headspace N_2 ($r = -0.565$, $p < 0.001$), neochlorogenic acid ($r = -0.684$, $p < 0.001$), and caffeic acid ($r = -0.587$, $p < 0.001$). Similarly, TFC was negatively correlated with headspace N_2 ($r = -0.771$, $p < 0.001$) and positively correlated with *p*-coumaric acid ($r = 0.645$, $p < 0.001$).

A nearly perfect negative correlation was observed between headspace O_2 and headspace N_2 ($r = -0.998$, $p < 0.001$), reflecting the expected inverse relationship between gas components in modified atmosphere packaging. Headspace CO_2 was positively correlated with neochlorogenic acid ($r = 0.658$, $p < 0.001$) and caffeic acid ($r = 0.715$, $p < 0.001$), whereas headspace N_2 showed positive correlations with neochlorogenic acid ($r = 0.759$, $p < 0.001$) and caffeic acid ($r = 0.592$, $p < 0.001$).

Sensory properties were positively correlated with neochlorogenic acid ($r = 0.405$, $p < 0.05$) and negatively correlated with *p*-coumaric acid ($r = -0.532$, $p < 0.05$), suggesting that the phenolic profile may significantly influence sensory acceptability.

Strong positive correlations were also identified among individual phenolic compounds, particularly between neochlorogenic and caffeic acids ($r = 0.855$, $p < 0.001$), as well as between chlorogenic and *p*-coumaric acids ($r = 0.573$, $p < 0.001$), indicating possible similarities in their biosynthetic pathways or degradation behavior during storage.

The correlation analysis demonstrated that headspace gas composition strongly influenced antioxidant properties, phenolic composition, and quality attributes, with oxygen generally associated with increased oxidation-related parameters, whereas nitrogen and carbon dioxide were linked to improved preservation of vitamin C and selected phenolic acids.

3.11.5. Principal Component Analysis

The PCA extracted three principal components (PCs) with eigenvalues >1 , indicating that these components explain a substantial proportion of the total variance in the dataset.

4. Conclusions

The results of this research show that preserving the quality of prunes during long-term storage depends on interconnected chemical, bioactive, microbiological, and sensory changes, with coatings applied having the greatest impact on degradation processes. Changes in total phenolic compounds and individual phenolic acids indicated the simultaneous presence of degradation and concentration-extraction processes. The results confirm that the effect of biopolymer coatings depends on the parameter observed: the zein coating showed good potential in preserving dry matter, vitamin C, and part of the antioxidant capacity, especially FRAP and CUPRAC values, indicating its pronounced barrier properties. In contrast, the chitosan coating provided the best balance between chemical stability and sensory acceptability of the product, probably due to its antimicrobial and antioxidant properties. The effect of temperature was particularly evident during storage at 4 °C, where better preservation of vitamin C and a more favorable profile of individual phenolic acids were achieved, although the lower temperature could not completely stop the changes occurring over time. During 12 months of storage, the quality of all samples gradually declined, but these changes were significantly slower in coated samples, particularly when a lower storage temperature was applied. The results demonstrate that extending shelf-life and maintaining physicochemical quality alone are insufficient criteria for selecting edible coatings intended for commercial application. While zein provided superior protection of several quality properties during 12 months of storage, chitosan achieved a more favorable balance between product preservation and sensory acceptance. The samples treated with chitosan and stored at 4 °C showed the most promising results, making this combination the most suitable solution for commercial storage. Therefore, future development of edible coatings should simultaneously optimize technological performance and consumer acceptability.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/coatings16070826/s1>, File S1 Aligned Rank Transformation (ART) ANOVA “ART_ANOVA_Tables.xlsx”, File S2 ART Post Hoc test “ART_PostHoc.xlsx”, File S3 ART Summary “ART_Summary.xlsx”, File S4 R code for Yeo–Johnson transformation “Normality Yeo–Johnson transformation.txt”, File S5 R code for Aligned Rank Transformation ANOVA “ART.txt”.

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