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Influence of drying technology on the bioactive composition and microstructural characteristics of West Indian cherry (Malpighia emarginata) powders

Harini Palani
Vellore Institute of Technology
Amrita Halder
Vellore Institute of Technology
Mangalambika Balaji
Vellore Institute of Technology
Utpal Das
utpal.das@vit.ac.in
Vellore Institute of Technology
Sandeep Singh Rana
Vellore Institute of Technology

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Influence of drying technology on the bioactive composition and microstructural characteristics of West Indian cherry (*Malpighia emarginata*) powders

Harini Palani[1], Amrita Halder[1], Mangalambika Balaji[1], Utpal Das[1*], Sandeep Singh Rana[2]

[1]*VIT School of Agricultural Innovations and Advanced Learning, Vellore Institute of Technology, Vellore, Tamil Nadu, India*

[2] *School of Biosciences and Technology, Vellore Institute of Technology, Vellore, Tamil Nadu, India*

*Corresponding author: Utpal Das, Email: utpal.das@vit.ac.in

ORCID ID: https://orcid.org/0000-0002-2618-0287

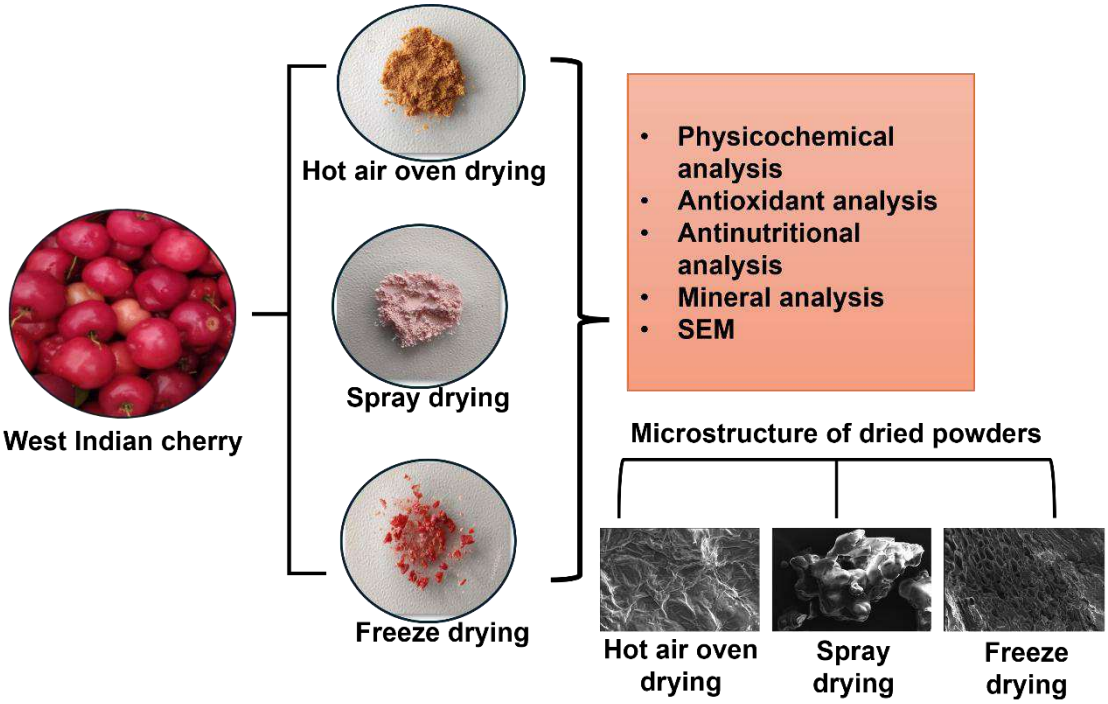
Influence of drying technology on the bioactive composition and microstructural characteristics of West Indian cherry (*Malpighia emarginata*) powders

Abstract

West Indian Cherry (WIC), *Malpighia emarginata*, commonly called acerola, is a tropical, highly perishable fruit rich in vitamin C and bioactive compounds. The current research aimed to compare the hot-air oven, spray, and freeze-drying methods to produce acerola pulp powder, assess changes in its composition and bioactive compounds, and evaluate the antioxidant activity and microstructure of the final product. The moisture content of the fresh pulp and the levels of ash, fibre, protein, and carbohydrates were also determined. Potassium, sodium, and magnesium were the most abundant minerals. Freeze-drying retained the highest levels, while hot-air drying led to the most deformed microstructure due to extended exposure to elevated temperatures. The powder microstructures differed significantly at the scanning electron microscopy level, ranging from consolidated, irregular surfaces to deformed, porous surfaces. Therefore, the current study revealed that the choice of drying technologies and conditions impacts the levels of most nutrients and the microstructure of acerola pulp powder. Among the methods, freeze-drying was found to be the most efficient in terms of retaining the properties of the original pulp. Meanwhile, the differences in the microstructure of the powders suggested the need to select the appropriate technologies for producing acerola-based functional food ingredients.

Keywords*:* Acerola, Antioxidant, Freeze-drying, Spray Drying, Microstructure

Graphical Abstract



Schematic representation of the study workflow illustrating the processing of West Indian Cherry (*Malpighia emarginata*) fruits into dried powders using different drying routes, followed by comprehensive characterization. Fresh fruits were converted into powders and evaluated for physicochemical properties, antioxidant activity, antinutritional factors, mineral composition, and microstructural features using scanning electron microscopy (SEM), highlighting the influence of drying on quality attributes relevant to functional food applications.

Highlights

- Freeze-drying preserved the maximum nutrients in West Indian Cherry powder.
- Hot air oven drying showed higher TPC due to heat-promoted release of bound compounds
- Antinutritional factors were low and within limits in all drying processes.
- Freeze-dried powder is suited for functional food and nutraceutical purposes.

1. Introduction

West Indian Cherry (*Malpighia emarginata*), belonging to the family *Malpighiaceae*, is a shrub or small tree producing highly nutritious fruits, particularly rich in vitamin C which is characterized by highly nutritious fruit, with higher amount of vitamin C [1]. *Malpighiaceae* is a family consisting of about 130 genera, such as *Malpighia emarginata, Malpighia glabra, Malpighia punicifolia,* and so on [2]. West Indian Cherry is an evergreen shrub that grows in humid tropical or subtropical areas and produces small fruits with a strong, sweet-tangy taste (commonly called Acerola Cherry or Barbados Cherry) [3]. Figure 1 represents the Morphological characteristics of West Indian Cherry (*Malpighia emarginata*). Southern Texas, Mexico, Central America, Northern South America region, and the Caribbean states are native to the crop, which has since been widely introduced into other areas like Brazil, Mexico, Southeast Asia, and India [4]. Its cultivation has expanded to spread in the Andaman and Nicobar Islands, Kerala, Tamil Nadu, Maharashtra, and Rajasthan in India. According to the concentration of ascorbic acid, West Indian Cherry varieties can be broadly categorized as sweet and sour, with sour ones having significantly more vitamin C content and being more appropriate to be used in processed forms such as juices and purees [2, 5]. ICAR-Central Island Agricultural Research Institute reports that adults need vitamin C as a dietary allowance of three West Indian Cherry fruits per day (Matta et al., 2003). The fruit is also abundant in essential minerals and electrolytes, such as potassium, iron, zinc, copper, and manganese [6]. This nutritional and antioxidant richness has led to increased consumer demand in some markets, especially the United States, Europe, and Japan, for acerola-based products, which is largely due to the increased awareness of health and wellness [6]. It also has bioactive compounds like lycopene and vitamin A, thus enhancing its functional and nutraceutical value [7]. Even though the nutritional benefits of West Indian Cherry are abundant, the fruit is very perishable due to its thin peel and sensitivity to environmental factors, which causes severe postharvest degradation and massive losses [6]. As a result, the preservation and processing methods should be properly utilized to increase shelf life and quality. One of the best preservation methods for fruits that contain high amounts of moisture is drying because it lowers water activity, prevents microbial growth, and allows storage of fruits over a long period [8].

