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Comparative Effects of Dehydration Methods on the Proximate Composition and Phytochemical Profile of *Spondias mombin* Pulp

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Abstract

Spondias mombin fruit is a seasonal product with limited valorization in Mexico, mainly because of its short shelf life and scarcity of available scientific information. In this study, two drying methods—hot air-drying and freeze-drying—were evaluated for the dehydration of *S. mombin* pulp. Freeze-dried samples presented a higher content of hydrolysable polyphenols (18.92 ± 5.31 mg GAE/g), whereas no significant differences were detected in condensed polyphenols. The total flavonoid content was significantly greater in the freeze-dried pulp (11.32 ± 1.27 mg CE/g). Antioxidant activity assessed by the ABTS and DPPH assays did not differ between treatments; however, the reducing power of the freeze-dried samples was greater than that of the control samples, as determined by the FRAP assay (14.40 ± 1.07 mg TE/g). HPLC–ESI–MS analysis enabled the identification and quantification of polyphenols, organic acids, and monosaccharides, highlighting the presence of compounds belonging to the methoxycinnamic acid family and ascorbic acid. Overall, these findings provide valuable insights that can serve as a basis for future research on the processing and valorization of *S. mombin*, contributing to the development of advanced processing strategies to improve the stability, quality, and utilization of underexploited fruits.

Keywords: dehydration methods; *Spondias mombin*; bioactive compounds

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1. Introduction

The potential of underutilized fruits for new food product development highlights the need for targeted research into their nutritional and functional value.

Nevertheless, their industrial-scale utilization requires the implementation of appropriate processing technologies to preserve their sensory, nutritional, and phytochemical properties while significantly reducing food loss, which is a global concern that is already widely reported [1].

Among these, technologies such as hot air-drying and freeze-drying stand out as key strategies in both research and industry for stabilizing plant matrices. Previous studies have focused on a wide variety of fruits, including citrus, berries, apples, grapes, avocados,

plums, and pomegranates, emphasizing the importance of exploring diverse food matrices to promote health benefits and foster innovation [2–4]. Drying methods are preservation processes commonly used in industry to extend the shelf life and maintain the characteristics of fruit-based products. Among the most widely used processes is hot air-drying, which is commonly chosen because of its accessibility and low cost, allowing for easy scalability at the industrial level. However, one of its major drawbacks is that it can cause the degradation of heat-sensitive compounds, such as polyphenols and vitamins. Unlike the heat-drying method, freeze-drying is a preservation method recognized for its significant advantages, as it maintains most of the characteristics of food matrices—such as nutrients and sensory properties due to its low-temperature processing and the absence of oxygen during the processing of food matrices.

However, it requires greater energy consumption because of processing times, which in turn results in higher costs, hindering its scalability. Despite these differences, both methods involve processes that can be applied to different fruits, resulting in different effects on their characteristics to support their potential industrial use.

In this context, countries such as Mexico exhibit a high diversity of fruits, including species belonging to the Anacardiaceae family. Within this family, *Spondias tuberosa* and *Spondias mombin* are native to Brazil and have spread to other countries. In Brazil, the annual production of these fruits ranges between 15 and 20 tons. In Mexico, *Spondias mombin*, commonly known as jobo, is a tropical species distributed across both the Americas and Africa. Depending on the region, it is known by various names, such as taperebá and cajá (Brazil) and jocote (Guatemala) [5]. *Spondias mombin* is a yellow–orange fruit with an average diameter of 20 mm and a weight of 4–43 g. It consists of peel, pulp, and a seed and is valued for its aromatic intensity and balanced sweet–acidic flavor [6]. Although nutritionally rich and sensory appealing, it is primarily used in traditional artisanal products, such as juices, jams, and liqueurs [7]. In Brazil, however, *S. mombin* features a wider range of value-added products, including frozen pulp, yogurt, ice cream, and popsicles [8].

Limited scientific information is available on the compositional profile of *S. mombin*. Assessing fundamental nutritional parameters—such as protein, carbohydrate, fiber, sugar, and fat contents—is essential for understanding their potential benefits and supporting their broader utilization [9]. In addition to nutritional benefits, *S. mombin* is rich in bioactive compounds—including polyphenols, anthocyanins, vitamin C, carotenoids, tocopherols, and glucosinolates—which contribute to protective health effects. Polyphenols and their major subclass, flavonoids, are notable for their antioxidant properties [4].

Antioxidants in bioactive compounds protect the body from oxidative stress caused by free radicals or reactive oxygen species. This biological activity is linked to delayed aging and the prevention of chronic diseases such as type 2 diabetes, inflammatory disorders, cardiovascular diseases, and cancer [10]. Antioxidants may be natural—such as vitamins, anthocyanins, and flavonoids—or synthetic, such as gallates and butylhydroxyanisole. Given the significance of antioxidants and bioactive compounds in *S. mombin* and the need for improved processing strategies, this study compared the effects of hot air-drying and freeze-drying methods on the proximate composition and phytochemical profile of the pulp.

Given the significance of the antioxidants and bioactive compounds present in *S. mombin*, it is imperative to optimize processing strategies through drying methods. These techniques serve as stabilization processes, extending the fruit's shelf life while preserving its functional value. The objective is to determine which method better preserves bioactive compounds and assess their technological feasibility for enhancing the agro-industrial value of this underutilized fruit.

2. Materials and Methods

2.1. Raw Material

Spondias mombin were collected in July 2023, between 27 and 31 July, in the Huasteca Potosina region, San Luis Potosí, specifically in the municipality of Tampamolón Corona (21°34′18″ N 98°47′42″ W 95 M), with the identification and record number 72,670 from the Isidro Palacios Herbarium (UASLP), Mexico. The fruits were harvested at commercial ripeness, as determined by their uniform yellow–orange coloration and soft texture, which is indicative of physiological maturity in the species. The average fruit weight was 9.78 ± 2.28 g. The fruits were selected according to defined physical quality criteria, including uniform size, absence of mechanical damage (cuts, bruises, or scars), characteristic external coloration, and freedom from abnormal growth or physiological disorders. A total of 12 kg of the selected fruits was washed and then disinfected with a 0.5 mL/L chlorine solution. After sanitation, the peel and seeds were manually removed using protective gloves to isolate the pulp. The resulting pulp was packed in plastic bags and stored under freezing conditions at −40 °C until processing.

2.2. Drying and Sample Preparation

Two drying methods were used: hot air-drying and freeze-drying. Air drying was performed in an electric dehydrator (Presto 06300) at 35 °C for approximately 4–5 h. Freeze-drying was carried out using a lyophilizer (Ecoshel, ECO-FD10PT, Pharr, TX, USA). The samples were previously frozen and then dried at −60 °C under a minimum pressure of 2 Pa for 24 h until a constant weight was reached. The dried samples were milled to obtain a fine powder, sieved to ensure a uniform particle size, and stored in airtight containers under refrigeration until analysis.

2.3. Proximal Composition

The proximate composition analysis of *S. mombin* pulp included moisture, dry matter, fat (AOAC 7.055), fiber (AOAC 7.061), and protein (AOAC 7.031). The ash content was measured by weight loss after incineration at 600 °C. Minerals were identified and quantified by X-ray fluorescence (XRF) on a Panalytical Epsilon 1 spectrometer (Malvern Panalytical, The Netherlands) with software épsilon 3. Mineral measurements were performed on 1 g samples and were run in triplicate.

Researchers have quantified the total and reducing sugars using anthrone and DNS colorimetric methods [11]. Titratable acidity, total soluble solids (°Brix), and pH (CONDUCTRONIC PH 104) were measured using standard procedures [12].

2.4. Hydrolysable Polyphenols

Hydrolysable polyphenols were determined using the Folin–Ciocalteu method, as described by Ramírez-Anguiano et al. (2007) and adapted by [13]. The pulp and peel samples (50 µL) were mixed with 1.48% HCl (300 µL) and methanol (150 µL) in triplicate. The mixtures were subsequently centrifuged at 13,000 rpm for 2 min (ThermoFisher, Germany).

Aliquots of the supernatant (50 µL) were transferred to 1 mL of 2% (w/v) Na_2CO_3, vigorously mixed, and incubated at room temperature for 3 min. Subsequently, 25 µL of Folin–Ciocalteu reagent was added. After the samples were incubated at room temperature for 30 min, the absorbance was measured at 750 nm. The hydrolysable polyphenol content was calculated using a gallic acid calibration curve, and the results are expressed as milligrams of gallic acid equivalents per gram (mg GAE/g).

2.5. Condensed Polyphenols

Condensed polyphenols were quantified using the acid–butanol assay described by [14]. A reaction mixture containing 0.5 mL of the sample, 3 mL of the HCl–ter-butanol solution (1:9, v/v), and 0.1 mL of the ferric reagent (7.4% HCl with 2% ammonium ferric sulfate) was prepared in screw-capped glass tubes. The tubes were heated to 100 °C in a water bath for 1 h and cooled to room temperature. The absorbance was measured at 460 nm.

Quantification was performed using a catechin standard curve (0–250 ppm) through linear regression analysis, and the results are expressed as milligrams of catechin equivalents per gram of sample (mg CE/g).

2.6. Total Flavonoids

The total flavonoid content was determined using the methodology of [15]. First, 310 µL of extract was mixed with 93 µL of 5% $NaNO_3$ and 93 µL of distilled water. The mixture was vortexed and incubated for 5 min. Subsequently, 93 µL of 10% $AlCl_3$ was added, and the mixture was incubated for 3 min. Finally, 125 µL of NaOH (0.5 M) was added, and the mixture was incubated for 30 min at room temperature in the absence of light. The absorbance of the reaction mixture was measured at 510 nm (BioTek, EPOCH2, Germany). Catechin was used as the standard (0–1000 ppm) and reported as a milligram equivalent per gram.

