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Tropical fruit peels as functional food ingredients: unlocking antioxidant and anti-glycation potential through innovative drying

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Introduction: The upcycling of food waste into natural sources of functional food ingredients presents a sustainable strategy to reduce environmental pollution while adding value to agro-industrial byproducts. This study evaluated the impact of different drying methods on the extraction of phytochemicals with antioxidant and anti-glycation activities from tropical fruit peels.

Methods: The peel samples of *Carica papaya*, *Citrus limon*, *Hylocereus polyrhizus*, *Musa acuminata*, and *Persea americana* were dried with four different methods, namely freeze-drying, microwave drying, hot air oven drying, and microwave-assisted hot air oven drying. The moisture content, browning index, total phenolics, flavonoids, tannin, polysaccharides, ascorbic acid equivalents, reducing potential, radical scavenging, and anti-glycation activities of the dried peel samples were quantified with colorimetric method and compared with their fresh counterparts via chemometric analysis.

Results and discussion: The drying process significantly enhanced ($p < 0.05$) the antioxidant and anti-glycation potential of fruit peels by at least 67.3 and 15.2%, respectively, when compared to fresh counterparts. Among the four drying methods, hot air oven drying produced the highest browning index in *P. americana* and *M. acuminata* samples. Microwave-assisted hot air oven drying yielded the greatest amounts of total phenolics and polysaccharides in *C. papaya*, while microwave drying maximized antioxidant and anti-glycation activities in *H. polyrhizus*. Freeze-drying preserved the highest ascorbic acid equivalents in *C. limon* and achieved the highest levels of polyphenols and ascorbic acid equivalents in *M. acuminata*. Principal component analysis revealed that fruit species and drying techniques accounted for 74.6 and 13.5% of the total variation in bioactivity, respectively. This study showed that, when properly processed, dried fruit peels have significant potential as natural functional ingredients for food and nutraceutical applications. It emphasizes the key role of drying not just as a preservation method, but as a strategy for enhancing functional properties.

KEYWORDS

advanced glycation end product, ascorbic acid, browning, food waste, nutraceutical, phenolic, phytochemical, polysaccharide

1 Introduction

Food waste that includes both edible and inedible components of discarded foods remains a pressing global issue. An estimated 1.05 billion tons of food are discarded annually, thereby contributing to environmental issues such as climate change, loss of biodiversity and greenhouse gas emissions (United Nations Environment Programme, 2024). Fruit and vegetable by-products are among the primary contributors to this waste stream, accounting for approximately 81% of the total fruit and vegetable waste generated (United Nations Environment Programme, 2024). Of these, fruit peels are routinely discarded as waste during processing, despite being rich in functional compounds (Rifna et al., 2021). Therefore, the recovery of these compounds is particularly significant given that oxidative stress is increasingly recognized as a critical factor in the development of chronic diseases such as diabetes mellitus and cardiovascular disorders, partly due to the excessive generation of free radicals and the accumulation of advanced glycation end products (Lim et al., 2025). Although synthetic antioxidants or anti-glycation agents like aminoguanidine have shown efficacy in reducing oxidative stress, their potential cytotoxicity and adverse side effects have raised safety concerns (Zhao et al., 2022). In this context, upcycling fruit peel waste into an alternative natural source of antioxidant and anti-glycation agents offers a promising strategy to replace the harmful synthetic compounds. This approach not only supports the United Nations Sustainable Development Goal 12.3, which aims to halve global food wastes per capita by 2030 through strategies such as redistribution, upcycling, and recycling to maximize food value, but also aligns with wider sustainability efforts and circular economy principles (Melini et al., 2020).

Among the many tropical fruit wastes, the peels of *Persea americana* Mill., *Musa acuminata* Colla, *Hylocereus polyrhizus* (F.A.C. Weber) Britton & Rose, *Citrus limon* (L.) Osbeck, and *Carica papaya* L. are particularly rich in bioactive compounds. Peel samples of *P. americana*, comprising 18% of the total fruit weight, exhibit higher antioxidant potential than the pulp due to their higher concentrations of procyanidins and flavonoids (Vega-Alvarez et al., 2024). In the case of *M. acuminata*, whose peel contributes to approximately 36 million tons of waste annually, the peels are particularly rich in phenolic compounds, anthocyanins, and carotenoids (Zaini et al., 2022). Similarly, peels of *H. polyrhizus* demonstrate potent antioxidant activity, largely attributed to betacyanins, a class of red pigments with promising applications as natural food preservatives and colorants (Chew and King, 2019; Khoo et al., 2022). *C. limon* peels, which are abundant in phenolic compounds and ascorbic acid, also represent a valuable functional ingredient for food applications (Mazi and San, 2023; Singh et al., 2020). Although *C. papaya* peels account for a smaller proportion of the fruit (~12%), they are particularly rich in phenolics and flavonoids, displaying stronger free radical scavenging activity than both the pulp and seeds (Pathak et al., 2018; Zhou et al., 2023).

Although the said fruit peel varieties are well-known for their bioactive compounds, their high moisture content makes them vulnerable to microbial contamination and enzymatic degradation (Vega-Alvarez et al., 2024). Drying is a fundamental postharvest processing technique widely used to extend the shelf life of fresh produce by reducing its moisture content and inhibiting microbial growth (Guclu et al., 2022). However, different drying methods may significantly impact the stability of heat-sensitive functional compounds such as polyphenols and ascorbic acid, which are susceptible to degradation under suboptimal drying

conditions (Ng et al., 2020). Previous studies have shown that both the method and parameters of drying markedly influence the stability and extractability of bioactive compounds (Rad et al., 2025; Singh et al., 2023). Among the commonly used drying methods, freeze-drying (FD) stands out for its ability to operate at low temperatures, which helps minimize structural shrinkage, preserve heat-sensitive compounds, and maintain color quality (Hu D. et al., 2023). In contrast, although microwave drying (MD) offers rapid dehydration of samples, the uneven internal heating may result in localized scorching and compound degradation (Nurhaslina et al., 2022). Microwave-assisted hot air oven drying (MHD) is a hybrid drying technique that combines the drying efficiency of MD with the uniformity of conventional hot air oven drying (HD). This method has previously demonstrated promising results in preserving polyphenols and antioxidant activity (Ng et al., 2020).

The impact of different drying methods on the extraction of bioactive compounds from fruit peels varies considerably among the fruit varieties. A systematic evaluation of the impact of drying on both antioxidant and anti-glycation activities across multiple fruit peel species has yet to be fully explored. This study aims to evaluate the influence of four distinct drying methods on the extraction of bioactive compounds exhibiting antioxidant and anti-glycation properties in selected five tropical fruit peels. It is hypothesized that optimized drying conditions could enhance the recovery of bioactive compounds with health-promoting benefits.

2 Materials and methods

2.1 Chemical and reagents

Absolute ethanol and hydrochloric acid were purchased from Merck (Darmstadt, Germany). Sodium acetate trihydrate, sodium carbonate, 2,4,6-tripyridyl-s-triazine (TPTZ), iron (II) sulphate heptahydrate, polyvinylpyrrolidone (PVPP), aluminum chloride, quercetin, L-ascorbic acid, ascorbate oxidase (EC 1.10.3.3), phosphate buffer saline (PBS), bovine serum albumin (BSA), trichloroacetic acid (TCA), 1 M glucose, Folin-Ciocalteu reagent and gallic acid were purchased from Sigma-Aldrich (St. Louis, MO, USA). Iron (III) chloride hexahydrate, glacial acetic acid, starch, phenol crystal, sulphuric acid, and potassium acetate were purchased from R&M Chemicals (Selangor, Malaysia). 2,2-diphenyl-1-picrylhydrazyl (DPPH) and tannic acid were purchased from respective TCI (Tokyo, Japan) and Friedemann Schmidt (Germany). Analytical-grade chemicals and reagents were used in this study.

2.2 Fruit peel samples collection

The fruit samples of *P. americana*, *M. acuminata*, *H. polyrhizus*, *C. limon* and *C. papaya* were sourced from a local market in Semeniyh, Malaysia. To minimize variability in the experimental replicates, only fruit samples that were uniformly ripe, intact in structure, and free from visible damage were included in this study. The fruit peels were manually separated from the fruits and sectioned into uniform pieces measuring approximately 3 cm × 1 cm.