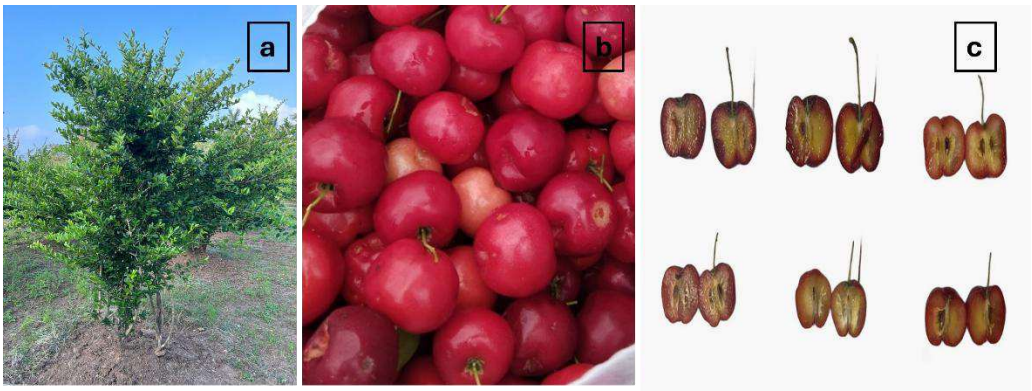


Fig 1. Morphological characteristics of West Indian Cherry (*Malpighia emarginata*).
(a) Fresh, fully ripened West Indian Cherry fruits.
(b) Transverse and longitudinal sections of West Indian Cherry fruits showing internal structure and seed

arrangement.

(c) West Indian Cherry plant grown under field conditions.

In earlier research, it has been demonstrated that vitamin C and other bioactive substances can be preserved in large concentrations through the application of an optimized drying method and hence maintain the health-promoting activity attributed to West Indian Cherry [9]. Besides, dried fruit powders have the benefits of being easy to handle, requiring less storage volume, and can be incorporated into functional foods and dietary supplements. Interestingly, the concentration of ascorbic acid in West Indian Cherry is much higher as compared to that found in popular edibles like oranges and guava; this further highlights that the application of effective drying processes to the final products is important in reducing the rate at which the compounds are destroyed during transportation [10]. Nevertheless, the effects that various drying methods have on the physicochemical quality, antioxidant activity, antinutritional properties, and mineral structure of West Indian Cherry have little comparative data available in existing studies. Thus, the aim of the current research was also to determine the influence of hot air oven drying, spray drying, and freeze drying on the physicochemical properties, antioxidant activity, antinutritional elements, and mineral composition of West Indian Cherry pulp and powders. Moreover, the microstructure of the powders obtained was studied to determine the most appropriate drying method to achieve high-quality fruit powders to be made commercially and functionally.

2. Materials and Methods

2.1. Sample preparation

The fruits of West Indian Cherry (*Malpighia emarginata*) used in this study were collected from locally selected plants maintained in the fruit orchard of the VIT School of Agricultural Innovations and Advanced Learning (VAIAL), Vellore Institute of Technology, Vellore, Tamil Nadu, India. The plants were cultivated and maintained through propagation using semi-hardwood stem cuttings. Mature fruits were harvested from these institutionally maintained plants for research purposes. No wild plant populations were sampled, and no protected or endangered plant species were involved. No specific collection permits or licences were obtained for this study. The fruits were rinsed with running tap water, cleaned, and manually examined to remove the samples that had mechanical damage, disease signs, or apparent deformities. The fruits were deseeded and blended for further treatments.

2.2. Drying methods

2.2.1. Hot air oven drying (HD)

The freshly prepared fruit pulp (250 mL) was mixed with the carrier agent, maltodextrin (10% w/w), then spread uniformly as a thin layer on drying trays in a hot air oven at 40 ℃ for 6 h, as per the procedure [11]. The samples were dried and cooled to ambient temperature and kept in airtight containers at 4 °C until further analysis.

2.2.2. Spray drying (SD)

Drying of the fruit pulp was carried out in a spray dryer (Mini Spray Dryer SD-19, Varcogroup, Mumbai, India). A carrier agent, maltodextrin (10% w/w), was added to fruit juice (250 mL) to reduce stickiness, improve powder recovery and flowability, and enhance the stability of bioactive compounds during drying. The mixture was pumped into the spray dryer using the peristaltic pump. The temperature of the inlet and discharge air was kept at 150 ℃ and 90 ℃, respectively, and the feed flow rate was kept at 10 mL/min^{-1}. The powder product was then scraped off the drying chamber and cyclone separator and stored in airtight containers at 4℃ until the analysis [12].

2.2.3. Freeze drying (FD)

In the case of freeze-drying, 250 mL fruit slurry was mixed with 10% (w/w) maltodextrin and then frozen before drying. A Lyodel freeze dryer with a pump (Model LYO 0585) was used to freeze-dry at 40 ℃ and under vacuum conditions for over 30 h. The freeze-dried product was converted into powder and kept under airtight conditions at 4 ℃ until analysed subsequently [11].

2.3. Physicochemical analysis of West Indian Cherry pulp and dried powders

Proximate composition, such as moisture, ash, crude fat, crude fibre, and protein, was established according to AOAC [13]. The content of moisture was obtained using the oven-drying technique, whereas ash content was obtained through incineration using a muffle furnace. The crude fat and crude fibre were analysed according to the procedures [14]. The method of identifying protein was the Kjeldahl method. The difference method of calculating the total carbohydrate was done using the following equation: Carbohydrate (%) = 100 − (Moisture + Protein + Fat + Ash + Fiber). The energy value was calculated using Atwater's conversion factors, where protein and carbohydrates contribute 4 kcal g^{-1} and fat contributes 9 kcal g^{-1} (Menezes et al., 2004). Energy (kcal/100 g) = (Protein × 4) + (Fat × 9) + (Carbohydrates × 4). A digital refractometer (0-30° Brix; Master 2 M, Japan) was used to measure total soluble solids (TSS) after following the AOAC protocol [13] and converted it into degrees Brix. Titratable acidity (TA) value was calculated based on the AOAC procedures and expressed as a percentage. The pH of the juice samples was determined by the digital pH meter (Systronics, Model 361, Navi Mumbai, India). The estimation of reducing and non-reducing sugars was done according to the AOAC procedures [13]. The methodology applied to the determination of reducing sugars was the Fehling solution method, and the methodology used to determine the non-reducing sugars was the difference between total sugars and reducing sugars [15].