2.7. Antioxidant Activity

Antioxidant activity was determined using the ABTS radical cation decolorization assay (ABTS+; Sigma-Aldrich) [16]. ABTS (7 mM) was reacted with potassium persulfate (2.45 mM) (Sigma-Aldrich) and kept in the dark at room temperature for 12–18 h to generate the ABTS$\bullet^+$ radical. The solution was diluted with 80% methanol to an absorbance of 0.70 ± 0.02 at 734 nm. For the assay, 5 µL of the sample was mixed with 95 µL of the ABTS$\bullet^+$ solution in a 96-well microplate. After 1 min of incubation at room temperature, the absorbance was measured at 734 nm. The results are expressed as Trolox (0–200 ppm) equivalents per gram of sample.

DPPH radical scavenging activity was evaluated using 60 µM 2,2-diphenyl-1-picrylhydrazyl (DPPH; Sigma-Aldrich), as described previously [16]. For the assay, 7 µL of sample was mixed with 200 µL of DPPH solution in a 96-well microplate. The reaction mixture was incubated for 30 min at room temperature in the dark. The absorbance was measured at 517 nm using a microplate reader (BioTek, EPOCH2, Germany).

The ferric reducing antioxidant power (FRAP; Sigma-Aldrich) assay was performed according to the method described by [16]. The FRAP reagent was prepared by mixing acetate buffer (0.3 M, pH 3.6), 0.001 M 2,4,6-Tris(2-pyridyl)-s-triazine, and $FeCl_3$ at a ratio of 10:1:1 ($v/v/v$). For the assay, 10 µL of the sample was mixed with 290 µL of freshly prepared FRAP reagent in a 96-well microplate. The reaction mixture was incubated for 15 min in the dark at room temperature, and the absorbance was measured at 593 nm (BioTek, EPOCH2, Germany). The results are expressed as Trolox (0–200 ppm) equivalents per gram of sample.

2.8. Identification and Quantification of Sugars and Organic Acids by HPLC

The detection of simple sugars and organic acids was carried out by chromatographic separation using HPLC coupled with IR (K-2301) and UV (K-2501) detectors (Knauer, Berlin, Germany), respectively [17]. Samples obtained from in vitro digestion were filtered (25 µm cellulose acetate filter); 20 µL of each sample was injected into an Aminex HPX-87H column (Bio-Rad, Hercules, CA, USA) at a temperature of 40 °C, with a 5 mM H_2SO_4 mobile phase

at a constant flow rate of 0.6 mL/min. Sample peaks were identified and quantified in triplicate by comparing retention times using calibration curves with standards of glucose, fructose, acetic acid, succinic acid, citric acid, tartaric acid, and ascorbic acid.

2.9. Characterization of Compounds by HPLC–ESI–MS

The characterization of phenolic compounds and organic acids in *S. mombin* pulp processed by the two drying methods was carried out using high-performance liquid chromatography coupled with electrospray ionization mass spectrometry (HPLC–ESI–MS). The chromatographic system consisted of an autosampler (Varian ProStar 410, Palo Alto, CA, USA), a ternary pump (Varian ProStar 230I, Palo Alto, CA, USA), and a photodiode array (PDA) detector (Varian ProStar 330, Atlanta, CA, USA). Compound identification was performed using a liquid chromatography–ion trap mass spectrometer (Varian 500-MS IT, Palo Alto, CA, USA) equipped with an electrospray ionization (ESI) source. The samples (5 µL) were injected onto a Denali C18 column (150 × 2.1 mm, 3 µm; Grace, Palo Alto, CA, USA), with the column temperature maintained at 30 °C. The mobile phase consisted of 0.2% (*v*/*v*) formic acid in water (solvent A) and acetonitrile (solvent B). The following gradient elution program was applied: 3% B initially; 0–5 min, linear increase to 9% B; 5–15 min, linear increase to 16% B; and 15–45 min, linear increase to 50% B. The column was subsequently washed and reconditioned prior to the next injection. The flow rate was set to 0.2 mL min^{-1}, and UV–Vis detection was performed at 254, 280, 320, and 550 nm. The entire column effluent (0.2 mL min) was directly introduced into the mass spectrometer without flow splitting. All mass spectrometric analyses were performed in negative ionization mode ($[M–H]^-$). Nitrogen was used as the nebulizing gas, while helium served as the damping gas. The ESI source parameters were as follows: spray voltage, 5.0 kV; capillary voltage, 90.0 V; and capillary temperature, 350 °C. The data acquisition and processing were conducted using MS Workstation software (version 6.9). The samples were initially analyzed in full-scan mode over a m/z range of 50–2000 [18].

2.10. Statistical Analysis

The data were analyzed by one-way analysis of variance (ANOVA). The differences between treatment means were evaluated using Student's *t*-test at a significance level of $p < 0.05$. Statistical analyses were performed using Statistica software (version 7.0; StatSoft Inc., Tulsa, OK, USA).

3. Results and Discussion

3.1. Proximal Analysis

The proximate composition of *S. mombin* pulp was evaluated using both freeze-drying and hot air-drying. As presented in Table 1, no significant differences ($p < 0.05$) were observed between the freeze-dried and hot air-dried samples for most of the analyzed parameters, except for the reducing sugars and °Brix values. *Spondias mombin* fruit is characterized by its high perishability and substantial carbohydrate content, primarily because of its elevated soluble sugar concentration. These sugars significantly influence consumer acceptance by contributing to key sensory attributes, particularly sweetness [19]. The high sugar content also enhances the technological potential of jobo pulp, making it a suitable substrate for diverse applications, including biological processes such as fermentation [20].

Table 1. Proximate composition of *Spondias mombin* pulp subjected to the two drying methods.

Component (%)	Method	
	Hot Air-Drying	**Freeze-Drying**
Moisture	84.05 ± 0.48 a	84.41 ± 0.26 a
Ash	3.00 ± 0.03 a	3 ± 0.05 a
Fat	1.17 ± 0.28 a	1.33 ± 0.28 a
Protein	0.10 ± 0.01 a	0.11 ± 0.00 a
Fiber	2.66 ± 0.57 a	2.33 ± 0.57 a
Total sugars	67.25 ± 2.89 a	75.72 ± 5.22 a
Reducing sugars	0.005 ± 0.00 b	0.059 ± 0.00 a
Acidity	10.96 ± 0.05 a	10.930 ± 0.47 a
°Brix	7.42 ± 0.31 a	8.02 ± 0.04 b
pH	2.71 ± 0.00 a	2.71 ± 0.02 a

Means were compared between drying methods using Student's *t*-test ($p < 0.05$). Means sharing the same letter indicate no significant differences.

The fruit's pH was 2.71 ± 0.02, indicating physiological maturity. During ripening, organic acid concentrations generally decrease while soluble sugar levels increase, resulting in higher pH values and enhanced perceived sweetness [21]. The values obtained in the present study are consistent with those previously reported in the literature, confirming the intrinsically high acidity of jobo fruit [22].

No significant differences were detected between the drying methods for most parameters, except for reducing sugar content and °Brix. The observed variation in reducing sugars may be attributed to thermal effects during hot air-drying, as heat exposure can promote partial hydrolysis of polysaccharides into simpler monosaccharides. Nevertheless, the magnitude of this difference was minimal, indicating that both drying processes exerted a comparable effect on the overall chemical composition of the pulp.

Air-drying is among the most widely used preservation techniques for fruits, as it effectively reduces the moisture content. However, exposure to elevated temperatures may compromise product quality, particularly through the degradation of thermolabile compounds and increased molecular mobility, which can increase the loss of sensitive constituents [23,24]. Despite these drawbacks, dehydration at moderate temperatures (≈50 °C) has been reported as a suitable strategy for producing fruit powders, in some cases yielding better quality attributes than high-temperature spray-drying or even freeze-drying [23]. Notably, industrial hot air-drying is typically conducted at higher temperatures (50–60 °C) to reduce the processing time and enhance the drying efficiency. Such conditions have been extensively documented in research aimed at mitigating the degradation of heat-sensitive bioactive compounds. Drying time reduction is temperature-dependent and varies according to the specific food matrix, sample characteristics, and drying conditions [25,26]. However, in the present study, a considerably lower temperature of 35 °C was employed, resulting in a processing time of 5 h under the applied experimental conditions. These findings suggest that factors such as sample load, rheological properties, and moisture content are pivotal in the drying process. Consequently, these results should be interpreted within the context of low-temperature drying, highlighting its potential advantages for preserving phytochemical properties while acknowledging possible limitations regarding industrial scalability. In contrast, freeze-drying is conducted under low-temperature and reduced-pressure conditions, minimizing thermal degradation. Its principal advantages include mild processing conditions and superior preservation of structural integrity, rheological behavior, and heat-sensitive bioactive compounds [27,28].

3.2. Mineral Composition

In this section, the mineral composition of *S. mombin* pulp is evaluated to further assess its nutritional value, and the effects of different drying methods are examined. As shown in Table 2, several minerals were identified in the *S. mombin* pulp, with potassium (K) being the predominant element. A significant difference was observed among the drying methods, with the dehydrated sample exhibiting the highest potassium content (1.61 ± 0.00). This effect may be attributed to the release of sugars, which can enhance the retention or protection of certain minerals during processing [29].