2.3 Drying treatments

The fruit peel samples in triplicate were subjected to four distinct drying treatments: freeze drying (FD), microwave drying (MD),

microwave-assisted hot air oven drying (MHD) and conventional hot air oven drying (HD). Drying procedures were conducted as previously described by Ng et al. (2020) with minor modifications. For FD, fruit peel samples were initially frozen at -30°C for 24 h and subsequently dehydrated in a freeze dryer (Martin Christ, Osterode am Harz, Germany) at -50°C under a vacuum of 0.025 mbar for 48 h. MD was carried out with a 900 W microwave oven under mid-low power setting (model: EMS3087X, 2,450 MHz; Electrolux AB, Stockholm, Sweden). HD was performed at $55 \pm 3^{\circ}\text{C}$ with an air velocity of 1.45 m/s using a conventional hot air oven (Memmert GmbH & Co. KG, Schwabach, Germany). The MHD method combined 3 min of MD with subsequent HD using the similar parameter mentioned above. With the exception of FD, the moisture content of the peel samples was systematically monitored throughout the drying process by periodic weighing until a constant mass was attained.

2.4 Extraction of fruit peel samples

All dried peel samples were finely ground into powder using a laboratory grinder and filtered through an 80-mesh sieve (177 μm) to obtain a uniform particle size. The powdered samples were extracted with distilled water (1:10 w/v) in a shaking water bath at $0.05 \times g$ and 80°C for 20 min. The resulting extracts were centrifuged at $4700 \times g$ for 10 min at 4°C . Fresh peel samples used as controls were similarly homogenized with distilled water at a 1:10 (w/v) ratio and centrifuged under identical conditions. All aqueous fruit peel extracts were subsequently lyophilized and stored at -20°C in the dark until further analyses.

2.5 Moisture content

The moisture content of peel sample was measured using the AOAC official gravimetric method 964.22 (AOAC International, 1995). The percentage of moisture content (%) was derived with the following equation:

$$\text{Moisture content (\%)} = \frac{\text{fresh sample weight} - \text{dry sample weight}}{\text{fresh sample weight}} \times 100$$

2.6 Browning index

The degree of browning in peel sample was quantified as described previously by Ng et al. (2020). Briefly, 1 g of each dried extract was incubated in 25 mL of 20% (v/v) acetic acid for 24 h at 25°C on an incubator shaker (200 rpm). The mixtures were then centrifuged at $4700 \times g$ for 10 min, and the supernatant was collected for spectrophotometric analysis at 420 nm, using 20% acetic acid as the blank.

2.7 Total phenolic content

The total phenolic content (TPC) in fruit peel sample was measured using the Folin–Ciocalteu assay (Luen et al., 2025). Briefly, fifty μL of 10 mg/mL of sample extract was mixed with 50 μL of Folin–Ciocalteu reagent (10% v/v) and incubated in the dark for 3 min. Subsequently, the reaction mixture was added with 100 μL of sodium carbonate (10% w/v) and incubated for 60 min before being measured at 750 nm using a microplate spectrophotometer. Gallic acid (0–100 $\mu\text{g/mL}$) served as the

calibration standard. The TPC was reported as mg gallic acid equivalent per 100 g dry weight (mg GAE/100 g DW).

2.8 Tannin content

The tannin content in fruit peel sample was measured using the PVPP precipitation method (Lim et al., 2026a). Briefly, a mixture of 500 μL sample extract (10 mg/mL) and 10 mg PVPP was incubated at 4°C for 15 min, then centrifuged at $3000 \times g$ for 10 min at room temperature to precipitate the tannin. Fifty microliter of PVPP-treated supernatant was analysed using similar Folin–Ciocalteu method described in Section 2.7, with tannic acid (0–100 $\mu\text{g/mL}$) serving as the calibration standard. Tannin content was determined by subtracting the TPC value of the PVPP-treated extract from that of the PVPP-untreated (control) extract. The tannin content was reported as mg tannic acid equivalent per 100 g dry weight (mg TAE/100 g DW).

2.9 Flavonoid content

The flavonoid content in the fruit peel sample was quantified using the aluminum chloride colorimetric assay (Ho et al., 2022). Briefly, a mixture of 25 μL sample extract (10 mg/mL), 10 μL aluminum chloride (10% w/v), 10 μL of 1 M potassium acetate, 75 μL ethanol, and 140 μL distilled water was incubated in the dark for 30 min. The absorbance of the mixture was captured at 415 nm with quercetin (0–250 $\mu\text{g/mL}$) serving as the calibration standard. The flavonoid content was reported as mg quercetin equivalent per 100 g dry weight (mg QE/100 g DW).

2.10 Polysaccharides

The polysaccharide content in fruit peel sample was assessed via the phenol-sulphuric acid method (Tan et al., 2026). Briefly, fifty μL of sample extract (10 mg/mL) was mixed with 150 μL of 98% sulphuric acid and 30 μL phenol solution (5% w/v) prior to incubation at 90°C for 5 min. The mixture absorbance was measured at 490 nm with starch (0–1.0 mM) serving as the calibration standard. The polysaccharide content was reported as mg polysaccharide equivalent per 100 g dry weight (mg PE/100 g DW).

2.11 Ascorbic acid equivalents (AAE)

The AAE in fruit peel samples were measured based on the ferric-reducing antioxidant power-ascorbic acid (FRASC) method (Ng and Kuppusamy, 2019). Briefly, in a paired treatment, one hundred microliter of sample extracts were incubated with or without ascorbate oxidase (EC 1.10.3.3) (4 IU/mL) in distilled water at 37°C for 5 min. The change in absorbance of the treated extracts was measured using the ferric reducing antioxidant power (FRAP) assay at 593 nm. The amount of AAE present in the sample peel extracts was determined from the differences in FRAP values between the ascorbate oxidase-treated and water-treated samples. L-ascorbic acid (0–150 $\mu\text{g/mL}$) was used as the calibration standard and the ascorbic acid was reported as mg ascorbic acid equivalents per 100 g dry weight (mg AAE/100 g DW).

2.12 Ferric reducing antioxidant power (FRAP)

The FRAP activity of fruit peel sample was determined using a TPTZ-based assay (Ho et al., 2022). Briefly, 300 μL of the FRAP

reagent was mixed with 10 μL of sample extract (10 mg/mL) and incubated for 4 min in the dark. The mixture absorbance was measured at 593 nm with iron (II) sulphate (0–1,000 μM) serving as the calibration standard. The FRAP value was reported as mg iron (II) equivalent per 100 g dry weight (mg Fe^{2+} /100 g DW).

2.13 DPPH radical scavenging activity

The DPPH radical scavenging potential of fruit peel sample was measured spectrophotometrically (Luen et al., 2025). Briefly, working DPPH reagent (100 μM) was prepared by dissolving DPPH radicals in ethanol at room temperature. One hundred ninety-five microliter of DPPH reagent was mixed with 5 μL of sample extract (10 mg/mL) and incubated in the dark. The change in absorbance of the reaction mixture was monitored at 515 nm using a microplate spectrophotometer over a 120 min period, with measurements recorded at 15 min intervals. The absorbance at 60 min, corresponding to the stabilization of DPPH radicals, was used to calculate the DPPH radical scavenging activity. L-ascorbic acid (0–1,000 μM) was used as the calibration standard. The DPPH radical scavenging potential was reported as mg ascorbic acid equivalent per 100 g dry weight (mg AAE/100 g DW).

2.14 Anti-glycation activity

The anti-glycation activity of fruit peel sample was quantified with a BSA-glucose system (Tan et al., 2026). Briefly, a reaction mixture containing 4 mg BSA, 400 μL of 50 mM sodium phosphate buffer, 80 μL of 1 M glucose, and 20 μL sample extract (10 mg/mL) was incubated at 80 $^{\circ}\text{C}$ for 7 days. The reaction was terminated by adding 100% TCA into the mixture, followed by centrifugation at $3000 \times g$ for 10 min at room temperature. The AGE-BSA precipitate was dissolved in PBS, and the fluorescence intensity was recorded at an excitation and emission wavelengths of 385 nm and 415 nm, respectively. Aminoguanidine (0–400 μg) was used as the calibration standard. The sample anti-glycation activity was reported as mg aminoguanidine equivalent per 100 g dry weight (mg AG/100 g DW).

2.15 Antioxidant index

The antioxidant index (AI) is a calculated composite score derived from the values of each bioassay (Ho et al., 2022). The highest observed value in each bioassay in this study was considered as 100 while the remaining values were converted in numerical scales into relative percentage values. These normalized values were then used to calculate the overall AI (%) for each sample, allowing comparison across both fresh and dried fruit peel samples. Based on the AI scores, peel samples were classified into four categories: very high (76–100%), high (51–75%), moderate (26–50%), and low (0–25%) AI species.