2.4.1. Antioxidant analysis

DPPH Radical Scavenging Activity

The radical scavenging activity of the ethanol fruit extract against DPPH free radical was determined using a modification of the method described by Blois [16]. The fruit extract was dissolved in ethanol to give a concentration of 1 mg/mL. The DPPH solution was prepared by dissolving 3.94 mg of 2,2-diphenyl-1-picrylhydrazyl in 100 mL of ethanol. Aliquots (10-100 µL) of the extract were reacted with the DPPH solution. The reaction mixture was left to incubate under experimental conditions. Absorbance was

measured at 517 nm using a UV-Visible spectrophotometer (Shimadzu UV-1260, Mumbai, India). Solutions of ascorbic acid were used as the reference antioxidant. The radical scavenging activity was expressed as a percentage of the control. The IC_{50} was calculated from the concentration-response curve.

ABTS Radical Cation Scavenging Activity

The ABTS radical cation scavenging activity of the ethanol fruit extracts was determined using a modified method described by Thaipong et al [17]. A solution of ABTS (7mM) and potassium persulphate (2.45mM) was prepared. These were mixed in a ratio of 1:0.1 and left to incubate in the dark for 12 - 16 h at room temperature to form the ABTS radical cation (ABTS •+). This solution was used as the working reagent. The ethanol fruit extract was dissolved in ethanol to produce a concentration of 1 mg/mL. The extract was mixed with the ABTS reagent and incubated for 6 minutes. The absorbance of the solution was measured at 734 nm using a UV-Visible Spectrophotometer (Shimadzu UV-1260, Mumbai, India). Solutions of ascorbic acid were used as the reference antioxidant. Radical scavenging activity was expressed as a percentage of the control. The IC_{50} was calculated using the concentration-response curve.

Ferric Reducing Antioxidant Power (FRAP)

The ferric reducing antioxidant power of the ethanol fruit extracts was determined using a modification of the FRAP method described by Thaipong et al [17]. The FRAP working reagent was prepared by mixing 300 mM Sodium Acetate Buffer (pH 3.6), 10 mM 2,4,6-tripyridyl-s-triazine (TPTZ) in Hydrochloric Acid, and 20 mM ferric chloride hexahydrate ($FeCl_3 .6H_2O$) in a ratio of 10:1:1. The ethanol fruit extract was dissolved in ethanol to produce a concentration of 1 mg/mL. This was mixed with the FRAP working reagent and left to incubate for 4 minutes. The absorbance of the solution was measured at 593 nm using a UV-Visible Spectrophotometer (Shimadzu UV-1260, Mumbai, India). A stock solution of ascorbic acid (5.67 mM) was used to produce a calibration curve. The FRAP values were calculated using the calibration curve and expressed in mg AAE/g DW.

2.4.2. Total phenolic content (TPC) and total flavonoid content (TFC)

In the Folin-Ciocalteu method by Singleton et al [18] The total phenolic content (TPC) was calculated. The absorbance was recorded at 765 nm, and the outcome was converted to mg gallic acid equivalents (GAE) per 100 g of solid sample. The level of total flavonoid content (TFC) was determined using a colorimetric method of aluminium chloride [19]. At 510 nm, absorbance was taken, and the obtained amounts were expressed as mg catechin equivalents (CE) per 100 g of sample.

2.4.3. Vitamin C, carotenoid, and anthocyanin analysis

2,6-dichlorophenolindophenol (DCPIP) titration was used to determine vitamin C content in fresh pulp and dried powders [20] . The total carotenoid concentration was determined through the UV-Visible spectrophotometry procedure according to the procedure [21], based on the use of β-carotene as the reference, which included the reagent, and the result was then expressed in mg per 100 g of sample. The amount of total anthocyanin was obtained using the pH differential method, as explained [21].

2.5. Antinutritional analysis

The pulp samples were dried at 40 °C in the oven until they attained a constant weight. Phytate analysis was done according to the procedure by Adeniyi et al [22]. The amount of total soluble tannins in a solution was determined by the copper acetate gravimetric reagent. Oxalate was also obtained through titration, and alkaloid was estimated by using the gravimetric method.

2.6. Mineral analysis

The West Indian Cherry pulp and dry powder mineral composition were identified using inductively coupled plasma-mass spectrometry (ICP-MS; PerkinElmer NexION 1000, Singapore) at the SMEC-DST-PURSE Centre, Vellore Institute of Technology, Vellore, Tamil Nadu, India, in accordance with the methodology [23]. The Promotion of University Research and Scientific Excellence (PURSE) program supports the facility.

2.7. Scanning electron microscopy (SEM)

A scanning electron microscope (EVO 18, Carl Zeiss) was used to investigate the surface morphology of the dried powders. The samples were attached to the aluminium stubs (12 mm diameter), sputtered with a thin layer of co-metallic gold plus palladium in high-vacuum conditions. The micrographs were taken at an accelerating voltage of 20 kV and 100 PA of the current flow of the electron beam at magnifications of 20 µm, 100 µm, and 200 µm. An associated energy-dispersive X-ray (EDAX) detector was used to analyse the elemental composition [24].

2.8. Statistical analysis

Each drying method was done in three replications. The results are in terms of mean ± standard deviation (SD). One-way analysis of variance (ANOVA) was used to statistically analyse the results, and the differences among the means were evaluated with the Tukey post hoc test HSD at a $p < 0.05$ level in the case of the JMP Pro 18 statistical software.

3. Results and Discussion

3.1 Physicochemical properties of fresh pulp and dried West Indian Cherry pulp and dried powders

Physicochemical properties of West Indian cherry pulp and powders obtained by hot-air drying (HD), spray drying (SD), and freeze-drying (FD) are presented in Table 1, with most properties showing significant differences among treatments ($p < 0.05$). Figure 2 displays the visual appearance of West Indian Cherry powders obtained by different drying methods.