Table 2. The mineral content of *Spondias mombin* pulp subjected to the two drying methods.

Minerals (mg/100 g DW)	Method	
	Hot Air-Drying	Freeze-Drying
Potassium	1.610 ± 0.00 a	1.574 ± 0.00 b
Magnesium	0.819 ± 0.03 a	0.818 ± 0.00 a
Calcium	0.186 ± 0.00 b	0.196 ± 0.00 a
Phosphorus	0.202 ± 0.00 b	0.205 ± 0.00 a
Sulfur	0.100 ± 0.00 a	0.093 ± 0.00 b
Chlorine	0.080 ± 0.00 b	0.083 ± 0.00 a
Iron	0.006 ± 0.00 a	0.006 ± 0.00 a
Zinc	0.003 ± 0.00 b	0.005 ± 0.00 a

Means were compared between drying methods using Student's *t*-test ($p < 0.05$). Means sharing the same letter indicate no significant differences. The values are expressed as mg/100 g dry weight (DW).

Potassium is an essential macromineral involved in key physiological processes in plants, including growth regulation, carbohydrate translocation, and photosynthetic activity [30]. From a nutritional perspective, adequate potassium intake is consistently associated with favorable health outcomes, including blood pressure regulation, nephroprotection, and a reduced risk of cardiovascular diseases and premature mortality [31,32].

The calcium and phosphorus contents were also significantly influenced by the drying method. The concentrations of calcium (0.19 ± 0.00) and phosphorus (0.20 ± 0.00) were higher in the freeze-dried samples than in the hot air-dried samples, suggesting improved mineral preservation under low-temperature processing conditions. Although the quantified levels do not independently fulfill the recommended daily intake requirements, their contribution to cumulative dietary mineral intake remains nutritionally relevant, supporting essential physiological processes, skeletal integrity, and immune function [33].

Freeze-drying is widely recognized as an effective preservation technique for maintaining food quality and nutrient content, including mineral composition, since certain elements may be indirectly affected by heat exposure, diffusion phenomena, or chemical interactions associated with conventional thermal processing [34]. Comparable trends have been observed in other drying processes, where elevated temperatures can alter both the physical structure and the chemical composition. Minerals such as potassium, magnesium, iron, and sulfur have been reported to be particularly susceptible to processing-related changes, with hot air-drying often showing greater variation than nonthermal methods do [35]. Although relatively low temperatures (35 °C) were employed in the present study, variations in mineral content were observed compared with those of the freeze-dried samples, demonstrating that even a 'mild' thermal treatment can influence mineral stability. This behavior is consistent with previous reports indicating that drying temperatures between 70 and 120 °C can induce significant changes in the mineral composition of the food matrix [36].

Owing to its content of lipids, dietary fiber, carbohydrates, and essential minerals—particularly potassium, magnesium, calcium, and phosphorus—the consumption of

Spondias mombin may confer metabolic benefits, especially for individuals with obesity or who are at risk of developing type 2 diabetes [5,37].

Notably, higher concentrations of minerals, including K, Fe, Na, and Cu, have been reported by other authors; however, such discrepancies are frequently attributed to differences in processing conditions, particularly the use of whole fruit versus pulp, as well as to geographic origin. Variations in soil composition, climate, and agronomic practices can lead to physicochemical differences in the fruit matrix, even within the same species, thereby influencing mineral profiles [38,39].

3.3. Phytochemical Content

Overall, the phytochemical composition of *S. mombin* pulp was characterized, and the influence of drying technology on its bioactive profile was assessed. The comparative effects of hot air-drying and freeze-drying on the phytochemical content of the pulp are shown in Figure 1.

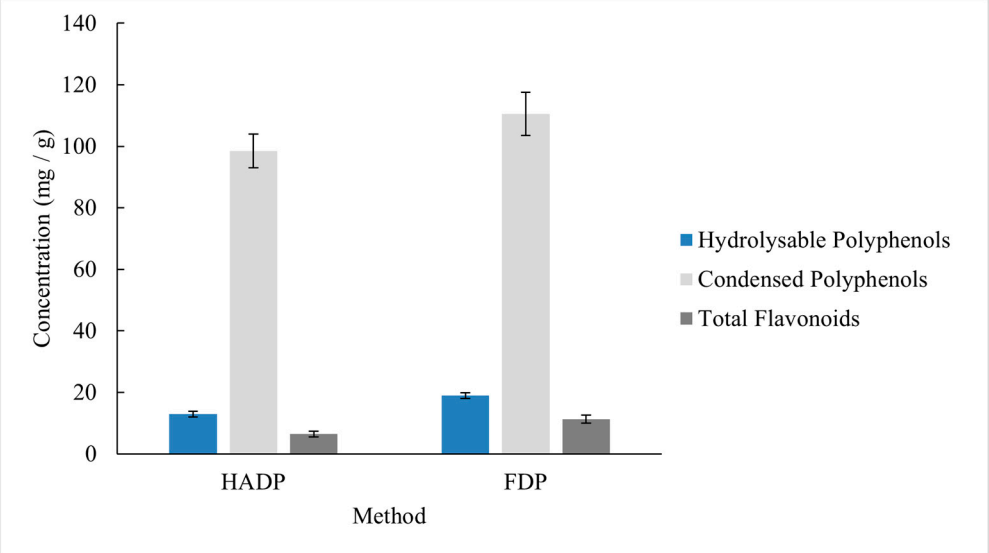

Figure 1. The effects of freeze-drying and hot air-drying on the phytochemical profile of *Spondias mombin* pulp. Means were compared between drying methods (Student's *t*-test, $p < 0.05$). Means sharing the same letter indicate no significant differences.

Quantitative analysis revealed significant differences in hydrolysable polyphenols among drying methods. Compared with hot air-dried pulp (12.92 ± 0.97 mg GAE/g), freeze-dried pulp exhibited a markedly higher concentration (18.92 ± 5.31 mg GAE/g), indicating superior preservation of these thermolabile compounds under low-temperature processing conditions. In contrast, no statistically significant differences in condensed polyphenol content were observed between treatments, with values of 98.46 ± 5.44 mg CE/g for HADP and 110.46 ± 7.01 mg CE/g for FDP.

The differences observed in hydrolysable polyphenol content align with previous reports, indicating that phenolic compounds are particularly susceptible to thermal degradation. Ref. [40] demonstrated that prolonged exposure to elevated temperatures can significantly reduce phenolic concentrations because of structural breakdown and oxidative reactions. This reduction has been partly attributed to the activation of oxidative enzymes, such as polyphenol oxidase and peroxidase, which catalyze the oxidation of phenolic substrates, leading to their degradation and a subsequent decline in antioxidant capacity.

Several studies have indicated that dehydration at temperatures below 50 °C is among the most suitable approaches for fruit preservation, as it promotes better nutrient retention than higher-temperature treatments; however, it may still trigger undesirable effects, such

as nonenzymatic browning reactions [41]. In contrast, freeze-drying has been shown to preserve phenolic compounds more effectively, as freezing at very low temperatures (e.g., −80 °C) and subsequent drying under reduced pressure minimize reactions that could compromise nutrient stability and intrinsic product characteristics, including oxidation, denaturation, and other degradation processes [42].

Comparisons with previously reported data indicate that the total phenolic contents of 13.40 ± 0.19 mg GAE/g and 3.26 ± 0.03 mg GAE/g have been reported for *S. mombin* pulp [43,44], which are values comparable to those obtained in the present study. This similarity may be due to the use of analogous dehydration procedures and extraction conditions, which both significantly influence phenolic recovery and quantification. Moreover, Ref. [45] reported a total phenolic content of 2.60 mg GAE/g in fresh pulp, which is lower than the values observed herein. Such discrepancies may be attributed to differences in sample state (fresh versus dried), moisture content, and processing conditions.

The total phenolic content was reported to be 185.00 ± 6.14 mg/g in fresh *Spondias mombin* pulp from Brazil, a value substantially higher than that observed in the present study [46]. Such discrepancies may be attributed to differences in geographic origin, cultivar, maturity stage, extraction methodology, and expression basis (fresh versus dry weight). The authors emphasized that elevated concentrations of bioactive compounds increase the potential of *S. mombin* as a suitable substrate for fermentation processes. Several studies have consistently identified polyphenols as the predominant class of secondary metabolites in *S. mombin*, occurring in both hydrolysable and condensed forms [47]. This pattern aligns with the findings of the present study, which confirm the relevance of phenolic compounds in the pulp's phytochemical profile.

Other studies have reported tannin contents of 2.99 mg/g in *S. mombin* pulp [4] and 2.00 ± 0.29 mg cianidina-3-glucósido/g in *S. purpurea* pulp [44]. Variability among reported values may be influenced by factors such as the fruit maturity stage, environmental and climatic conditions, geographic origin, and differences in analytical methodology. The importance of investigating and preserving these compounds lies in their wide range of biological activities, particularly their recognized contribution to the prevention and management of chronic diseases [48].

A significant effect of the drying method on the total flavonoid content was also observed. Compared with the hot air-dried samples (HADP) (6.42 ± 0.89 mg CE/g), freeze-dried samples (FDP) exhibited markedly higher concentrations (11.32 ± 1.27 mg CE/g), indicating superior preservation under low-temperature processing conditions. Ref. [49] similarly reported that drying treatments conducted below 60 °C are more effective at retaining flavonoids, given their pronounced sensitivity to heat. In the present study, although dehydration was performed at a relatively mild temperature (37 °C for 4 h), thermal exposure may still have contributed to partial degradation.