2.16 Statistical analysis

All data were analyzed using GraphPad Prism 8 and XLSTAT 2014, with results expressed as mean $\pm$ standard deviation ($n = 3$). One-way analysis of variance (ANOVA) with Tukey's *post hoc* test was used to analyze the differences in mean values among the different sample groups. Pearson's linear correlation and regression analyses were applied to evaluate the relationships between the measured variables. Principal component analysis (PCA) was applied to examine the contribution of investigated variables to the antioxidant and

anti-glycation activities variation across the whole dataset. Differences were considered statistically significant at $p < 0.05$.

3 Results and discussion

3.1 Moisture content

Table 1 depicts *H. polyrhizus* with the highest moisture content (~90%) across all four drying methods, followed by *C. papaya*, *M. acuminata*, *P. americana*, and *C. limon*. The moisture content of *H. polyrhizus* remained stable across all four drying methods and was consistent with the previously reported value at 91.2% (Chia and Chong, 2015). Notably, the FD peel samples of *M. acuminata* displayed the lowest moisture content across all drying treatments. This finding agreed with a previous study by Vu et al. (2016), who demonstrated that FD yielded lower moisture content in plant samples when compared to the MD samples. In contrast, *P. americana*, *M. acuminata*, and *C. limon* generally displayed lower moisture values while *C. papaya* showed higher moisture content than those reported in previous studies (Aboul-Enein et al., 2016; Babiker et al., 2021; Mazi and San, 2023; Pathak et al., 2018). These variations are likely attributable to differences in fruit variety, ripening stage, cultivation conditions, and drying parameters (Wani and Uppaluri, 2022).

3.2 Drying duration and browning index

From Table 1, the drying duration for the selected four drying methods across all fruit peel samples decreased in the following order: FD > HD > MHD > MD. The volumetric heating characteristic of MD facilitates rapid internal vaporization and significantly shortens the drying duration. On the contrary, the relatively low operating temperature and pressure in the FD resulted in prolonged drying duration (Chew and King, 2019). The browning index of dried fruit peel samples, ranging from 0.19 to 1.18, showed a decreasing trend in the following order: *H. polyrhizus* > *C. limon* > *P. americana* > *C. papaya* > *M. acuminata* (Table 1). The HD samples of *P. americana* (0.92) and *M. acuminata* (0.40) exhibited the highest browning indices among their dried counterparts. This was likely due to the extended exposure duration to heat and oxygen during HD, which facilitated polyphenol oxidation and non-enzymatic browning reactions (Hu J. et al., 2023; Huang et al., 2024). In contrast, most FD samples of *P. americana* and *C. papaya* displayed lower browning indices than their other dried counterparts (Table 1), a difference that was visually apparent in the lighter peel colours (Figure 1). However, FD samples of *H. polyrhizus* (1.18) and *C. limon* (1.11) showed higher browning indices than the other dried counterparts. This finding deviates from previous studies by Guclu et al. (2022), which reported minimal browning in FD-treated samples due to the low-temperature and vacuum drying conditions. The increased browning observed in both FD-treated *H. polyrhizus* and *C. limon* suggests that enzymatic browning may have occurred during pre-processing or the initial stages of drying, with FD treatment preserving the pre-formed brown pigments (Hu D. et al., 2023). Additionally, the high sugar and ascorbic acid content in *C. limon* may have facilitated the formation of furfural under acidic conditions, which could be retained during FD due to the minimal thermal degradation associated with this drying method (Mazi and San, 2023).

TABLE 1 Drying duration, moisture content, and browning index in dried fruit peel samples.

Fruit samples	Drying duration (min)	Moisture content (%)	Browning index
<i>Persea americana</i>			
FD	(2880.00 ± 0.00) ^c	(77.42 ± 1.21) ^a	(0.61 ± 0.03) ^a
MD	(16.25 ± 0.00) ^a	(77.73 ± 0.23) ^a	(0.79 ± 0.02) ^b
MHD	(510.00 ± 0.00) ^b	(79.42 ± 0.09) ^b	(0.77 ± 0.05) ^b
HD	(1110.00 ± 0.00) ^d	(78.15 ± 0.20) ^{ab}	(0.92 ± 0.06) ^c
<i>Musa acuminata</i>			
FD	(2880.00 ± 0.00) ^c	(80.45 ± 1.02) ^a	(0.26 ± 0.01) ^b
MD	(9.29 ± 0.74) ^a	(82.81 ± 0.26) ^b	(0.24 ± 0.00) ^b
MHD	(506.25 ± 48.02) ^b	(86.83 ± 0.52) ^c	(0.19 ± 0.00) ^a
HD	(1110.00 ± 0.00) ^d	(85.82 ± 0.41) ^c	(0.40 ± 0.00) ^c
<i>Hylocereus polyrhizus</i>			
FD	(2880.00 ± 0.00) ^c	(89.55 ± 0.86) ^{ab}	(1.18 ± 0.03) ^d
MD	(15.22 ± 0.70) ^a	(89.21 ± 0.76) ^a	(0.99 ± 0.05) ^c
MHD	(549.00 ± 25.10) ^b	(90.30 ± 0.22) ^b	(0.74 ± 0.04) ^a
HD	(1110.00 ± 0.00) ^d	(89.44 ± 1.06) ^{ab}	(0.84 ± 0.02) ^b
<i>Citrus limon</i>			
FD	(2880.00 ± 0.00) ^c	(74.68 ± 1.04) ^{ab}	(1.11 ± 0.04) ^d
MD	(13.88 ± 0.14) ^a	(73.14 ± 0.49) ^a	(0.44 ± 0.02) ^b
MHD	(555.00 ± 0.00) ^b	(75.89 ± 0.22) ^b	(0.56 ± 0.02) ^c
HD	(1110.00 ± 0.00) ^d	(74.68 ± 0.88) ^{ab}	(0.32 ± 0.02) ^a
<i>Carica papaya</i>			
FD	(2880.00 ± 0.00) ^c	(85.70 ± 1.03) ^a	(0.60 ± 0.04) ^a
MD	(9.50 ± 0.53) ^a	(86.93 ± 0.50) ^b	(0.79 ± 0.03) ^c
MHD	(528.75 ± 22.50) ^b	(88.60 ± 0.34) ^c	(0.81 ± 0.02) ^c
HD	(1110.00 ± 0.00) ^d	(87.95 ± 0.10) ^c	(0.70 ± 0.02) ^b

Values were expressed as mean ± standard deviation ($n = 3$). Different superscript lowercase letters within the same column indicate statistically significant differences ($p < 0.05$) among samples of the same fruit species.

3.3 Total phenolic, flavonoid, and tannin content

Majority of the drying treatments significantly ($p < 0.05$) increased the TPC, flavonoid, and tannin contents in fruit peel samples when compared to the fresh samples, except for a few cases involving tannin content, as shown in Table 2. TPC increased by 185 to 1,416%, while tannin and flavonoid levels rose by 54 to 1869% and 220 to 1,524%, respectively. These substantial increases were likely attributed to the disruption of the intracellular matrix during the drying process, which facilitated the liberation of bound phenolic compounds into more extractable forms (Rad et al., 2025). Among the dried peel extracts, *C. limon* exhibited the most significant increase in flavonoid content, ranging from 900 to 1,524%. In contrast, *H. polyrhizus* showed the greatest increase in both tannin (29–1869%) and TPC, with values ranging from 1,073 to 1,416%. These variations indicated that the response of fruit peel samples to drying was strongly influenced by the chemical characteristics of individual bioactive compounds and the structural integrity of the fruit peel matrix (Saifullah et al., 2019). It was noteworthy that both fresh and dried *P. americana* consistently displayed exceptionally high phytochemical levels, exceeding those in the other fruit peel samples. This aligns with Akan (2021), who

reported higher TPC and flavonoid content in both fresh and dried *P. americana* peels relative to *M. acuminata* and *C. papaya*. Suleria et al. (2020) also reported the highest tannin content in *P. americana* peel among the selected tropical fruit peels, including *M. acuminata* and *H. polyrhizus*. The enhanced phytochemical profile of *P. americana* dried samples was likely due to its high concentration of hydroxycinnamic acids, procyanidins, and other phenolic compounds (Akan, 2021).