Table 1. The physicochemical properties of West Indian Cherry fruit pulp and dried powders

Physicochemical properties (g/100 g)	West Indian Cherry pulp	HD powder	SD powder	FD powder
Moisture (%)	88.95 ± 0.76^{a}	6.13 ± 0.55^{b}	4.83 ± 0.85^{bc}	3.33 ± 0.40^{c}
Ash (%)	0.40 ± 0.28^{a}	2.83 ± 0.31^{b}	2.53 ± 0.21^{b}	3.17 ± 0.38^{b}
Fiber (%)	1.24 ± 0.03^{c}	6.27 ± 0.65^{b}	4.57 ± 0.95^{b}	8.60 ± 0.80^{a}
Fat (%)	0.40 ± 0.09^{a}	0.12 ± 0.01^{b}	0.23 ± 0.04^{ab}	0.28 ± 0.02^{ab}
Protein (%)	0.33 ± 0.00^{d}	4.50 ± 0.30^{c}	6.70 ± 0.66^{b}	7.90 ± 0.30^{a}
Carbohydrates (%)	8.68 ± 0.6^{d}	80.15 ± 0.4^{a}	81.14 ± 1.73^{ab}	76.7 ± 1.17^{c}
Energy (Kcal/100g)	39.64 ± 0.2^{d}	339.68 ± 1.6^{b}	353.43 ± 0.2^{a}	340.92 ± 0.8^{bc}
Titratable Acidity (%)	1.48 ± 0.07^{d}	5.30 ± 0.01^{c}	6.27 ± 0.01^{b}	9.36 ± 0.01^{a}
Total Soluble Solids °Brix	7.57 ± 0.06^{b}	14.30 ± 0.46^{ab}	15.53 ± 0.21^{a}	16.73 ± 0.52^{a}
pH	3.56 ± 0.00^{a}	3.45 ± 0.03^{b}	3.27 ± 0.02^{c}	3.12 ± 0.05^{d}
Reducing sugar (%)	2.58 ± 0.05^{c}	36.67 ± 0.53^{b}	41.17 ± 0.02^{a}	43.23 ± 0.12^{a}
Non-reducing sugar (%)	1.89 ± 0.03^{b}	17.33 ± 0.05^{a}	20.43 ± 0.46^{a}	22.73 ± 0.20^{a}

Values are expressed as mean ± standard deviation (SD) of three independent determinations (n = 3). Values within the same row followed by different superscript letters (a–d) are significantly different at $p < 0.05$ according to one-way ANOVA followed by Tukey's HSD post hoc test. Differences between fresh pulp and dried powders should be interpreted in light of moisture reduction and differences in the product matrix and formulation. HD: hot-air-dried powder; SD: spray-dried powder; FD: freeze-dried powder; TSS: total soluble solids.

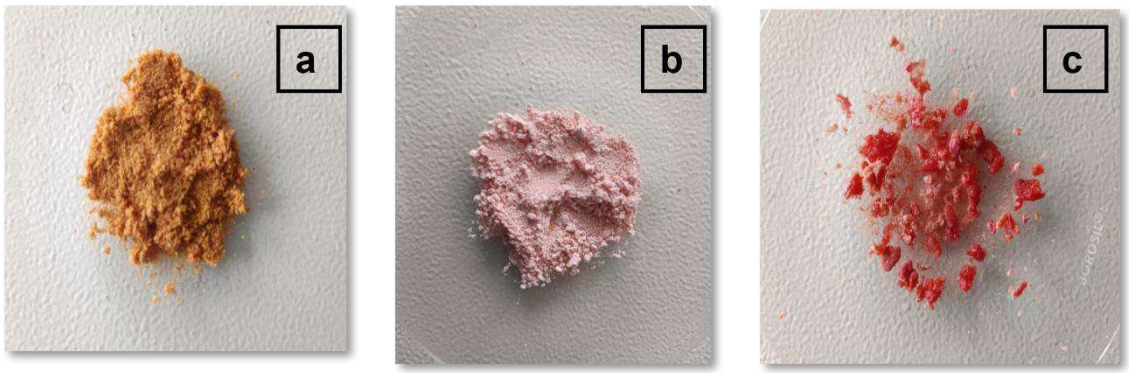


Fig 2. Visual appearance of West Indian Cherry powders obtained by different drying methods. (a) Hot-air-dried (HD) powder. (b) Spray-dried (SD) powder. (c) Freeze-dried (FD) powder.

Moisture contents were significantly reduced upon drying, ranging from 88.95 ± 0.76 % in the pulp to 6.13 ± 0.5 %, 4.83 ± 0.85 %, and 3.33 ± 0.40 % in HD, SD, and FD powders, respectively, with FD showing the lowest moisture content. Low moisture contents are commonly associated with improved storage stability due to reduced water availability for microbial growth and moisture-related deterioration reactions. Similar trends have been reported for fruit powders, with moisture contents varying depending on the raw material and processing conditions [25].

Ash, fiber, protein, carbohydrate, and energy contents were significantly higher in dried powders than in the original pulp, with differences ranging from 3- to 10-fold increases. Such increases were expected due to the removal of a substantial amount of water during drying. FD powder showed the highest fiber 8.60 ± 0.80 % and protein 7.90 ± 0.30 % contents, while SD powder had the highest carbohydrate 81.14 ± 1.73% and energy 353.43 ± 0.2 kcal/100 g contents. The higher contents of fiber and protein in FD powder may be explained by the lower temperatures used in freeze-drying, which could have minimized their degradation or loss during processing. In contrast, the higher carbohydrate and energy contents in SD powder could be explained by the higher levels of soluble solids and sugars retained by this method. Fat contents were low in all powders, suggesting fat was a minor pulp component, with HD showing the lowest fat content, possibly due to thermal degradation and/or exclusion during drying. Titratable acidity increased upon drying, ranging from 1.4 ± 0.07 % in the pulp to 5.30 ± 0.01 %, 6.27 ± 0.01 %, and 9.36 ± 0.01 % in HD, SD, and FD powders, respectively, while pH values decreased from 3.56 ± 0.00 in the pulp to 3.45 ± 0.03, 3.27 ± 0.02, and 3.12 ± 0.05 in the powders. The inverse relationship between pH and titratable acidity is expected, as both are indicators of the number of organic acids in the product. FD powder showed the highest titratable acidity and the lowest pH, suggesting that it retained the highest amount of organic acids during drying. Total soluble solids content increased from 7.57 ± 0.06 °Brix in the pulp to 14.30 ± 0.46 and 15.53 ± 0.21 °Brix in HD and SD powders, respectively, while FD showed the highest content (16.73 ± 0.52 °Brix). The high total soluble solids content in SD powder is consistent with its higher carbohydrate and energy content. The large variability observed for FD powder could be due to differences in reconstitution. Reducing sugar content increased upon drying, ranging from 2.58 ± 0.05 % in the pulp to 36.67 ± 0.53 %, 41.17 ± 0.02 %, and 43.23 ± 0.12 % in HD, SD, and FD powders, respectively. SD and FD powders showed significantly higher contents of reducing sugars than HD powder, indicating that they retained more sugars during drying. Non-reducing sugars also increased upon drying, from 1.89 ± 0.03 % in the pulp to 17.33 ± 0.05 % to 22.73 ± 0.20 % in the powders, with no significant differences among treatments.

The higher contents of sugars and acids in FD powder could be explained by the lower temperatures used during drying, which could have minimized their degradation and/or loss. This hypothesis is consistent with previous studies reporting that acerola powders obtained by FD showed low water activity and good physicochemical properties while retaining phytochemicals during storage [26]. However, the method used for drying is not the sole factor determining the quality of the final product. According to a systematic review, FD powders generally showed higher porosity and better rehydration properties than those obtained by SD, while the latter showed smaller particle sizes, higher bulk density, and lower moisture content; these properties were also dependent on the process conditions and the composition of the raw material [25]. Studies conducted specifically on acerola showed that SD produced spherical particles, while FD resulted in more irregular structures [27]. Overall, FD was the most efficient method in terms of producing a low-moisture powder, and it could be considered a better option for retaining heat-labile components, while SD could be used to produce a concentrated fruit powder with a high amount of carbohydrates and energy. Spray drying is generally associated with higher production rates and lower costs than freeze-drying, although process optimization is required to ensure desirable product characteristics [28].