Although flavonoid degradation typically occurs at higher temperatures (>50 °C), thermal processing at 35 °C may have promoted oxidative reactions, particularly because of prolonged oxygen exposure. This exposure was the primary factor contributing to the partial loss of flavonoids. Furthermore, mechanisms such as the Maillard reaction may lead to the formation of complexes with sugars, which reduce the bioavailability of these compounds and result in lower detection levels [50]. Notably, the drying conditions applied in this study were not optimized for each method, and further optimization of the processing parameters could influence the extent of the differences observed between treatments.

Conversely, freeze-drying enhances the preservation of flavonoids and other thermolabile constituents by avoiding high temperatures and limiting oxidative and degradative reactions, thereby maintaining structural integrity and bioactive potential [50].

In *Spondias purpurea* L., flavonoid contents of 13.8 ± 0.9 mg QE/g have been reported, exceeding the concentrations observed in the present study. Such differences may be attributed to species-specific metabolic profiles, environmental conditions, maturity stage, and methodological variations in extraction and quantification. Flavonoids are widely recognized for their health-promoting properties, primarily because of their antioxidant activity, which helps prevent cardiovascular diseases and other oxidative stress-related disorders [51].

3.4. Free Radical–Scavenging Activity

The evaluation of antioxidant activity by the DPPH radical-scavenging assay revealed no statistically significant differences between hot air-dried (17.48 ± 0.40 mg TE/g) and freeze-dried (17.07 ± 0.18 mg TE/g) samples. A similar pattern was observed for the ABTS assay, with HADP and FDP exhibiting values of 14.40 ± 3.20 mg TE/g and 11.36 ± 0.40 mg TE/g, respectively (Figure 2). These findings indicate that the overall antioxidant potential of *S. mombin* pulp was not markedly influenced by the drying method. This behavior may be explained by the relative stability and preservation of phenolic compounds, which largely contribute to antioxidant activity and are strongly affected by processing conditions, particularly temperature control during dehydration [52].

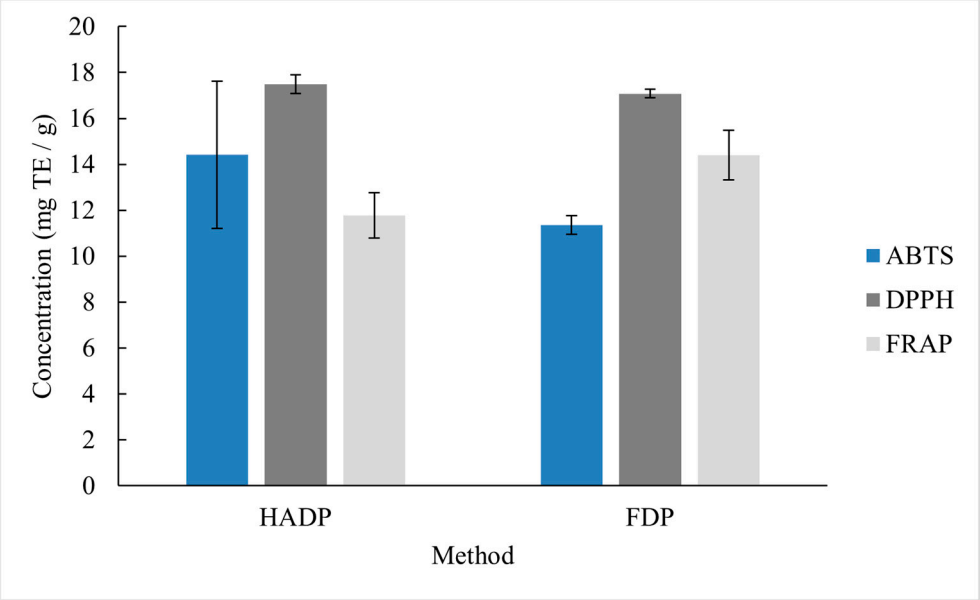

Figure 2. The antioxidant activity of *Spondias mombin* pulp subjected to freeze-drying and hot air-drying. Means were compared between drying methods (Student's *t*-test, $p < 0.05$). Means sharing the same letter indicate no significant differences.

Both the DPPH and ABTS assays are based on the capacity of antioxidants to neutralize free radicals via hydrogen atom transfer (HAT) and/or single-electron transfer (SET). In contrast, the FRAP assay specifically measures the reducing power of a sample by assessing its ability to donate electrons and reduce ferric ions. In the present study, the FRAP assay revealed lower reducing activity for the hot air-dried sample (11.76 ± 0.98 mg TE/g), whereas the freeze-dried sample exhibited higher reducing activity (14.40 ± 1.07 mg TE/g). These differences may be attributed to the greater preservation of phenolic compounds with strong electron-donating capacity in the freeze-dried samples, which would preferentially influence the FRAP results.

The application of multiple antioxidant assays enables a more comprehensive assessment of antioxidant potential, as each method is based on distinct reaction mechanisms

and may respond differently to the phytochemical composition of the matrix [53]. The interest in studying food matrices such as *S. mombin* pulp lies in their potential incorporation into functional foods, which may provide health-promoting effects while enhancing both nutritional and commercial value [54]. These findings are consistent with those of previous reports that attributed the antioxidant properties of *S. mombin* primarily to its phenolic compounds (2.60 ± 11.89 mg GAE/g), reinforcing the relevance of these bioactive compounds within its phytochemical profile [6].

The use of multiple antioxidant assays allows for a more comprehensive evaluation of antioxidant activity, as different methods assess distinct mechanisms of action [53]. One of the main motivations for studying foods with this type of matrix is their potential application in functional foods, which may confer health benefits while increasing nutritional and commercial value [54]. These findings are consistent with previous reports attributing the antioxidant capacity of *S. mombin* fruit to its phenolic and flavonoid contents [9].

3.5. HPLC–ESI–MS Analysis

3.5.1. Organic Acids and Monosaccharides

High-performance liquid chromatography (HPLC) analysis was performed to assess the impact of the preservation methods on *S. mombin* pulp, with a particular emphasis on the profiles of organic acids and monosaccharides. As shown in Table 3, both drying techniques significantly influenced the organic acid composition, resulting in distinct qualitative and quantitative differences. Notably, succinic acid and tartaric acid were detected exclusively in the freeze-dried pulp, indicating enhanced retention of these compounds under lyophilization conditions and highlighting the greater effectiveness of low-temperature processing in preserving thermolabile organic acids.

Table 3. The organic acid and monosaccharide concentrations in *Spondias mombin* pulp as influenced by drying method.

Pulp	Compound	RT [min]	Area [mAU·s]	g/100 g
Freeze-driying	Citric acid	7.983	3422.055	NQ
	Tartaric acid	8.517	294.037	NQ
	Malic acid	9.4	6578.125	0.16 ± 0.05 b
	Ascorbic acid	9.950	156.409	NQ
	Succinic acid	11.133	760.703	NQ
	Glucose	8.933	1.26	2.02 ± 0.11 a
	Fructose	9.75	1.523	2.08 ± 0.04 b
Hot air-drying	Citric acid	8.017	381.886	NQ
	Malic acid	9.350	1929.708	0.64 ± 0.03 a
	Ascorbic acid	10	1009.102	NQ
	Glucose	8.817	0.779	1.56 ± 0.07 b
	Fructose	9.75	1.125	2.27 ± 0.13 a

RT: retention time and NQ: detected but not quantified. Means were compared between drying methods (Student's *t*-test, $p < 0.05$). Means with different letters indicate that significant differences exist.

Citric acid was detected in both drying treatments. This organic acid is a key determinant of fruit quality, as it is among the principal contributors to acidity and overall flavor perception. Beyond its sensory relevance, citric acid is a central metabolic intermediate of the tricarboxylic acid (Krebs) cycle and plays a fundamental role in cellular energy metabolism. Owing to its physicochemical properties, it is widely employed in the food industry as an acid regulator, preservative, and antimicrobial agent, and it has extensive applications in pharmaceutical formulations [55,56].

Tartaric acid was detected exclusively in the freeze-dried samples, whereas it remained below the limits of quantification (LOQs) in the hot air-dried pulp. This behavior suggests

that lyophilization preserves the integrity of the food matrix and prevents the thermal degradation or transformation of organic acids. Nevertheless, the potential presence of related derivatives—specifically feruloyl tartaric acid—is proposed as a possible precursor resulting from structural modifications or esterification during processing. Although more exhaustive or specific analyses are needed to confirm these transformations, these findings reinforce the premise that low-temperature processing enhances the stability and retention of organic acids within the fruit pulp [57].

Malic acid was detected in both samples, in the freeze-dried pulp and in the hot air-dried pulp, indicating that it is present in both samples. Malic acid is widely distributed in fruits and, together with citric acid, plays a key role in shaping the characteristic acidic, fresh flavor profile of jobo fruit [58].

Ascorbic acid (vitamin C) was detected in both drying treatments, in agreement with the colorimetric results, which showed a comparable trend. Notably, the chromatographic peak area was greater in the hot air-dried sample (1009.12 mAU·s) than in the freeze-dried sample (156.41 mAU·s), which may contradict the well-known thermal sensitivity of ascorbic acid. These results may be influenced by several factors beyond thermal degradation. Ascorbic acid can undergo oxidation to dehydroascorbic acid even at low temperatures, such as the 35 °C temperature employed in this study. Furthermore, the physical composition of the samples can significantly affect extraction efficiency and compound detectability during chromatographic analysis [59].