The TPC of dried fruit peel samples varied substantially, ranging from 287.88 mg GAE/100 g DW to 12577.16 mg GAE/100 g DW. Among the selected fruit varieties, *P. americana* showed the highest TPC, followed by *C. limon*, *M. acuminata*, *C. papaya*, and *H. polyrhizus*. This finding concurs with a previous study by Suleria et al. (2020) reporting a similar trend in TPC. Notably, FD-treated *C. limon* recorded higher TPC ($p < 0.05$) than the other drying methods and this finding concurred Tekgöl and Baysal (2018). In contrast, HD-treated *P. americana* recorded the highest TPC (12577.16 mg GAE/100 g DW) which was statistically comparable to its MHD counterparts (12287.04 mg GAE/100 g DW). This pattern aligned Akan (2021) who suggested the thermal exposure in HD may stimulate the release of bound phenolic compounds in *P. americana*, thus enhancing their extractability. This was further supported by another study,

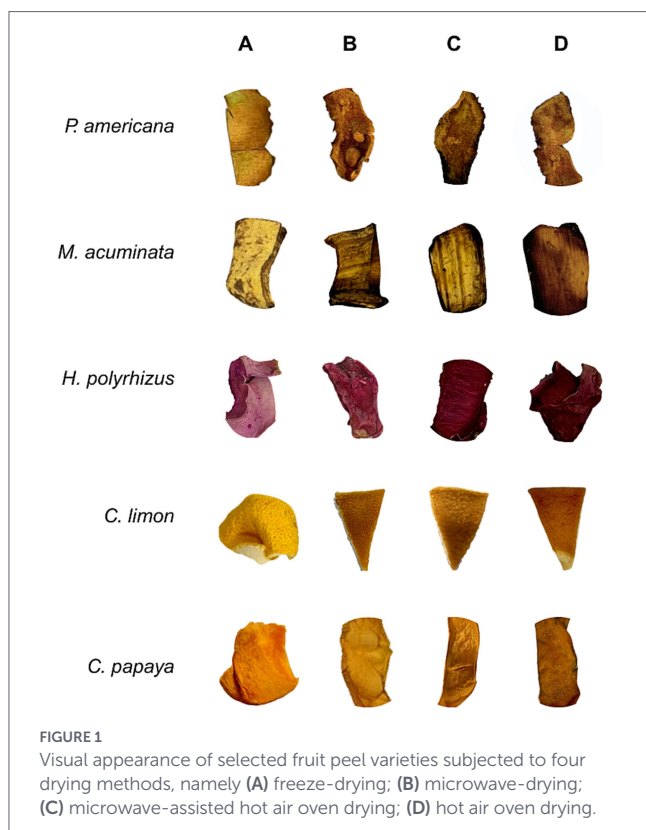


FIGURE 1

Visual appearance of selected fruit peel varieties subjected to four drying methods, namely (A) freeze-drying; (B) microwave-drying; (C) microwave-assisted hot air oven drying; (D) hot air oven drying.

which demonstrated that the optimal range of drying temperature for phenolic content extraction from *P. americana* was 45–75 °C (Figuerola et al., 2018). Similarly, HD-treated *H. polyrhizus* also showed the highest TPC among its dried counterparts. The increased TPC in HD-treated peel samples likely arise from the cleavage of phenolic-sugar glycosidic bonds, which enhanced the availability of free phenolic groups that were reactive towards the Folin–Ciocalteu reagent (Chew and King, 2019). Interestingly, *C. papaya* demonstrated a distinct behavior, with MHD samples showing the highest TPC, followed by MD, FD, and HD samples. This may be attributed to the microwave-induced disruption of fruit peel cellular matrix, which facilitates phenolic release. In addition, the uniform heat distribution from HD helps prevent localized overheating that might occur with MD alone (Ramírez-Pulido et al., 2021). The synergistic effect of MHD appears to enhance phenolic extractability more effectively than either MD or HD alone, consistent with previous findings that microwave-assisted pre-treatment prior to hot air drying improved the retention of phenolic compounds (Ozkan-Karabacak et al., 2023).

The tannin content in the dried peel samples varied from 5 mg TAE/100 g DW to 11,000 mg TAE/100 g DW, following this descending order: *P. americana* > *M. acuminata* > *C. limon* > *C. papaya* > *H. polyrhizus* (Table 2). Among the dried peel samples, HD samples of *P. americana*, *C. limon*, *C. papaya*, and *H. polyrhizus* exhibited the highest tannin content, surpassing that of the other drying treatments. Although FD with its low-temperature conditions, is typically considered superior for preserving polyphenols (Tekgül and Baysal, 2018), the elevated tannin levels in HD-treated samples could be partly due to the thermal disruption of the fruit peel cellular matrix, which facilitates the release of bound tannins (Upa et al., 2024). Furthermore, the moderate drying temperature (55 °C) used in this study likely provided sufficient energy to enhance the liberation of tannins while remaining below the threshold for thermal hydrolysis and degradation

that typically occur at high temperature (Upa et al., 2024). Additionally, the greater thermal stability of condensed tannins, particularly proanthocyanidins, which possess complex aromatic structures, likely contributed to their retention during HD (Zubia et al., 2023). Although the MHD samples of *H. polyrhizus* (5.00 mg TAE/100 g DW) exhibited tannin content similar to that of the fresh samples (3.86 mg TAE/100 g DW), the potential cross-reactivity of PVPP with certain flavonoids may have contributed to an underestimation of the actual tannin levels (Ng et al., 2020).

In contrast to TPC and tannin, flavonoid content of dried peel samples demonstrated a narrower concentration range between 22.22 mg QE/100 g DW and 477.99 mg QE/100 g DW (Table 2). *P. americana* showed the highest flavonoid content, followed by *C. papaya*, *C. limon*, *H. polyrhizus*, and *M. acuminata*. Notably, *P. americana* exhibited a distinct pattern of flavonoid content when compared to its TPC and tannin profiles, with FD-treated samples showing the highest flavonoid content, significantly surpassing all other drying methods. The greater thermal sensitivity of flavonoids than non-flavonoid phenolics could have explained the above observation (Kittibunchakul et al., 2023). Interestingly, MD- and MHD-treated *H. polyrhizus* yielded higher flavonoid content than its FD and HD counterparts. This finding could be driven by MD-induced cell wall rupture, which creates porous microstructures that enhance the extractability of intracellular flavonoids (Hu D. et al., 2023). Moreover, electromagnetic drying of MD induces rapid volumetric heating from the interior to the exterior, thereby minimizing prolonged surface heating and reducing overall drying time, which in turn helps preserve the flavonoids (Bassey et al., 2023). In contrast to an earlier finding by Annegowda et al. (2013), the highest flavonoid content was observed in HD samples of *C. papaya* and *C. limon*. The effectiveness of HD in these samples could potentially be driven by the moderate drying temperatures applied, which facilitated the release of glycosylated flavonoids while effectively suppressing polyphenol oxidase activity, thereby limiting the enzymatic degradation (Papoutsis et al., 2017). Similar observations have been reported for citrus pomace, where mild HD drying temperature preserved flavonoids, while FD-induced pore formation during sublimation resulted in partial degradation of bioactive compounds such as the flavonoids (Li et al., 2023). It was notable that FD samples of *M. acuminata* consistently exhibited the highest levels of TPC, tannin, and flavonoid content when compared to the other drying methods (Table 2). This observation aligns with previous findings by Hu D. et al. (2023) and Rad et al. (2025), which highlighted the effectiveness of FD in preserving phytochemicals by minimizing heat and oxygen exposure, as well as reducing hydrolytic degradation through direct sublimation.

3.4 Polysaccharides

The polysaccharide content (Table 2) of fresh peel extracts ranged from 662.16 mg PE/100 g DW to 5329.65 mg PE/100 g DW, with *P. americana* demonstrating the highest value, followed by *C. limon*, *M. acuminata*, *C. papaya*, and *H. polyrhizus*. Upon drying, all peel samples showed a significant increment in polysaccharide content (1.9-fold to 20-fold) when compared to their respective fresh counterparts. Notably, *H. polyrhizus* showed the largest increase in polysaccharide content, with an 18- to 20-fold rise. This enhancement was likely due to the structural disruption of the cell wall matrix during the drying process that promoted the release and extractability of polysaccharides for quantification (Ma et al., 2018).

TABLE 2 Phytochemical content, polysaccharide, ascorbic acid, antioxidant and anti-glycation activities in both fresh and dried fruit peel samples.