3.2 Antioxidant properties and bioactive compounds of fresh pulp and dried West Indian Cherry powders

The antioxidant and bioactive compound contents of West Indian cherry pulp and dried powders are displayed in Table 2. Different letters indicate significant differences among treatments. Fresh pulp exhibited the highest DPPH radical-scavenging activity (93.41 ± 0.55%), followed by the FD powder (86.33 ± 1.43%), HD powder (66.23 ± 0.82%), and the SD powder (48.26 ± 0.62%), with significant activity differences among treatments. The high antioxidant activity of fresh pulp is consistent, since the acerola fruit is well-known for its high content of vitamin C, phenolic compounds, flavonoids, carotene, and anthocyanins [29]. In turn, the high antioxidant activity found in FD powder, due to the freeze-drying process, is less aggressive, thus better preserving the active compounds than HD or SD. Figure 3. Shows the effect of three different drying methods on selected physicochemical and antioxidant parameters of West Indian Cherry pulp and dried powders.

Table 2. The Antioxidant properties and bioactive compounds of West Indian Cherry pulp and dried powders

Antioxidant properties	West Indian Cherry pulp	HD-powder	SD-powder	FD- powder
DPPH% (mg AAE/g)	93.41 ± 0.55^{a}	66.23 ± 0.82^{c}	48.26 ± 0.62^{d}	86.33 ± 1.43^{b}
ABTS (µmol/g)	22.4 ± 0.7^{d}	42.0 ± 0.4^{a}	31.3 ± 1.5^{b}	25.8 ± 1.1^{c}
FRAP (µmol/g)	566.0 ± 0.20^{a}	494.17 ± 0.78^{d}	514.27 ± 1.0^{c}	555.40 ± 0.46^{b}
TPC (mg GAE/ 100g)	101.28 ± 1.33^{d}	126.59 ± 2.6^{c}	202.2 ± 1.1^{b}	264.93 ± 13.4^{a}
TFC (mg QE/ 100g)	156.73 ± 0.27^{c}	178.33 ± 1.4^{bc}	191.07 ± 4.79^{b}	236.30 ± 25.6^{a}
Vitamin C (mg/ 100g)	354.10 ± 0.46^{a}	115.53 ± 1.25^{d}	260.84 ± 0.49^{c}	296.19 ± 0.79^{b}
Anthocyanins (mg/ 100g)	8.42 ± 0.72^{a}	4.48 ± 0.44^{c}	6.36 ± 0.18^{b}	7.62 ± 0.17^{a}
Carotenoids (mg/ 100g)	1.91 ± 0.18^{a}	0.61 ± 0.14^{c}	1.03 ± 0.15^{bc}	1.51 ± 0.36^{ab}

Values are expressed as mean ± standard deviation (SD) of triplicate analyses (n = 3). Different superscript letters within the same row indicate significant differences at $p < 0.05$ (one-way ANOVA, Tukey's HSD test). Antioxidant activities were determined using DPPH, ABTS, and FRAP assays, while bioactive compounds were quantified as total phenolic content (TPC), total flavonoid content (TFC), vitamin C,

anthocyanins, and carotenoids. Variations among samples may reflect dehydration effects, processing conditions, and differences in sample matrix and formulation.

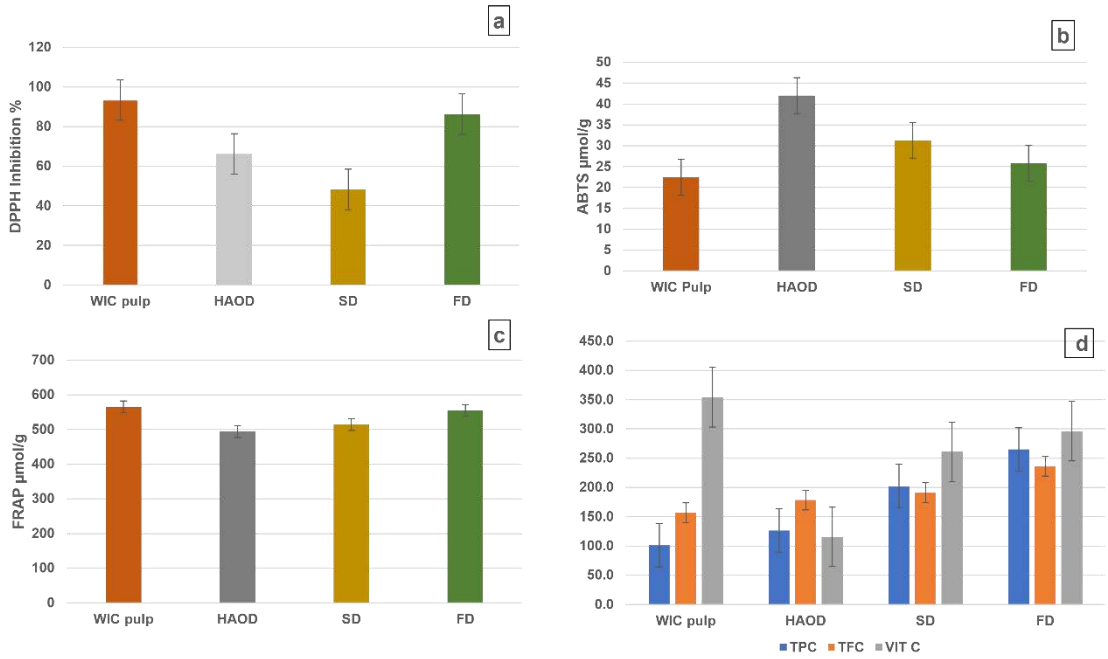


Fig 3. Effect of three different drying methods on antioxidant, phytochemical, and Vitamin C content of West Indian Cherry pulp and dried powders. (a) DPPH inhibition (%). (b) ABTS radical scavenging activity (µmol/g), (c) FRAP assay (µmol/g), (d) Total phenolic content (TPC) (mg GAE/ 100g), Total flavonoid content (TFC) (mg QE/ 100g), and Vitamin C (mg/ 100g) (n = 3).