Although ascorbic acid is well known for its high thermal sensitivity, the application of relatively mild dehydration conditions (35 °C) may have favored its retention in hot air-dried pulp. Nevertheless, compared with more aggressive techniques, such as spray-drying, both hot air-drying and freeze-drying have been reported to be effective preservation methods for ascorbic acid, which often result in substantial losses of thermolabile vitamins [23], given its essential role in antioxidant defense, immune function, and collagen synthesis. Overall, these results indicate that *S. mombin* represents a valuable dietary source of vitamin C and may contribute meaningfully to daily nutritional intake [60].

The study of organic acids is highly relevant because of their contribution to food quality, particularly in terms of sensory attributes (acidity and flavor), nutritional value, and preservation capacity. Additionally, these compounds play important roles in human health, participating in metabolic pathways and contributing to physiological homeostasis and immune function [61]. Beyond their technological importance, certain organic acids also exhibit antioxidant properties, as documented in previous studies, highlighting their relevance in both health-related research and food science applications [62].

An inverse relationship typically exists between the sugar content and organic acid concentration during fruit ripening, characterized by the accumulation of sugars concomitant with a decrease in the organic acid concentration. This compositional shift should be considered when specific attributes are prioritized according to the intended application of the fruit [63,64]. Sugars are among the major constituents of fruits and play a central role in quality determination, as they strongly influence sweetness and overall sensory acceptance. In addition, sugars are involved in key physiological processes, including the biosynthesis of aroma compounds, and their progressive accumulation during ripening is associated with structural changes such as tissue softening [65].

Freeze-drying removes a large proportion of free water without heat, thereby minimizing enzymatic and nonenzymatic reactions, including Maillard reactions and caramelization, that can alter the chemical composition and visual attributes of the product. As a result, this process favors the enhanced preservation of sugars. In contrast, slow dehydration results in the retention of more residual moisture, which may promote hydrolytic reactions,

although it can reduce the extent of browning. Collectively, these mechanisms govern sugar stability and compositional changes during processing [66].

The main sugars detected were the monosaccharides glucose and fructose in both drying methods. Glucose was present at a higher concentration in the freeze-dried pulp (2.02 ± 0.11 mg/100 g) than in the hot air-dried pulp (1.56 ± 0.07 mg/100 g). In contrast, fructose was more abundant in the hot air-dried sample (2.27 ± 0.13 mg/100 g) than in the freeze-dried sample (2.08 ± 0.04 mg/100 g). These monosaccharides constituted the predominant carbohydrate fraction detected in the analyzed samples. The absence or low detectability of disaccharides, such as sucrose, may be attributed to the enzymatic hydrolysis occurring during processing, particularly under dehydration conditions, where sucrose can be cleaved into glucose and fructose [65]. Comparable trends have been reported in studies assessing the effects of freeze-drying and hot air-drying on fruit powders, supporting the influence of processing conditions on sugar composition [23]. In the sugar chromatograms (b and d), peaks 2 and 3 were identified as glucose and fructose, respectively. In the organic acid chromatograms, the detected compounds were assigned as follows: peak 1 corresponds to citric acid, peak 2 to malic acid, peak 3 to ascorbic acid, and peak 4 to succinic acid (Figure 3).

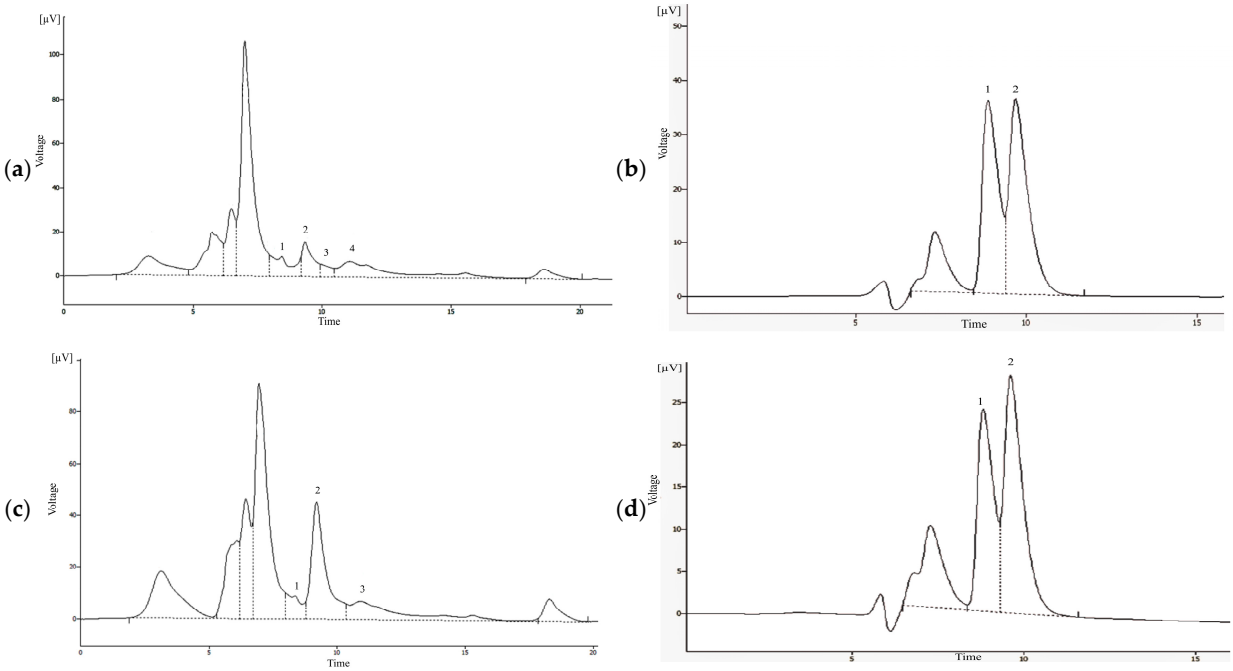

Figure 3. Representative HPLC chromatograms of *Spondias mombin* pulp used for compound quantification: (**a**) organic acids (1: citric acid, 2: malic acid, 3: ascorbic acid, and 4: succinic acid); (**b**) monosaccharides (1: glucose and 2: fructose) in freeze-dried pulp; (**c**) organic acids (1: citric acid, 2: malic acid, and 3: ascorbic acid); and (**d**) monosaccharides (1: glucose and 2: fructose) in hot air-dried pulp.

The monosaccharides glucose and fructose accumulate during fruit maturation and represent the predominant sugars in most fruits [65]. In fact, sugars can account for up to 80% of the dry weight of a fruit, underscoring their quantitative and nutritional significance [67]. Both sugars and organic acids play a fundamental role in shaping fruit sensory attributes, as their relative balance largely governs flavor perception. Notably, certain organic acids, including ascorbic acid, originate from carbohydrate metabolism, highlighting the close biochemical interrelationship between these compound classes [67]. Furthermore, previous studies have demonstrated that soluble solid content does not

necessarily correlate directly with the total sugar concentration, emphasizing the complexity of fruit composition and quality assessment [65].

The consumption of sugars that naturally occur in fruits is generally not associated with adverse health effects, as these carbohydrates are classified as intrinsic sugars and are consumed within a complex food matrix rich in fiber, vitamins, and bioactive compounds. Nevertheless, their intake should remain moderate to avoid excessive sugar consumption. Glucose plays a central role in human metabolism, serving as the primary energy substrate required for normal physiological function [68]. Adequate cognitive performance is particularly dependent on glucose availability, given that the brain accounts for approximately 20% of the body's total glucose-derived energy expenditure in the form of adenosine triphosphate (ATP) [68]. Fructose also serves as a readily available energy source and participates in glycolytic and ancillary metabolic pathways involved in the biosynthesis of the essential biomolecules necessary for human metabolism [69].

3.5.2. Phenolic Compound Content

The identification of phenolic compounds is crucial for elucidating the chemical composition of plant matrices; accordingly, Table 3 summarizes the phenolic metabolites detected and classified in *Spondias mombin* pulp. Consistent with previous reports, this fruit was confirmed to be a rich source of phenolic compounds, underscoring its potential functional and health-promoting properties [38]. Notably, methoxyflavones, such as sinensetin and tangeretin, as well as several hydroxycinnamic acid derivatives—including 1-sinapoyl-2-feruloylgentiobiose, feruloyl tartaric acid, and sinapoylquinic acid—were identified, reflecting the structural diversity of the phenolic profile present in the pulp.

Methoxyflavones are flavone derivatives composed of two aromatic rings linked by an oxygen-containing heterocyclic ring, in which methoxy substituents confer enhanced chemical stability and increased resistance to metabolic degradation. These structural features are associated with a broad spectrum of biological activities, including antimicrobial and antioxidant effects, rendering methoxyflavones of particular interest for functional food and nutraceutical applications [70].

Hydroxycinnamic acids are derivatives of cinnamic acid and are widely distributed in fruits and vegetables, where they perform important metabolic and structural functions. Structurally, they are characterized by a phenyl ring linked to a three-carbon side chain bearing a vinyl group and a carboxyl moiety, a configuration that underlies their reactivity and biological activity [71].

Souza de Freitas [38] reported the presence of several carotenoids in fresh *S. mombin* fruit that were not detected in either freeze-dried or hot air-dried pulps in the present study, suggesting that these compounds may undergo degradation during processing. Such losses can result from hydrolytic and oxidative reactions, which may promote the breakdown of carotenoid structures or their transformation into simpler esterified forms with greater chemical stability. Collectively, these findings indicate that drying processes can markedly influence the phytochemical profile of *S. mombin* pulp by modifying both the concentration and the composition of bioactive compounds, with potential implications for its functional and biological activities [72].