Fruit samples	TPC (mg GAE/100 g DW)	Tannin (mg TAE/100 g DW)	Flavonoids (mg QE/100 g DW)	Polysaccharides (mg PE/100 g DW)	Ascorbic acid equivalents (mg AAE/100 g DW)	FRAP (mg Fe ²⁺ /100 g DW)	DPPH (mg AAE/100 g DW)	Anti-glycation (mg AG/100 g DW)
<i>Persea americana</i>								
Fresh	(2836.42 ± 13.65) ^a	(2656.84 ± 13.15) ^a	(81.76 ± 7.86) ^a	(5329.65 ± 34.96) ^a	(75.12 ± 1.63) ^a	(2071.23 ± 18.74) ^a	(4852.51 ± 27.36) ^a	(143.53 ± 80.01) ^a
FD	(10944.44 ± 275.14) ^c	(9731.29 ± 302.76) ^c	(477.99 ± 21.79) ^d	(24133.93 ± 156.14) ^d	(244.13 ± 21.51) ^c	(6164.67 ± 56.10) ^d	(13383.96 ± 217.92) ^c	(1626.11 ± 137.25) ^c
MD	(8083.33 ± 97.99) ^b	(6547.62 ± 100.67) ^b	(383.65 ± 10.89) ^c	(9946.22 ± 97.24) ^b	(197.18 ± 14.08) ^{bc}	(3465.49 ± 109.07) ^b	(8715.33 ± 129.55) ^b	(2043.30 ± 346.32) ^c
MHD	(12287.04 ± 162.76) ^d	(10751.70 ± 173.57) ^d	(358.49 ± 18.87) ^c	(19304.37 ± 349.32) ^c	(342.72 ± 21.51) ^d	(5938.19 ± 103.64) ^c	(14766.97 ± 295.52) ^d	(807.44 ± 260.13) ^b
HD	(12577.16 ± 391.23) ^d	(11000.00 ± 440.20) ^d	(289.31 ± 21.79) ^b	(19568.30 ± 68.52) ^c	(192.49 ± 40.66) ^b	(6260.85 ± 23.42) ^d	(17084.25 ± 305.99) ^e	(1824.66 ± 348.73) ^c
<i>Musa acuminata</i>								
Fresh	(95.68 ± 1.05) ^a	(16.91 ± 0.85) ^a	(6.67 ± 0.44) ^a	(3926.63 ± 201.46) ^a	(8.64 ± 0.59) ^a	(33.44 ± 0.78) ^a	(40.25 ± 8.04) ^a	(80.36 ± 17.62) ^{ab}
FD	(1205.25 ± 9.90) ^c	(216.67 ± 8.92) ^d	(34.57 ± 4.28) ^b	(31889.94 ± 262.59) ^b	(53.05 ± 3.25) ^d	(542.32 ± 19.31) ^c	(1323.69 ± 11.32) ^c	(107.89 ± 14.93) ^{bc}
MD	(925.62 ± 4.37) ^d	(185.67 ± 9.45) ^c	(22.22 ± 6.42) ^c	(41836.16 ± 248.63) ^d	(36.15 ± 4.30) ^c	(375.71 ± 17.62) ^d	(773.17 ± 12.51) ^d	(135.99 ± 10.25) ^{cd}
MHD	(824.24 ± 5.50) ^c	(147.33 ± 7.57) ^b	(22.22 ± 3.21) ^c	(34635.80 ± 335.22) ^c	(17.84 ± 2.93) ^b	(334.45 ± 8.34) ^c	(678.71 ± 16.55) ^c	(45.03 ± 18.59) ^a
HD	(287.88 ± 4.55) ^b	(26.00 ± 10.39) ^a	(26.54 ± 8.55) ^{bc}	(32417.81 ± 210.37) ^b	(12.68 ± 4.23) ^{ab}	(93.08 ± 15.38) ^b	(146.12 ± 11.70) ^b	(141.39 ± 8.45) ^d
<i>Hylocereus polyrhizus</i>								
Fresh	(44.75 ± 1.50) ^a	(3.86 ± 1.37) ^a	(10.19 ± 0.38) ^a	(662.16 ± 32.08) ^a	(3.76 ± 0.16) ^a	(23.58 ± 0.21) ^a	(21.58 ± 1.46) ^a	(18.55 ± 5.63) ^a
FD	(605.25 ± 15.78) ^c	(72.11 ± 11.74) ^c	(86.93 ± 15.85) ^b	(13256.99 ± 332.91) ^d	(27.70 ± 10.38) ^{bc}	(203.21 ± 6.20) ^c	(184.98 ± 12.91) ^b	(443.74 ± 35.85) ^b
MD	(634.44 ± 8.76) ^d	(48.33 ± 16.62) ^b	(149.02 ± 12.86) ^c	(11603.92 ± 325.88) ^b	(25.35 ± 2.44) ^b	(228.96 ± 37.47) ^c	(314.45 ± 15.00) ^d	(714.33 ± 63.28) ^c
MHD	(525.07 ± 4.84) ^b	(5.00 ± 3.46) ^a	(147.06 ± 16.05) ^c	(12974.53 ± 357.15) ^{cd}	(36.62 ± 9.24) ^{bc}	(174.36 ± 22.05) ^b	(228.07 ± 20.17) ^c	(642.32 ± 43.25) ^c
HD	(678.51 ± 9.09) ^c	(76.00 ± 6.56) ^c	(89.54 ± 11.98) ^b	(12391.10 ± 260.25) ^c	(44.13 ± 5.33) ^c	(179.63 ± 20.14) ^b	(234.26 ± 11.38) ^c	(340.68 ± 98.91) ^b
<i>Citrus limon</i>								
Fresh	(211.17 ± 1.44) ^a	(27.44 ± 0.64) ^a	(9.69 ± 0.58) ^a	(4014.60 ± 204.63) ^a	(6.85 ± 0.43) ^a	(67.70 ± 1.68) ^a	(33.85 ± 5.85) ^a	(99.26 ± 15.89) ^{bc}
FD	(1269.97 ± 7.45) ^c	(191.00 ± 12.49) ^b	(123.46 ± 5.66) ^c	(24467.32 ± 129.07) ^c	(406.57 ± 5.33) ^c	(692.79 ± 14.61) ^c	(872.97 ± 50.34) ^d	(143.95 ± 22.20) ^d
MD	(925.90 ± 11.16) ^b	(188.33 ± 14.84) ^b	(96.91 ± 16.80) ^b	(19072.84 ± 55.57) ^b	(17.37 ± 1.63) ^b	(284.81 ± 7.62) ^b	(328.47 ± 21.71) ^b	(79.00 ± 11.97) ^{ab}
MHD	(1076.86 ± 1.43) ^d	(197.67 ± 10.50) ^b	(113.58 ± 6.50) ^{bc}	(28190.21 ± 208.52) ^c	(141.78 ± 5.69) ^d	(419.77 ± 6.52) ^d	(648.50 ± 15.42) ^c	(114.31 ± 4.86) ^c
HD	(994.77 ± 5.05) ^c	(208.33 ± 11.02) ^c	(157.41 ± 10.31) ^d	(26111.13 ± 115.67) ^d	(68.54 ± 3.54) ^c	(381.61 ± 11.44) ^c	(924.92 ± 41.61) ^d	(58.62 ± 17.30) ^a
<i>Carica papaya</i>								
Fresh	(176.79 ± 0.47) ^a	(20.56 ± 1.04) ^a	(28.18 ± 0.79) ^a	(2301.34 ± 375.41) ^a	(28.92 ± 1.81) ^b	(69.56 ± 1.60) ^a	(189.54 ± 5.10) ^a	(7.22 ± 4.35) ^a
FD	(920.66 ± 7.88) ^c	(69.00 ± 16.46) ^{bc}	(90.20 ± 8.99) ^b	(13701.52 ± 347.38) ^c	(84.51 ± 2.44) ^d	(290.39 ± 5.81) ^d	(826.58 ± 17.06) ^c	(440.18 ± 90.54) ^b
MD	(968.32 ± 9.54) ^d	(43.00 ± 10.82) ^{ab}	(109.15 ± 16.33) ^b	(10923.24 ± 340.93) ^b	(40.38 ± 2.15) ^c	(241.37 ± 5.45) ^c	(894.31 ± 20.49) ^c	(632.20 ± 22.92) ^c

(Continued)

TABLE 2 (Continued)