The ABTS IC_{50} values followed the same trend as for the DPPH assay, with the lowest IC50 (22.4 ± 0.7 µmol/g DW) found in the fresh pulp, while the highest one (42.0 ± 0.4 µmol/g DW) was found in the HD powder, with FD (25.8 ± 1.1 µmol/g DW) and SD powders (31.3 ± 1.5 µmol/g DW) showing intermediate IC50 values. Again, in the ABTS assay, a lower IC_{50} value means higher antioxidant activity and, therefore, higher FRAP values. Thus, again, fresh pulp showed the highest reducing power (566.0 ± 0.20 µmol/g DW) followed by the FD (555.40 ± 0.46), SD (514.27 ± 1.0), and HD powders (494.17 ± 0.78 µmol/g DW). It is noticeable that the FRAP values obtained were different from the DPPH and ABTS ones since all assays were based on different reaction mechanisms. Moreover, the FRAP assay can better distinguish between hydrophilic and lipophilic antioxidants than DPPH and ABTS, and therefore it is possible that the differences between the antioxidant assays are caused by differences in the hydrophobicity of the extracts. Unlike in the antioxidant assays, in the case of TPC, the dried powders showed a much higher content than that found in the fresh pulp. Indeed, among the samples, FD powder showed the highest TPC (264.93 ± 13.4 mg GAE/100 g) followed by the SD powder (202.2 ± 1.1 mg GAE/100 g), HD powder (126.59 ± 2.6

mg GAE/100 g) and the fresh pulp (101.28 ± 1.33 mg GAE/100 g). As for the TPC, a similar trend was observed for the total flavonoid content (TFC), with the highest content being found in FD powder (236.30 ± 25.6 mg QE/100 g) and the lowest one in the fresh pulp (156.73 ± 0.27 mg QE/100 g). The reason for higher values for dried powders might be that during the drying process, some of the cell walls are broken due to the removal of water, facilitating the release of bound phenolic compounds that are commonly not accessible to solvents during extraction. It is noticeable that the acerola fruit contains a wide range of phenolic compounds, among which flavonoids and phenolic acids predominate [29].

The fresh pulp showed the highest vitamin C content (354.10 ± 0.46 mg/100 g), followed by the FD powder (296.19 ± 0.79 mg/100 g), the SD powder (260.84 ± 0.49 mg/100 g), and the HD powder (115.53 ± 1.25 mg/100 g). The significant decrease in vitamin C content found in HD powder is most likely explained by the fact that ascorbic acid is highly sensitive to thermal and oxidative stresses. On the other hand, previous studies have shown that freeze-dried acerola pulp has a high content of ascorbic acid [26]. The significant decrease in carotenoid content found in HD pulp might be explained by the fact that high temperatures induce oxidation processes. Indeed, previous studies have shown that hot air drying causes a significant reduction in total carotenoids, anthocyanins, ascorbic acid, and antioxidant activity of acerola [30]. FD powder showed the best results regarding the content of antioxidants, vitamin C, and pigments. However, a significantly higher TPC and TFC were found for all dried powders in comparison to the fresh pulp, which might be explained by an increased bio accessibility of active compounds after the removal of water and damage to the plant tissue during drying.

3.3 Antinutritional components of fresh pulp and spray-dried West Indian Cherry powder

Table 3 below shows the phytate, alkaloid, tannin, and oxalate content of the fresh West Indian cherry pulp and dried powders. Phytate content ranged between 0.4 and 0.78 mg/100g. Fresh pulp had the lowest alkaloid content (0.05 ± 0.00 mg/100g), whereas HD, SD, and FD powders had the highest alkaloid content (25.7 ± 1.1, 25.1 ± 1.4, and 24.2 ± 1.2 mg/100g respectively). The values of the powders were not significantly different from each other but were significantly higher than the fresh pulp. The difference could be due to the high moisture content removed from the powders, causing an increase in alkaloid concentration rather than the formation of new alkaloids. The tannin content of the fresh pulp was 2.48 ± 0.26 mg/100g, whereas the HD, SD, and FD powders had 53.5 ± 2.0, 47.5 ± 0.7, and 45.3 ± 1.9 mg/100g respectively. The HD powder was not significantly different from the fresh pulp. On the other hand, the SD and FD powders were significantly different from the fresh pulp. The high content of tannin in the powders could be due to moisture loss and high concentration. It is also possible that processing breaks down some of the components, causing more tannin to be extracted [31]. The oxalate content ranged from 0.60 ± 0.04 mg/100g in the fresh pulp to 20.6 ± 1.0 mg/100g in HD, 18.2 ± 0.6 mg/100g in SD, and the highest was 16.9 ± 0.6 mg/100g in the FD powder. HD powder had the highest oxalate content and was significantly different from the other treatments. The FD powder had a lower oxalate content compared to HD. This might be due to the low-temperature drying that caused minimal breakdown of components to form oxalate. Therefore, the high concentrations of alkaloid, tannin, and oxalate content observed in the powders could be due to moisture loss leading to higher concentrations and easy extractability of these compounds. However, the processing method has no significant effect on phytate content. Some antinutrients such as

oxalate and phytate were significantly reduced when drying was achieved with sun drying, hot-air drying, steaming, or pretreatment with hot or cold water. Additionally, it was observed that the temperature at which drying occurred significantly reduced the amounts of tannin in the powder. For example, lower temperatures were associated with lower tannin content [32]. In conclusion, although higher antinutrient levels were observed in the powders than in the fresh fruit, the FD powder had lower concentrations compared to HD.

Table 3. Antinutritional analysis of West Indian Cherry pulp and dried powders

Antinutritional properties	West Indian Cherry pulp	HD-powder	SD-powder	FD- powder
Phytate (mg/100g)	0.43 ± 0.05^{a}	0.78 ± 0.0^{a}	0.4 ± 0.0^{a}	0.5 ± 0.0^{a}
Alkaloids (mg/100g)	0.05 ± 0.00^{b}	25.7 ± 1.1^{a}	25.1 ± 1.4^{a}	24.2 ± 1.2^{a}
Tannins (mg/100g)	2.48 ± 0.26^{a}	53.5 ± 2.0^{a}	47.5 ± 0.7^{b}	45.3 ± 1.9^{b}
Oxalate (mg/100g)	0.60 ± 0.04^{c}	20.6 ± 1.0^{a}	18.2 ± 0.6^{b}	16.9 ± 0.6^{bc}

Values represent mean ± standard deviation (SD) of three replicates (n = 3). Means followed by different superscript letters within a row differ significantly at $p < 0.05$ (one-way ANOVA with Tukey's HSD test). Apparent increases in antinutritional components in dried powders may be influenced by moisture removal and enhanced extractability of compounds following dehydration. HD: hot-air-dried powder; SD: spray-dried powder; FD: freeze-dried powder.

3.4 Mineral composition of fresh pulp and dried West Indian Cherry powders

Table 4 represents the mineral composition of the fresh West Indian cherry pulp and HD, SD, and FD powders. The calcium (Ca) content was found to be significantly higher ($p<0.05$) in HD (0.45 ± 0.02 ppm) and FD (0.42 ± 0.010 ppm) compared to the fresh pulp (0.34 ± 0.05 ppm). The SD powder (0.41 ± 0.005 ppm) had an intermediate level. The Cu contents were found to be almost similar, with values of approximately 0.01 ppm and no significant differences between the samples. Iron (Fe) was observed to increase from 0.03 ± 0.00 ppm in the fresh pulp to 0.07 ± 0.01 ppm in HD powder. Similar increases were recorded for the SD and FD powders, with values of 0.05 ppm. The enhanced Fe content in the HD sample could be associated with the solid's retention during moisture removal.