Previous studies have documented the presence of diverse phenolic compounds, including glycosylated compounds and their methoxylated derivatives, in *S. mombin* pulp [73]. Compared with other polyphenolic subclasses, methoxylated phenolic acids and lignans are generally characterized by greater thermal stability. Accordingly, these compounds were retained at detectable levels in the freeze-dried samples, whereas they were not detected in the hot air-dried pulp (Table 4). This difference in preservation can be attributed to the distinct processing conditions, as compared with conventional dehydration meth-

ods, freeze-drying more effectively minimizes thermal and oxidative degradation, thereby favoring the retention of thermolabile bioactive compounds [72].

Table 4. Identification and classification of phenolic metabolites in jobo pulp samples according to the drying method.

Compound	Family	Mass [M–H]⁻	RT (min)	FDP	HADP
Sinensetin	Methoxyflavones	371.7	29.163	-	+
Tangeretin	Methoxyflavones	370.9	35.1415	+	+
1-Sinapoyl-2-feruloylgentiobiose	Methoxycinnamic acids	723	43.251	+	+
Rosmanol	Phenolic terpenes	344.8	50.086	-	+
Cinnamoyl glucose	Hydroxycinnamic acids	308.8	53.143	-	+
Feruloyl tartaric acid	Methoxycinnamic acids	324.9	56.2865	+	+
3-Sinapoylquinic acid	Methoxycinnamic acids	396.7	8.895	+	-
Pyrogallol	Other polyphenols	125.8	21,449	+	-
Medioresinol	Lignans	386.7	27.328	+	-
Caffeoyl tartaric acid	Hydroxycinnamic acids	310.8	310.8	+	-

RT: retention time; (+): compound presence; (-): absence of detectable compounds.

4. Conclusions

The drying process did not cause major changes in the overall chemical makeup of *Spondias mombin* pulp. However, a closer phytochemical analysis revealed that the method used affected certain metabolites. Freeze-drying better preserves thermolabile compounds, such as some polyphenols, flavonoids, and organic acids. Air-drying altered the monosaccharide distribution and induced minor changes in selected metabolites, although it did not significantly reduce the antioxidant capacity. While no significant differences in antioxidant activity were detected via the DPPH assay, variations were detected using the FRAP method. This contrast highlights that the impact of drying is dependent on the chemical mechanism employed (electron transfer vs. free radical scavenging). Consequently, these results emphasize the importance of selecting an appropriate drying method on the basis of the targeted bioactive compounds and their intended application. These results highlight the need to choose a drying method with the intended bioactive compounds and their use in mind. *S. mombin* contains high levels of simple sugars and many types of phytochemicals. This makes it promising for bioprocessing and as a source of stable, bioavailable bioactive compounds after suitable processing.

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Abbreviations

The following abbreviations are used in this manuscript:

HADP	Hot air-dried pulp
FDP	Freeze-dried pulp
DPPH	2,2-diphenyl-1-picrylhydrazyl
FRAP	Ferric reducing antioxidant power

References

1. Kahraman, O.; Malvandi, A.; Vargas, L.; Feng, H. Drying Characteristics and Quality Attributes of Apple Slices Dried by a Non-Thermal Ultrasonic Contact Drying Method. *Ultrason. Sonochem.* **2021**, *73*, 105510. [CrossRef]
2. Rahaman, M.; Hossain, R.; Torequl, M.; Olubunmi, I.; Oluyomi, A.; Adeyemi, S.; Abibat, O.; Learnmore, O.; Sevgi, K.; Daştan, D.; et al. Natural antioxidants from some fruits, seeds, foods, natural products, and associated health benefits: An update. *Food Sci. Nutr.* **2023**, *11*, 1657–1670. [CrossRef] [PubMed]
3. Pruteanu, L.L.; Bailey, D.S.; Gradinaru, A.C.; Jäntschi, L. Biochemistry and Effectiveness of Antioxidants in Food, Fruits, and Marine Algae. *Antioxidants* **2023**, *12*, 860. [CrossRef]
4. Saini, R.K.; Ranjit, A.; Sharma, K.; Prasad, P.; Shang, X.; Gowda, M.; Keum, Y. Bioactive Compounds of Citrus Fruits: A Review of Composition and Health Benefits of Carotenoids, Flavonoids, Limonois, and Terpenes. *Antioxidants* **2022**, *11*, 239. [CrossRef]
5. Bukunmi Ogunro, O.; Oluwatomide Oyeyinka, B.; Ampoma Gyebi, G.; El-saber Batiha, G. Nutritional benefits, ethnomedicinal uses, phytochemistry, pharmacological properties and toxicity of *Spondias mombin* Linn: A comprehensive review. *J. Pharm. Pharmacol.* **2023**, *75*, 162–226. [CrossRef]
6. Galliano, J.; Laura Cardozo, M.; Rodriguez Livov, L.; Gianina Bottero, M.; Baldor, S.; del Rosario Venica, D.; Giudici, A.; Diani, V.; Paruzzo, B.; Medeiros de Azevedo, W.; et al. Evaluación de alternativas para el aprovechamiento de biomoléculas y materiales de interés a partir de subproductos de la industria alimentaria. *Energeia* **2023**, *16*, 4–11.
7. Toloza, L.; Ramírez, J.; Rondón, M. Actividad antioxidante de los extractos alcohólicos de los frutos de las especies Manilkara achras (Mill.) Fosberg (níspero); *Averrhoa carambola* L. (tamarindo chino) y *Spondias mombin* L. (jobo). *Rev. Fac. Farm.* **2022**, *64*, 11–19. [CrossRef]
8. Adetuyi, A.R.; Ayenero, M.E.; Olaleye, M.T.; Akindahunsi, A.A.; Akinmoladun, A.C. Antioxidant and acetylcholinesterase inhibitory activities, in silico analyses, and anti-Alzheimer's disease potential of leaf extracts of three Nigerian endemic medicinal plants (*Spondias mombin*, *Carica papaya* and *Kalanchoe crenata*). *Future J. Pharm. Sci.* **2024**, *10*, 6. [CrossRef]
9. Ahmad, M.; Punam, F.S.; Amanullah, M.; Sarwar, N.; Haque, M.M.; Yeasmin, N.; Akther, S. Health Dynamics Antioxidant Activity and Bioactive Compounds of Fruits Available in Bangladesh. *Health Dyn.* **2024**, *1*, 22–29. [CrossRef]
10. Dhalaria, R.; Verma, R.; Kumar, D.; Puri, S.; Tapwal, A.; Kumar, V.; Nepovimova, E.; Kuca, K. Bioactive Compounds of Edible Fruits with Their Anti-Aging Properties: A Comprehensive Review to Prolong Human Life. *Antioxidants* **2020**, *9*, 1123. [CrossRef]
11. Bello Gil, D.; Carrera Bocourt, E.; Díaz Maqueira, Y. Determinación de Azúcares Reductores Totales En Jugos Mezclados de Caña de Azúcar Utilizando El Método de Ácido 3,5 Dinitrosalicílico. *Inst. Cuba. Investig. Deriv. Caña Azúcar* **2006**, *40*, 45–50.
12. Pastrana-Pastrana, Á.J.; Rodríguez-Herrera, R.; López-Badillo, C.M.; Bravo-Gómez, J.E.; Esparza-González, S.C.; Solanilla-Duque, J.F.; Flores-Gallegos, A.C. Physicochemical and Functional Properties of High-Protein Flour for Lentil–Rice Meat Analog Nuggets. *Food Chem.* **2026**, *514*, 149128. [CrossRef]
13. Tejedor-Calvo, E.; Morales, D. Chemical and Aromatic Changes during Fermentation of Kombucha Beverages Produced Using Strawberry Tree (*Arbutus unedo*) Fruits. *Fermentation* **2023**, *9*, 326. [CrossRef]
14. Espitia-Hernández, P.; Ruelas-Chacón, X.; Chávez-González, M.L.; Ascacio-Valdés, J.A.; Flores-Naveda, A.; Sepúlveda-Torre, L. Solid-State Fermentation of Sorghum by *Aspergillus oryzae* and *Aspergillus niger*: Effects on Tannin Content, Phenolic Profile, and Antioxidant Activity. *Foods* **2022**, *11*, 3121. [CrossRef] [PubMed]
15. Rosa, L.A.; Vazquez-Flores, A.A.; Alvarez-Parrilla, E.; Rodrigo-García, J.; Medina-Campos, O.N.; Ávila-Nava, A.; González-Reyes, S.; Pedraza-Chaverri, J. Content of major classes of polyphenolic compounds, antioxidant, antiproliferative, and cell protective activity of pecan crude extracts and their fractions. *J. Funct. Foods* **2014**, *7*, 2019–2228. [CrossRef]
16. Cruz-Casas, D.E.; Aguilar, C.N.; Ascacio-Valdés, J.A.; Rodríguez-Herrera, R.; Chávez-González, M.L.; Flores-Gallegos, A.C. Bioactive protein hydrolysates obtained from amaranth by fermentation with lactic acid bacteria and *Bacillus* species. *Heliyon* **2023**, *9*, e13491. [CrossRef]
17. Gómez-García, R.; Sánchez-Gutiérrez, M.; Freitas-Costa, C.; Vilas-Boas, A.A.; Campos, D.A.; Aguilar, C.N.; Madureira, A.R.; Pintado, M. Prebiotic effect, bioactive compounds and antioxidant capacity of melon peel (*Cucumis melo* L. *inodorus*) flour subjected to in vitro gastrointestinal digestion and human fecal fermentation. *Food Res. Int.* **2022**, *154*, 111045. [CrossRef]