Fruit samples	TPC (mg GAE/100 g DW)	Tannin (mg TAE/100 g DW)	Flavonoids (mg QE/100 g DW)	Polysaccharides (mg PE/100 g DW)	Ascorbic acid equivalents (mg AAE/100 g DW)	FRAP (mg Fe ²⁺ /100 g DW)	DPPH (mg AAE/100 g DW)	Anti-glycation (mg AG/100 g DW)
MHD	(1000.28 ± 8.36) ^e	(53.67 ± 9.87) ^b	(96.73 ± 12.61) ^b	(1382.91 ± 291.06) ^c	(27.70 ± 1.63) ^b	(291.95 ± 9.37) ^d	(933.51 ± 7.82) ^d	(550.34 ± 44.62) ^{bc}
HD	(877.69 ± 6.76) ^b	(84.33 ± 12.06) ^c	(178.43 ± 14.80) ^c	(10483.35 ± 262.59) ^b	(19.25 ± 2.93) ^a	(196.70 ± 4.20) ^b	(760.68 ± 10.29) ^b	(538.71 ± 73.69) ^{bc}

Values were expressed as mean ± standard deviation ($n = 3$). Different superscript lowercase letters within the same column indicate statistically significant differences ($p < 0.05$) among samples of the same fruit species ($p < 0.05$). AAE, ascorbic acid equivalents; AG, aminoguanidine; DPPH, 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity; DW, dry weight; FD, freeze drying; FRAP, ferric reducing antioxidant power; GAE, gallic acid equivalent; HD, hot air oven drying; MHD, microwave-assisted hot air oven drying; PE, polysaccharide equivalent; QE, quercetin equivalent; TAE, tannic acid equivalent; TPC, total phenolic content.

Among the dried peel samples, polysaccharide content ranged from 9946.2 mg PE/100 g DW to 41836.2 mg PE/100 g DW, decreased in this order: *M. acuminata* > *C. limon* > *P. americana* > *C. papaya* > *H. polyrhizus*. The consistently high polysaccharide content in *M. acuminata* across all drying treatments corresponded with a low browning index (Table 1). This phenomenon may result from the high molecular weight pectin in *M. acuminata* peels, which could potentially suppress enzymatic oxidation through steric hindrance (Hu D. et al., 2023; Pereira et al., 2021). Moreover, the viscous matrix formed by polysaccharides may have hindered the interaction between polyphenol oxidase and phenolic substrates, thereby reducing the formation of brown pigments (Hu D. et al., 2023; Li et al., 2022). The strong inverse correlation ($r = -0.7105$, $p < 0.001$) between polysaccharide content and browning index (Table 3) further supported the potential regulatory role of polysaccharides in non-enzymatic browning reactions (Li et al., 2022; Pereira et al., 2021).

Among the four drying methods, polysaccharide content was significantly higher ($p < 0.05$) in MD-treated *M. acuminata* and MHD-treated *C. limon* when compared to the other drying treatments. A similar increasing trend was observed in MHD-treated *C. papaya* samples, although the increase was not statistically significant ($p > 0.05$). This finding reflects the rapid internal heating characteristic of MD, which effectively disrupted the cell wall integrity and improved polysaccharide extractability (Vu et al., 2016). In MHD, the combined effects of MD and HD may prevent cell wall collapse and improve structural permeability, leading to greater polysaccharide recovery than HD alone (Talens et al., 2016). Similarly, FD peel samples of *P. americana* and *H. polyrhizus* exhibited the highest polysaccharide content within their respective drying groups. This may be attributed to the porous structure generated by ice crystal sublimation during FD, which enhanced solvent permeability and facilitates polysaccharide extraction (Ma et al., 2018). In contrast, MD samples of *P. americana* and *H. polyrhizus* displayed the lowest polysaccharide contents, possibly due to polysaccharide depolymerization and the occurrence of Maillard reactions induced by rapid internal heating during MD (Hu J. et al., 2023).

3.5 Ascorbic acid equivalents

The amount of AAE in fresh fruit peel samples, ranging from 3.76 mg AAE/100 g DW to 75.12 mg AAE/100 g DW, decreased as follows: *P. americana* > *C. papaya* > *M. acuminata* > *C. limon* > *H. polyrhizus* (Table 2). The above trend agreed with Gopalraaj and Velayudhannair (2024). Unlike phytochemicals and polysaccharides, the amount of AAE in fruit peel samples did not consistently increase after the drying treatments. For instance, the AAE in *C. papaya* peel samples decreased after MHD (27.70 mg AAE/100 g DW) and HD (19.25 mg AAE/100 g DW) treatments, likely due to the prolonged thermal exposure during these drying methods, given the heat-sensitive nature of ascorbic acid (Silva et al., 2020).

Among the dried peel samples with AAE between 17.37 mg AAE/100 g DW and 406.57 mg AAE/100 g DW, *C. limon* showed the highest AAE, followed by *P. americana*, *C. papaya*, *M. acuminata* and *H. polyrhizus*. The significant increase in AAE of FD-treated *C. limon* was consistent with a previous finding demonstrating greater retention of ascorbic acid level under FD when compared to MD and HD (Tekgül and Baysal, 2018). Besides, FD samples of *C. limon*, *C. papaya*, and *M. acuminata* also displayed significantly higher AAE than their MD, MHD, and HD counterparts. These findings concur with Hu D. et al. (2023), who attributed the superior retention of ascorbic acid in FD samples to the low-temperature sublimation process that minimized thermal

degradation, oxidation, and hydrolytic losses. Despite the superior performance of FD in most samples, MHD-treated *P. americana* and HD-treated *H. polyrhizus* retained the highest AAE within their dried sample groups. Although the HD-treated *H. polyrhizus* samples remained statistically comparable to their FD- and MHD-treated counterparts, the present findings are inconsistent with those reported by Tran et al., who demonstrated greater ascorbic acid retention in FD-treated samples relative to HD-treated samples. This discrepancy may be attributed to differences in drying conditions, which can markedly influence the stability of ascorbic acid during processing (Tran et al., 2024). In the present study, the FD treatment involved substantially longer freezing (24 h) and dehydration (48 h) durations when compared with the 8 h-freezing and 24 h-sublimation periods employed by Tran et al. (2024). Extended processing durations may have induced greater cellular disruption and structural modifications, potentially enhancing the susceptibility of ascorbic acid to degradation during drying and subsequent handling. These variations in processing conditions may therefore account for the contrasting findings observed between the two studies. Interestingly, the high AAE observed in *P. americana* and *C. limon* was associated with their relatively low moisture content (Table 1). The modest inverse correlation between AAE and moisture content ($r = -0.5905$, $p < 0.01$) (Table 3) further corroborates this association, suggesting that high moisture content in fruit peel samples may accelerate the hydrolysis and oxidation of water-soluble ascorbic acid (Giannakourou and Taoukis, 2021).

3.6 Reducing potential and radical scavenging activity

The FRAP values for selected fresh fruit peel samples decreased in the following order: *P. americana* > *C. papaya* > *C. limon* > *M. acuminata* > *H. polyrhizus*. In comparison, their DPPH radical scavenging activities showed a similar trend: *P. americana* > *C. papaya* > *M. acuminata* > *C. limon* > *H. polyrhizus*. All drying treatments generally increased the antioxidant activities of majority fruit peel samples, with FRAP values increasing by 1.7- to 16.2-fold and DPPH radical scavenging activity by 1.8- to 32.9-fold. The increase in antioxidant potential was primarily attributed to the enhanced release of phytochemicals, while the retention or relative liberation of ascorbic acid in selected samples (Table 2) may have provided an additional contribution to the observed antioxidant trend. This suggests that the drying process may have released bound bioactive compounds, thereby enhancing the overall antioxidant capacity (Gopalraaj and Velayudhannair, 2024).

The FRAP values of dried samples, ranging from 93.08 mg Fe²⁺/100 g DW to 6260.85 mg Fe²⁺/100 g DW, closely mimicked the TPC and tannin trends (Table 2). Significantly higher FRAP values were observed in FD-treated *M. acuminata* and *C. limon* compared to the other dried samples, consistent with the findings reported by Papoutsis et al. (2017). However, the FRAP values of FD and HD samples of *P. americana* were not significantly different, despite a slightly lower value recorded by the FD sample. Likewise, both FD and MHD samples of *C. papaya* demonstrated comparable FRAP values, likely attributed to the greater retention of AAE in FD-treated *C. papaya* peels. The strong positive linear correlation of FRAP with flavonoids ($r = 0.8552$, $p < 0.0001$) and AAE ($r = 0.6827$, $p < 0.001$) (Table 3) further supported these observations (Table 3), suggesting a strong association of these bioactive compounds with the reducing potential of fruit peel samples (Zhou et al., 2023).