The contents of potassium (K) and magnesium (Mg) were observed to be significantly higher ($p<0.05$) in the fresh pulp as compared to all the powders. For instance, the K content was 0.66 ± 0.08 ppm in the fresh pulp, as compared to 0.34-0.39 ppm in the powders. Similarly, Mg content was 0.92 ± 0.25 ppm in the fresh pulp, while it ranged from 0.32 to 0.35 ppm in the powders. Sodium (Na) and phosphorus (P) contents were also found to be higher in the fresh pulp. Minerals are not typically destroyed by the drying process. The Mn contents were found to be significantly higher ($p<0.05$) in all the powders as compared to the fresh pulp. The levels were similar across the three types of powders, suggesting that the differences in processing had little effect on the Mn content. The application of freeze-drying resulted in higher Mn retention. Similar

to Mn, zinc (Zn) was found to be enriched in the powders, with FD having the highest content (0.09 ± 0.04 ppm). HD and SD powders had intermediate levels of 0.08 ppm each, while the FD powder had the lowest level of 0.05 ± 0.04 ppm. No significant differences in selenium (Se) were recorded between the treatments, indicating that the concentrations were relatively stable throughout the processing. In *Prunus avium*, freeze-drying was found to be more efficient in retaining anthocyanins, while convective drying resulted in higher total phenolic and flavonoid contents [33]. Similarly, another study on the effects of drying methods on dehydrated sweet cherry found that freeze-drying retained higher anthocyanin contents, while air-drying retained higher total phenolic contents [34].

Table 4. Mineral composition of West Indian pulp and dried powders

Minerals (ppm)	West Indian Cherry pulp	HD-powder	SD-powder	FD- powder
Ca	0.34 ± 0.05^{b}	0.45 ± 0.02^{a}	0.41 ± 0.005^{ab}	0.42 ± 0.010^{a}
Cu	0.01 ± 0.00^{ab}	0.01 ± 0.002^{ab}	0.01 ± 0.001^{b}	0.01 ± 0.001^{a}
Fe	0.03 ± 0.0^{c}	0.07 ± 0.01^{a}	0.05 ± 0.0004^{ab}	0.05 ± 0.002^{b}
K	0.66 ± 0.08^{a}	0.39 ± 0.01^{b}	0.34 ± 0.002^{b}	0.36 ± 0.003^{b}
Mg	0.92 ± 0.25^{a}	0.35 ± 0.01^{b}	0.33 ± 0.003^{b}	0.32 ± 0.001^{b}
Mn	0.002 ± 0.02^{b}	0.003 ± 0.037^{a}	0.003 ± 0.0002^{a}	0.003 ± 0.03^{a}
Na	15.86 ± 6.69^{a}	4.04 ± 0.50^{b}	3.79 ± 0.034^{b}	3.80 ± 0.04^{b}
P	0.11 ± 0.00^{a}	0.006 ± 0.01^{b}	0.05 ± 0.000^{b}	0.05 ± 0.01^{b}
Se	0.032 ± 0.060^{a}	0.006 ± 0.01^{a}	0.037 ± 0.026^{a}	0.013 ± 0.012^{a}
Zn	0.05 ± 0.04^{c}	0.08 ± 0.004^{b}	0.07 ± 0.0003^{b}	0.09 ± 0.04^{a}

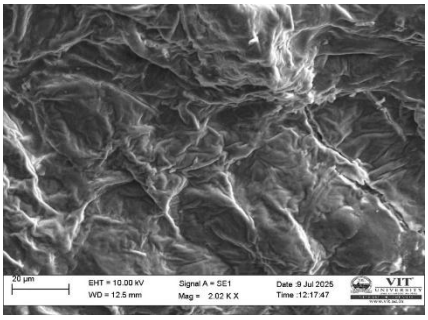
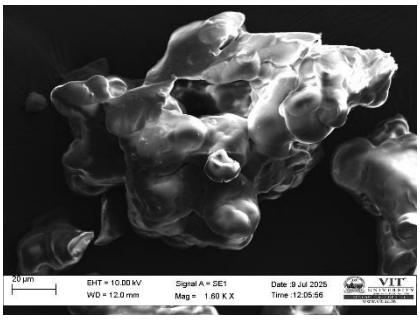
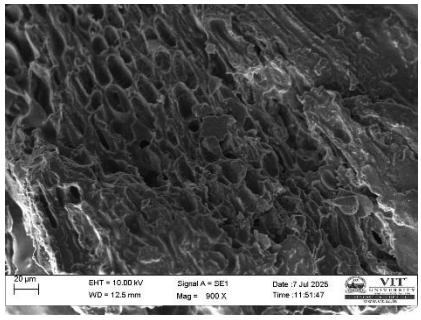
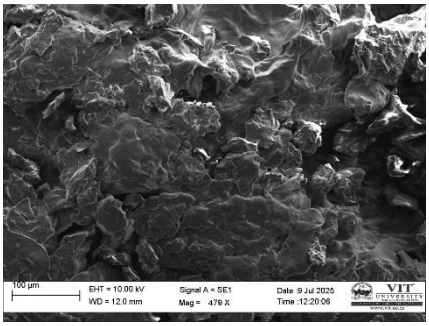
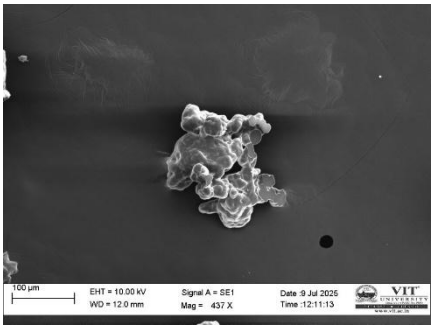
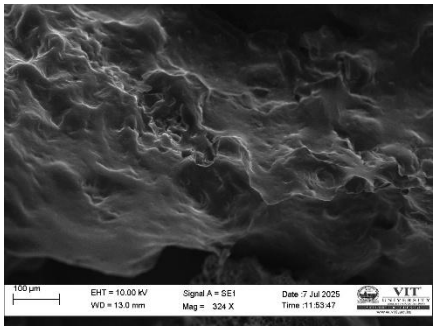
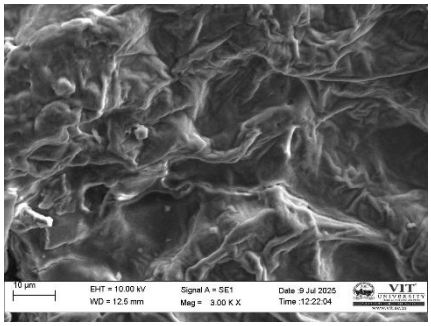
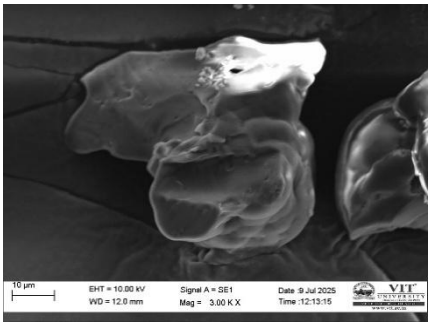
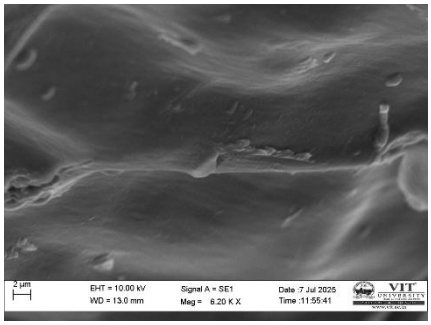
Mineral contents are expressed as mean ± standard deviation (SD) of triplicate determinations (n = 3). Values within the same row followed by different superscript letters indicate significant differences at $p < 0.05$ as determined by one-way ANOVA and Tukey's HSD test. Observed variations in mineral concentrations among samples may result from dehydration effects, processing steps, and formulation differences. ND: not detected.