18. Cerda-Cejudo, N.D.; Buenrostro-Figueroa, J.J.; Sepúlveda, L.; Torres-Leon, C.; Chávez-González, M.L.; Ascacio-Valdés, J.A.; Aguilar, C.N. Recovery of ellagic acid from mexican rambutan peel by solid-state fermentation-assisted extraction. *Foods Bioprod. Process.* **2022**, *134*, 86–94. [CrossRef]
19. Li, J.; Zhang, C.; Liu, H.; Liu, J.; Jiao, Z. Profiles of Sugar and Organic Acid of Fruit Juices: A Comparative Study and Implication for Authentication. *J. Food Qual.* **2020**, *2020*, 7236534. [CrossRef]
20. Praia, A.B.; Herkenhoff, M.E.; Broedel, O.; Frohme, M.; Saad, S.M.I. Sour Beer with *Lacticaseibacillus paracasei* subsp. *paracasei* F19: Feasibility and Influence of Supplementation with *Spondias mombin* L. Juice and/or By-Product. *Foods* **2022**, *11*, 4068. [CrossRef] [PubMed]
21. Alonso-Salinas, R.; López-Miranda, S.; Pérez-López, A.; Noguera-Artiaga, L.; Carbonell-Barrachina, Á.A.; Núñez-Delicado, E.; Acosta-Motos, J.R. Novel combination of ethylene oxidizers to delay losses on postharvest quality, volatile compounds and sensorial analysis of tomato fruit. *LWT* **2022**, *170*, 114054. [CrossRef]
22. Camara Rocha, J.; Silva Araújo, J.; Vital de Paiva, W.K.; Sena Ribeiro, E.S.; Araújo Padilha, C.E.; Fernandes de Assis, C.; Santos, E.S.; Macedo, G.R.; Sousa Junior, F.C. Yello mombin pulp residue valorization for pectinases production by *Aspergillus niger* IOC 4003 and its aplication in juice clarification. *Biocatal. Agric. Biotechnol.* **2020**, *30*, 101876. [CrossRef]
23. Li, S.; Mao, X.; Guo, L.; Zhou, Z. Comparative Analysis of the Impact of Three Drying Methods on the Properties of *Citrus reticulata* Blanco cv. Dahongpao Powder and Solid Drinks. *Foods* **2023**, *12*, 2514. [CrossRef]
24. Cervera-Chiner, L.; Vilhena, N.Q.; Larrea, V.; Moraga, G.; Salvador, A. Influence of temperature on 'Rojo Brillante' persimmon drying. Quality characteristics and drying kinetics. *LWT* **2024**, *197*, 115902. [CrossRef]
25. Korotkiy, I.; Neverov, E.; Gorelkina, A.; Korotkaya, E.; Zadesenets, A. The Dehydrator Parameters Drying of Food Products for Convective. *Agro-Bio-Technologies* **2023**, *64*, 01023. [CrossRef]
26. Rumicha, T.D.; Hirko, F.; Forsido, S.F.; Tola, Y.B.; Yimer, A.; Kuyu, C.G.; Teka, T.A.; Hailu, A. Drying Temperature and Storage Duration for the Retention of Bioactive Compounds of Selected Wild Edible Plants From Ethiopia. *Food Sci. Nutr.* **2025**, *13*, e70782. [CrossRef]
27. Ma, Y.; Yi, J.; Jin, X.; Li, X.; Feng, S.; Bi, J. Freeze-Drying of Fruits and Vegetables in Food Industry: Effects on Phytochemicals and Bioactive Properties Attributes—A Comprehensive Review. *Food Rev. Int.* **2023**, *39*, 6611–6629. [CrossRef]
28. Pateiro, M.; Vargas-Ramella, M.; Franco, D.; Gomez da Cruz, A.; Zengin, G.; Kumar, M.; Dhama, K.; Lorenzo, J.M. The role of emerging technologies in the dehydration of berries: Quality, bioactive compounds, and shelf life. *Food Chem. X* **2022**, *16*, 100465. [CrossRef]
29. Layeghinia, N.; Karimi, S.; Abbasi, H.; Silavi, K. Effect of osmotic dehydration on qualitative and nutritional characteristics and kinetics of microwave drying of Iranian Quince slices. *J. Agric. Food Res.* **2025**, *20*, 101749. [CrossRef]
30. Okba, S.K.; Mazrou, Y.; Elmenofy, H.M.; Ezzat, A.; Salama, A.-M. New Insights of Potassium Sources Impacts as Foliar Application on 'Canino' Apricot Fruit Yield, Fruit Anatomy, Quality and Storability. *Plants* **2021**, *10*, 1163. [CrossRef]
31. Turban, S.; Juraschek, S.P.; Miller, E.R., III; Anderson, C.A.M.; White, K.; Charleston, J.; Appel, L.J. Randomized Trial on the Effects of Dietary Potassium on Blood Pressure and Serum Potassium Levels in Adults with Chronic Kidney Disease. *Nutrients* **2021**, *13*, 2678. [CrossRef]
32. Gan, L.; Zhao, B.; Choi, M.I.; Liao, L.M.; Graubard, B.I.; Weinstein, S.J.; Albanes, D.; Huang, J. Sex-specific associations between sodium and potassium intake and overall and cause-specific mortality: A large prospective U. S. cohort study, systematic review, and updated meta-analysis of cohort studies. *BMC Med.* **2024**, *22*, 132. [CrossRef]
33. Schulz, M.T.; Rink, L. Zinc deficiency as possible link between immunosenescence and age-related diseases. *Immun. Aging* **2025**, *22*, 19. [CrossRef]
34. Bhatta, S.; Janezic, T.S.; Ratti, C. Freeze-Drying of Plant-Based Foods. *Foods* **2020**, *9*, 87. [CrossRef]
35. Kocaman, B.; Acun, S.; Seyrekoğlu, F.; Ay, E.B. Impact of drying techniques on strawberry powder characteristics. *J. Food Meas. Charact.* **2025**, *19*, 6694–6704. [CrossRef]
36. Özcan, M.M.; Uslu, N. The Effects of Oven Dehydration on Bioactive Compounds, Antioxidant Activity, Fatty Acids and Mineral Contents of Strawberry Tree Fruit. *Processes* **2023**, *11*, 541. [CrossRef]
37. Omoboyowa, D.A.; Agoi, M.D.; Shodehinde, S.A.; Saibu, O.A.; Saliu, J.A. Antidiabetes study of *Spondias mombin* (Linn) stem bark fractions in high-sucrose diet-induced diabetes in *Drosophila melanogaster*. *J. Taibah Univ. Med. Sci.* **2023**, *18*, 663–675. [CrossRef]
38. Ribeiro, L.D.O.; Viana, E.d.S.; Godoy, R.L.d.O.; Freitas, C.d.F.; Freitas, S.P.; da Matta, V.M. Nutrients and bioactive compounds of pulp, peel and seed from umbu fruit. *Ciênc. Rural* **2019**, *49*, e20180806. [CrossRef]
39. Souza De Freitas, J.; De Aguiar Novo, A.; Kunigami, C.N.; De Lima Moreira, D.; Pereira Freitas, S.; Martins da Matta, V.; Przytyk Jung, E.; de Oliveira Ribeiro, L. *Spondias tuberosa* and *Spondias mombi*: Nutritional Composition, Bioactive Compounds, Biological Activity and Technological Applications. *Resources* **2024**, *13*, 68. [CrossRef]
40. Kumar, D.; Ladaniya, M.S.; Gurjar, M.; Kumar, S. Impact of drying methods on natural antioxidants, phenols and flavanones of immature dropped *Citrus sinensis* L. Osbeck fruits. *Sci. Rep.* **2022**, *12*, 6684. [CrossRef]