In comparison to FRAP, the wider variation in DPPH radical scavenging activities across all five fruit peel varieties suggests a higher sensitivity of DPPH radicals towards lipophilic antioxidants (Lim et al., 2026b).

Among the dried peel samples, *P. americana* consistently exhibited the highest DPPH scavenging activity across all drying methods. This was followed by *M. acuminata*, *C. papaya*, *C. limon*, and *H. polyrhizus*. These findings are in agreement with Kamaraj et al. (2019), who similarly reported the superior radical scavenging potential of *P. americana* peel. Notably, HD-treated *P. americana* and *C. limon* showed the highest DPPH scavenging values, with FD-treated *C. limon* displaying statistically similar DPPH scavenging values to its HD counterpart. The higher DPPH radical scavenging activity observed in the FD-treated *C. limon* sample (Table 2) may be attributed to its elevated AAE. DPPH assay has been previously reported to quantify antioxidant activity derived from both phenolic and non-phenolic compounds, including ascorbic acid (Suleria et al., 2020). The strong positive linear correlations between DPPH scavenging activity and phytochemicals, particularly AAE (Table 3), further support the association of these bioactive compounds with radical scavenging capacity (Gopalraaj and Velayudhannair, 2024).

Within each fruit peel species, the highest FRAP and DPPH scavenging values were observed in the HD-treated samples of *P. americana*, the MD-treated samples of *H. polyrhizus*, the MHD-treated *C. papaya*, and the FD-treated samples of *M. acuminata* and *C. limon*. Although FRAP and DPPH scavenging assays operate with distinct mechanisms (Zhou et al., 2023), both assays are influenced by similar groups of bioactive compounds investigated in this study. The very strong positive linear correlation between FRAP and DPPH scavenging values ($r = 0.9939$, $p < 0.0001$) (Table 3) further underscores the premise that these assays largely reflect antioxidant activity associated with the same bioactive constituents. Although MD is generally regarded as favourable for preserving antioxidant capacity due to its shorter drying time (Babiker et al., 2021), most MD-treated samples exhibited lower FRAP and DPPH scavenging values. An exception was observed in MD-treated *H. polyrhizus*, which recorded the highest FRAP (228.96 mg Fe²⁺/100 g DW) and DPPH scavenging (314.45 mg AAE/100 g DW) values among its dried counterparts. This variation may indicate a sample-specific response to microwave exposure, highlighting the importance of optimizing MD power settings. Excessive energy input may lead to thermal degradation of heat-sensitive bioactive compounds (Guclu et al., 2022).

3.7 Anti-glycation activity

All four drying methods significantly increased the anti-glycation activity in the majority of fruit peel samples, with increments ranging between 15 and 8,656% when compared to their respective fresh counterparts. *C. papaya* showed the most pronounced improvement among the fruit peels, irrespective of the drying methods. The anti-glycation activities of dried fruit peels decreased as follows: *P. americana* > *H. polyrhizus* > *C. papaya* > *C. limon* > *M. acuminata*, with values ranging from 45.03 mg AG/100 g DW to 2043.30 mg AG/100 g DW. Among the four drying methods, MD consistently yielded relatively high anti-glycation values in *P. americana*, *H. polyrhizus*, *C. papaya*, and *M. acuminata*. The increased anti-glycation activity in the dried fruit peel samples could be explained by the potential formation of protein-polyphenol complexes after thermal drying (Chew and King, 2019). The combined effects of protein-binding interference and carbonyl-scavenging actions of these protein-polyphenol complexes may contribute to the inhibition of advanced glycation end product formation (Zhao et al., 2022). However, *C. limon* deviated from the above trend, as MD (79.00 mg AG/100 g DW) and HD treatments (58.62 mg AG/100 g DW) produced lower anti-glycation activity than the fresh counterparts (99.26 mg AG/100 g DW), whereas FD treatment markedly enhanced

TABLE 3 Pearson correlation and regression among variables in fresh and dried fruit peel samples.

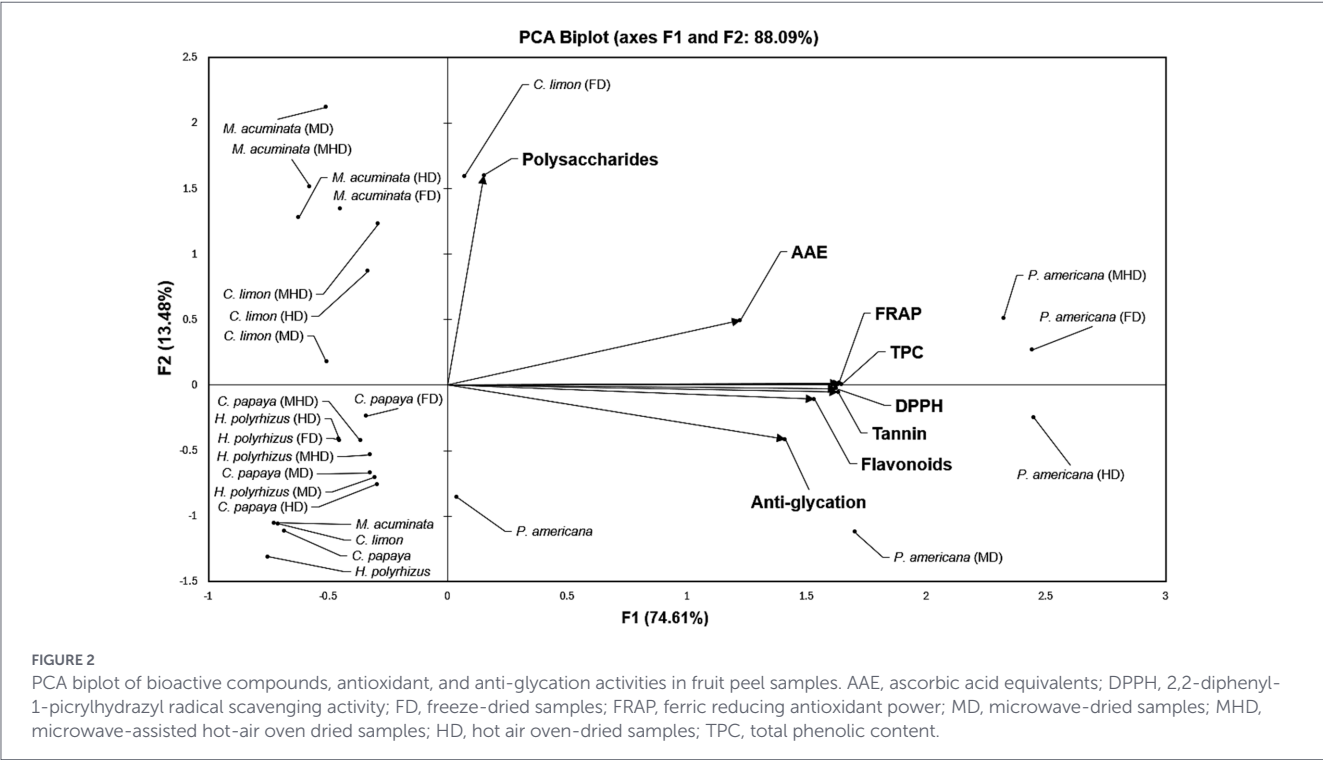
Activity variables	R^2	r	Significance
Between moisture content and browning index			
Moisture content vs. Browning index	0.0461	0.2146	ns
Between moisture content and bioactive compounds			
Moisture content vs. TPC	0.1688	−0.4108	ns
Moisture content vs. Tannin	0.1542	−0.3927	ns
Moisture content vs. Flavonoids	0.1399	−0.3741	ns
Moisture content vs. Polysaccharides	0.1240	−0.3522	ns
Moisture content vs. Ascorbic acid equivalents	0.3487	−0.5905	**
Between moisture content and antioxidant activities			
Moisture content vs. FRAP	0.1734	−0.4164	ns
Moisture content vs. DPPH	0.1540	−0.3924	ns
Between moisture content and anti-glycation activity			
Moisture content vs. Anti-glycation	0.0137	−0.1170	ns
Between browning index and bioactive compounds			
Browning index vs. TPC	0.0392	0.1979	ns
Browning index vs. Tannin	0.0376	0.1938	ns
Browning index vs. Flavonoids	0.0957	0.3094	ns
Browning index vs. Polysaccharides	0.5048	−0.7105	***
Browning index vs. Ascorbic acid equivalents	0.1319	0.3632	ns
Between browning index and antioxidant activities			
Browning index vs. FRAP	0.0344	0.1855	ns
Browning index vs. DPPH	0.0364	0.1907	ns
Between browning index and anti-glycation activity			
Browning index vs. Anti-glycation	0.1633	0.4042	ns
Among the bioactive compounds			
TPC vs. Flavonoids	0.7548	0.8688	****
Flavonoids vs. Tannin	0.7238	0.8508	****
TPC vs. Tannin	0.9932	0.9966	****
TPC vs. Ascorbic acid equivalents	0.4682	0.6842	***
Tannin vs. Ascorbic acid equivalents	0.4336	0.6585	***
Flavonoids vs. Ascorbic acid equivalents	0.4502	0.6709	***
TPC vs. Polysaccharide	0.0094	0.0970	ns
Tannin vs. Polysaccharide	0.0034	0.0587	ns
Flavonoids vs. Polysaccharide	0.0018	0.0426	ns
Ascorbic acid equivalents vs. Polysaccharide	0.04456	0.2111	ns
Between bioactive compounds and antioxidant activities			
TPC vs. FRAP	0.9847	0.9923	****
Tannin vs. FRAP	0.9895	0.9947	****
Flavonoids vs. FRAP	0.7314	0.8552	****
Ascorbic acid equivalents vs. FRAP	0.4660	0.6827	***
Polysaccharide vs. FRAP	0.0091	0.0954	ns
TPC vs. DPPH	0.9878	0.9939	****
Tannin vs. DPPH	0.9905	0.9952	****
Flavonoids vs. DPPH	0.6906	0.8310	****