3.5 Scanning electron microscopy

The surface structure of the West Indian cherry powders obtained by different drying methods is presented in Figure 4. Figure 4A illustrates the surface structure of the powder produced using the hot-air oven drying method. The structure displays highly deformed, uneven, and wrinkled surfaces. Some parts of it are consolidated into thick, rough plates, while other parts exhibit porous surfaces with marked folds. These features could be related to the mechanism of hot-air drying, which implies the removal of moisture from the material via convection. The process typically involves a gradual dehydration of the product under the influence of heat and air flow, which could lead to a partial contraction of the fruit tissue.

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a - Hot-air oven-dried	b -Spray-dried powder	c - Freeze-dried powder
		
		
		

458

459 **Fig 4.** Scanning electron micrographs showing surface morphology of West Indian Cherry powders
460 produced by different drying methods. (a) Hot-air-dried (HD) powder exhibiting compact, irregular, and
461 collapsed structures. (b) Spray-dried (SD) powder showing predominantly spherical particles with smooth
462 surfaces and slight indentations. (c) Freeze-dried (FD) powder displaying a highly porous, sponge-like
463 microstructure with minimal aggregation. All images were captured at the indicated magnifications.

Figure 4B represents the spray-dried acerola powder, which is characterized by an uneven surface structure with rounded and aggregated fragments. Some parts of the surface are smooth, while others are highly swollen or broken. Overall, the structure of this sample appears to be relatively loose, with several cavities visible on the surface of the particles. This could result from the specific mechanism of spray drying, which is based on the evaporation of water from the fine mist of the liquid feedstock. Depending on the properties of the feed solution and process conditions, various defects such as hollow structures, cracks, and wrinkles could be observed in the final product [28]. This implies that its feedstock was subjected to air heating followed by the separation of dry particles and exhaust gases. The least deformed surface structure was observed for the freeze-dried acerola powder Figure 4C. Overall, the structure appeared to be highly cellular, with multiple pores, which was probably caused by the sublimation of the ice from the frozen material. Such a defect could be related to the properties of the acerola puree, which is a highly cellular tissue. Upon conventional freezing, the water contained in the cells freezes into ice crystals, which, upon sublimation, leave behind characteristic voids in the cell walls. A similar structure was reported for freeze-dried samples [26]. In particular, the freeze-drying of sweet cherry was found to be more efficient at preserving the total anthocyanin content, phenolic compounds, and flavonoids compared to other conventional drying procedures [33]. At the same time, the convective drying of sweet cherry was more effective at maintaining total phenolic and flavonoid contents than freeze-drying. Similar results were also described for the osmotic dehydration of sweet cherry, which led to a significant darkening of the sample surface, as compared to the control. On the contrary, the freeze-dried product exhibited a higher degree of lightness and better preservation of its visual appearance [34].

The visual data obtained from the SEM microphotographs showed that the hot-air oven drying resulted in the most significant modifications of the surface structure of the initial acerola puree. On the contrary, the freeze-drying method preserved the majority of the cellular structures of the fruit tissue, which might positively impact the rehydration properties and extractability of the final powder. Energy-dispersive X-ray (EDX) analysis confirmed the presence of major elements, including carbon, oxygen, potassium, calcium, and magnesium, in all powder samples. The elemental distribution patterns were consistent with the mineral composition obtained from chemical analysis, supporting the reliability of the mineral profiling results.

Conclusion

This study presents a detailed evaluation of the physicochemical composition, antioxidant properties, antinutritional properties, mineral composition, and microstructure of West Indian Cherry (*Malpighia emarginata*) pulp and its powders dried using various methods. The results prove that West Indian Cherry is a nutritious fruit with high antioxidant properties, which makes it a useful functional food and nutraceutical constituent. Drying also greatly impacted the composition and properties of the fruit primarily because of moisture loss, structural changes of the matrix, processing conditions, and the addition of carrier agents in powdery sprays and freeze-dried powder. The dehydration method and formulation had a strong effect on variations in proximate composition, bioactive compounds, and antioxidant activity. The freeze-drying method was chosen as one of the methods that yielded the best quality of powders produced, such as low moisture content, porous structure, and preservation of antioxidants and minerals. Spray drying

produced powders that were highly soluble and had other desirable properties, such as sugar, as opposed to hot-air drying, which led to high structural destruction and increased losses of nutrients because of heat and mass transfer constraints. In general, the experiment proves that various drying procedures produce powders with different quality profiles that are to be chosen depending on the purpose of their use in foods or other functional activities and not by merely trying to find the best one. Standardized compositional reporting, stability of storage and bio accessibility of bioactive compounds, and performance of such powders in real food systems should be researched in the future to allow these powders to be used effectively as industrial products.

Authors contribution statement

Harini Palani: Visualization, Formal analysis, Writing – original draft, Writing – review & editing, Methodology, Conceptualization, Investigation. Amrita Halder and Mangalambika Balaji: Investigation, Conceptualization, Visualization, Methodology, Formal analysis, Writing – original draft. Utpal Das and Sandeep Singh Rana: Supervision, Investigation, Validation.

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Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Declaration of competing interests

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval and consent to participate

The collection and use of plant material in this study followed relevant institutional, local, and national guidelines and regulations. The West Indian cherry (*Malpighia emarginata*) fruits were collected from cultivated plants maintained in the fruit orchard of VIT School of Agricultural Innovations and Advanced Learning (VAIAL), Vellore Institute of Technology, Vellore, Tamil Nadu, India. The plants were propagated through semi-hardwood stem cuttings and maintained under cultivated conditions. No wild plant populations or protected or endangered plant species were involved. No specific collection permits or licences were obtained for this study. This study did not involve human participants or animals. Ethics approval and consent to participate.

Consent for publication

Not applicable.

ORCID ID

Harini Palani: https://orcid.org/0009-0004-1989-526X

Amrita Halder: https://orcid.org/0009-0002-9160-5234

Mangalambika Balaji: https://orcid.org/0009-0009-0289-9076

Utpal Das: https://orcid.org/0000-0002-2618-0287

Sandeep Singh Rana: https://orcid.org/0000-0001-9875-692X

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