41. Wojdyło, A.; Lech, K.; Nowicka, P.; Hernandez, F.; Figiel, A.; Carbonell-barrachina, A.A. Influence of Different Drying Techniques on Phenolic Compounds, Antioxidant Capacity and Color of *Ziziphus jujube* Mill. Fruits. *Molecules* **2019**, *24*, 2361. [CrossRef]
42. Nowak, D.; Jakubczyk, E. The Freeze-Drying of Foods—The Characteristic of the Process Course and the Effect of Its Parameters on the Physical Properties of Food Materials. *Foods* **2020**, *9*, 1488. [CrossRef] [PubMed]
43. Aniceto, A.; Montenegro, J.; da Silva Cadena, R.; Junger Teodoro, A. Physicochemical Characterization, Antioxidant Capacity, and Sensory Properties of Murici (*Byrsonima crassifolia* (L.) Kunth) and Taperebá (*Spondias mombin* L.) Beverages. *Molecules* **2021**, *26*, 332. [CrossRef]
44. Sollano-Mendieta, X.C.; Meza-Márquez, O.G.; Osorio-Revilla, G.; Téllez-Medina, D.I. Effect of In Vitro Digestion on the Antioxidant Compounds and Antioxidant Capacity of 12 Plum (*Spondias purpurea* L.) Ecotypes. *Foods* **2021**, *10*, 1995. [CrossRef] [PubMed]
45. Konfo, C.T.R.; Tchekessi, C.C.K.; Bleoussi, R.T.M.; Koudoro, A.Y.; Olayé, T.; Dahouenon-Ahoussi, E.; Yoau Bokossa, I.; Sohounhloue, D.C.K. Functional potential of yellow mombin (*Spondias mombin* L.) grape, fruit from a neglected and underutilized species. *GSC Biol. Pharm. Sci.* **2022**, *19*, 139–147. [CrossRef]
46. Sousa, R.P.D.; Assis, J.P.D.; Reinaldo, I.; Lima, P.D.; Sousa, R.P.D.; Rodrigues, W.M.; Cardoso, E.d.A.; Linhares, P.C.F. Biometric analysis of cajazeira fruits (*Spondias mombin* L.) in the northeastern Brazil. *Rev. Obs. Econ. Latinoam.* **2023**, *21*, 8804–8826. [CrossRef]
47. Santos, É.M.; Ataide, J.A.; Coco, J.C.; Masquetti Fava, A.L.; Luna Silvério, L.A.; Sueiro, A.C.; Alves Silva, J.R.; Lopes, A.M.; Paiva-Santos, A.C.; Mazzola, P.G. *Spondias* sp: Shedding Light on Its Vast Pharmaceutical Potential. *Molecules* **2023**, *28*, 1862. [CrossRef]
48. Rodrigues, N.L.; Souza Costa, A.L.; de Carvalho, M.G.; de Lima, B.R.; de Almeida Akutsu, R.d.C.; de Lana, V.S.; Raposo, A.; Saraiva, A.; Han, H.; Montezano de Carvalho, I.M. Nutritional and biological attributes of *Spondias tuberosa* (Umbu) fruit: An integrative review with a systematic approach. *J. Food Compos. Anal.* **2024**, *130*, 106196. [CrossRef]
49. Granja-Cabrera, J.; Timaná, R.; Osorio, O.; Paredes, K. Effect of Drying on the Concentration of Bioactive Compounds and Antioxidant Activity of Forage Plants. *TecnoLógicas* **2025**, *28*, e3379. [CrossRef]
50. Duan, M.; Feng, J.; Feng, J.-H.; Wang, X.; Xiao, X.; He, S.; Guo, H.; Zhang, W.; Jiang, Z.; Wan, T.; et al. Optimizing processing methods for maximum bioactive retention: Comparative metabolomic analysis of dried loquat (*Eriobotrya japonica*) flowers and their powdered extracts. *Front. Nutr.* **2025**, *12*, 1637247. [CrossRef] [PubMed]
51. de Brito, G.O.; Reis, B.C.; Ferreira, E.A.; Junqueira, N.T.V.; Sá-Barreto, L.C.L.; Mattivi, F.; Vrhovsek, U.; Gris, E.F. Phenolic Compound Profile by UPLC-MS/MS and Encapsulation with Chitosan of *Spondias mombin* L. Fruit Peel Extract from Cerrado Hotspot—Brazil. *Molecules* **2022**, *27*, 2382. [CrossRef]
52. Bayman, H.M.; Ozkan, K.; Ozturkan, A.; Sagdic, O.; Gunes, E.; Karadag, A. Effect of drying methods on free and bound phenolic compounds, antioxidant capacities, and bioaccessibility of Cornelian cherry. *Eur. Food Res. Technol.* **2024**, *250*, 2461–2478. [CrossRef]
53. Rumpf, J.; Burger, R.; Schulze, M. Statistical evaluation of DPPH, ABTS, FRAP, and Folin-Ciocalteu assays to assess the antioxidant capacity of lignins. *Int. J. Biol. Macromol.* **2023**, *233*, 123470. [CrossRef]
54. Li, L.; Wang, Q.; Cao, Y.; Li, J.; Wu, Y.; Hua, C.; Zhou, F.; Li, S.; Liu, S. Antioxidant action and potential neuroprotection of polyphenolics extracted from Astragalus membranaceus residue. *Front. Nutr.* **2025**, *12*, 1621848. [CrossRef]
55. Ksiazek, E. Citric Acid: Properties, Microbial Production, and Applications. *Molecules* **2024**, *29*, 22. [CrossRef]
56. Ikegaya, A.; Toyoizumi, T.; Ohba, S.; Nakajima, T.; Kawata, T.; Ito, S.; Arai, E. Effects of distribution of sugars and organic acids on the taste of strawberries. *Food Sci. Nutr.* **2019**, *7*, 2419–2426. [CrossRef] [PubMed]
57. Ferreira, A.M.; Mendes-Faia, A. The Role of Yeasts and Lactic Acid Bacteria on the Metabolism of Organic Acids during Winemaking. *Foods* **2020**, *9*, 1231. [CrossRef]
58. Zheng, H.; Lin, H.; Qin, X. Effect of Drying Process on the Formation of the Characteristic Flavor of Oyster (*Crassostrea hongkongensis*). *Foods* **2023**, *12*, 2136. [CrossRef] [PubMed]
59. Paiva, Y.F.; Feitosa de Figueiredo, R.M.; José de Melo Queiroz, A.; Santos Amadeu, L.T.; Suelia dos Santos, F.; Gomes dos Reis, C.; Júlia de Brito Araújo Carvalho, A.; Santos Lina, M.; Barbosa de Lima, A.G.; Palmeira Gomes, J.; et al. Physicochemical Aspects, Bioactive Compounds, Phenolic Profile and In Vitro Antioxidant Activity of Tropical Red Fruits and Their Blend. *Molecules* **2023**, *28*, 4866. [CrossRef]
60. Yin, X.; Chen, K.; Cheng, H.; Chen, X.; Feng, S.; Song, Y.; Liang, L. Chemical Stability of Ascorbic Acid Integrated into Commercial Products: A Review on Bioactivity and Delivery Technology. *Antioxidants* **2022**, *11*, 153. [CrossRef]
61. Shi, Y.; Pu, D.; Zhou, X.; Zhang, Y. Recent Progress in the Study of Taste Characteristics and the Nutrition and Health Properties of Organic Acids in Foods. *Foods* **2022**, *11*, 3408. [CrossRef]
62. Zhou, S.; Zhang, M.; Zhu, L.; Zhao, X.; Chen, J.; Chen, W.; Chang, C. Hydrolysis of lignocellulose to succinic acid: A review of treatment methods and succinic acid applications. *Biotechnol. Biofuels Bioprod.* **2023**, *16*, 1. [CrossRef]

63. Batista-Silva, W.; Nascimento, V.L.; Medeiros, D.B.; Nunes-Nesi, A.; Ribeiro, D.M.; Zsögön, A.; Araújo, W.L. Modifications in Organic Acid Profiles During Fruit Development and Ripening: Correlation or Causation? *Front. Plan Sci.* **2018**, *9*, 1689. [CrossRef] [PubMed]
64. Brizzolara, S.; Manganaris, G.A.; Fotopoulos, V.; Watkins, C.B.; Tonutti, P. Primary Metabolism in Fresh Fruits During Storage. *Front. Plan Sci.* **2020**, *11*, 80. [CrossRef]
65. Zhong, H.; Yadav, V.; Wen, Z.; Zhou, X.; Wang, M.; Han, S.; Pan, M.; Zhang, C.; Zhang, F.; Wu, X. Comprehensive metabolomics-based analysis of sugar composition and content in berries of 18 grape varieties. *Front. Plant Sci.* **2023**, *14*, 1200071. [CrossRef] [PubMed]
66. Zhou, Z.; Langrish, T. A review of Maillard reactions in spray dryers. *J. Food Eng.* **2021**, *305*, 110615. [CrossRef]
67. Yahia, E.M.; Carrillo-López, A.; Bello-Perez, L.A. Chapter 9. Carbohydrates. In *Postharvest Physiology and Biochemistry of Fruits and Vegetables*; Elsevier: Amsterdam, The Netherlands, 2019. [CrossRef]
68. Gillespie, K.M.; Kemps, E.; White, M.J.; Bartlett, S.E. The Impact of Free Sugar on Human Health—A Narrative Review. *Nutrients* **2023**, *15*, 889. [CrossRef]
69. Zhang, D.-M.; Jiao, R.-Q.; Kong, L.-D. High Dietary Fructose: Direct or Indirect Dangerous Factors Disturbing Tissue and Organ Functions. *Nutrients* **2017**, *9*, 335. [CrossRef]
70. Chaisuwan, V.; Dajanta, K.; Srikaeo, K. Effects of extraction methods on antioxidants and methoxyflavones of Kaempferia parviflora. *Food Res.* **2022**, *6*, 374–381. [CrossRef] [PubMed]
71. Shende, V.V.; Bauman, K.D.; Moore, B.S. The shikimate pathway: Gateway to metabolic diversity. *Nat. Prod. Rep.* **2025**, *41*, 604–648. [CrossRef]
72. Ojediran, J.O.; Okonkwo, C.E.; Olaniran, A.F.; Iranloye, Y.M.; Adewumi, A.D.; Erinle, O.; Tokunbo, Y.; Adeyi, O.; Adeyi, A. Hot air convective drying of hog plum fruit (*Spondias mombin*): Effects of physical and edible-oil-aided chemical pretreatments on drying and quality characteristics. *Heliyon* **2021**, *7*, e08312. [CrossRef]
73. Ajaegbu, E.E.; Uzochukwu, I.C.; Okoye, F.B.C. Antioxidant and Anti-inflammatory Activities of Extract and Fractions of *Spondias mombin* Leaf and Isolation of its Active Principles. *Trop. J. Nat. Prod. Res.* **2022**, *6*, 80–86. [CrossRef]