(Continued)

TABLE 3 (Continued)

Activity variables	R^2	r	Significance
Polysaccharide vs. DPPH	0.0058	0.0763	ns
Ascorbic acid equivalents vs. DPPH	0.4260	0.6527	***
Between bioactive compounds and anti-glycation activity			
TPC vs. Anti-glycation	0.6462	0.8039	****
Tannin vs. Anti-glycation	0.6192	0.7869	****
Flavonoids vs. Anti-glycation	0.7458	0.8636	****
Ascorbic acid equivalents vs. Anti-glycation	0.2055	0.4534	*
Polysaccharide vs. Anti-glycation	0.0052	−0.0719	ns
Among antioxidant and anti-glycation activities			
FRAP vs. DPPH	0.9878	0.9939	****
Anti-glycation vs. FRAP	0.5973	0.7729	****
Anti-glycation vs. DPPH	0.6114	0.7819	****

Analysis was performed using twenty-five paired samples per assay. The R^2 value corresponds to the coefficient of determination from linear regression, while the r value represents the Pearson correlation coefficient. The level of significance was expressed as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$. ns: non-significant.



the activity (143.95 mg AG/100 g DW). The enhanced anti-glycation activity of FD sample may be attributed to the effective retention of AAE, as ascorbic acid is a well-known antioxidant capable of inhibiting the formation of advanced glycation end products via the radical scavenging mechanism (Valle-Sánchez et al., 2024).

3.8 Principal component analysis

PCA was utilized to visualize the multivariate relationships among the studied variables in this study. The first two principal components (F1 and F2) collectively explained 88% of the total activity variance, with F1 accounting for 74.6%, as illustrated in the PCA biplot (Figure 2). F1 primarily distinguished variables based

on fruit peel species, as evidenced by the distinct positioning of both fresh and dried *P. americana* samples along the positive region of the x -axis. FD- and MHD-treated samples were clustered on the positive region of the y -axis, while HD and MD samples were associated with the negative region. This secondary distribution pattern suggests drying method as the second component (F2) that explained the remaining 13.5% of activity variance. The phytochemicals (flavonoids, tannin, TPC) in the dried fruit peel samples were positively associated with both antioxidant ($r = 0.6906$ – 0.9905 , $p < 0.0001$) and anti-glycation ($r = 0.6192$ – 0.7458 , $p < 0.0001$) activities (Tables 2, 3). This relationship was further supported by the strong vector alignment of these phytochemicals with FRAP, DPPH, and anti-glycation activity variables, as revealed

in the PCA loading plot (Figure 2). The above findings agreed with previous studies by Saifullah et al. (2019) and Suleria et al. (2020), indicating that phenolic and flavonoid compounds exhibited strong antioxidant potential. Besides, AAE also contributed to the overall functional properties of fruit peels, though to a lesser extent. For instance, FD-treated *C. limon* sample which was positioned at the upper right quadrant of the biplot, retained a relatively higher level of AAE and exhibited strong antioxidant and anti-glycation activities (Table 2). The positive linear correlation of AAE with FRAP ($r = 0.6827$, $p < 0.001$), DPPH scavenging ($r = 0.6527$, $p < 0.001$), and anti-glycation activity ($r = 0.4534$, $p < 0.05$) (Table 3) further supports this notion. All the above findings underscore the contribution of both polyphenols and AAE to the enhanced functional properties of dried fruit peels (Valle-Sánchez et al., 2024), with polyphenols likely being the dominant factor. In addition, the anti-glycation activities of fruit peels are likely mediated through antioxidant-related mechanisms, including the free radical scavenging and metal ion chelation pathways, which together help to trap reactive α -dicarbonyl intermediates, the key precursors of advanced glycation end products (Valle-Sánchez et al., 2024). Therefore, optimization of the drying process is critical to maximize the yield of functional compounds exhibiting antioxidant and anti-glycation activities from fruit peels.

3.9 Antioxidant index (AI)

An integrated AI was used to provide a comprehensive ranking of functional activity across all fruit peel samples as previously described by Ho et al. (2022). The AI presented in Table 4 revealed that FD consistently yielded higher AI values for *P. americana*, *C. limon*, *M. acuminata*, and *C. papaya* than the samples treated with other drying methods. This finding agreed with earlier reports that demonstrated improved radical scavenging and metal ion chelation activities, as well as greater extraction of flavonoids and phenolics from FD fruit peels (Tekgül and Baysal, 2018; Papoutsis et al., 2017). Although the AI of MD-treated *M. acuminata* was slightly higher than that of the FD-treated sample by 1%, the FD samples of *M. acuminata* showed higher phenolics, AAE, and corresponding antioxidant activities. Similarly, both MD and MHD samples of *H. polyrhizus* showed comparable AI at 14%. However, MD-treated *H. polyrhizus* exhibited higher phytochemical content, FRAP and DPPH scavenging values, suggesting MD as an optimal drying approach for this particular fruit peel matrix (Table 2). The lower activities of antioxidant and anti-glycation observed in the MHD sample of *H. polyrhizus* may be attributed to its reduced tannin content, which was statistically comparable to that of its fresh sample (Table 2). This interpretation was further reinforced by the positive linear correlation between the tannin content and antioxidant activities (Table 3).

4 Conclusion

This study underscores the pivotal role of drying as a functional enhancement strategy rather than solely a preservation technique. All drying methods improved the extraction of bioactive compounds and their associated antioxidant and anti-glycation capabilities in the selected tropical fruit peel samples. These

present findings suggest FD as an ideal drying method for *P. americana*, *M. acuminata*, *C. limon*, and *C. papaya*, while MD was more favourable for *H. polyrhizus*. PCA further revealed that *P. americana* consistently exhibited the strongest overall antioxidant profile across all drying methods. The impact of drying was both matrix-specific and compound-dependent, highlighting the importance of customized drying strategies based on fruit species and desired functional outcomes. The valorization of fruit peels aligns with the growing demand for clean-label product development, circular bioeconomy principles, and sustainable innovation. Future research should explore the *in vivo* bio-efficacy and long-term safety of these fruit peels, facilitating their application as commercially viable and health-promoting functional food ingredients.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HL: Formal analysis, Writing – original draft, Data curation, Investigation. PY: Supervision, Validation, Writing – review & editing, Funding acquisition. ZN: Methodology, Project administration, Conceptualization, Supervision, Writing – review & editing, Resources, Software.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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TABLE 4 Antioxidant index of both fresh and dried fruit peel samples.

Fruit samples	FRAP (mg Fe ²⁺ /100 g DW)	DPPH (mg AAE/100 g DW)	TPC (mg GAE/100 g DW)	Tannin (mg TAE/100 g DW)	Flavonoids (mg QE/100 g DW)	Polysaccharides (mg PE/100 g DW)	Ascorbic acid equivalents (mg AAE/100 g DW)	Anti-glycation (mg AG/100 g DW)	Relative %								AI ^a (%)	Category
									FRAP	DPPH	TPC	Tannin	Flavonoids	Polysaccharides	AAE	Anti-glycation		
FD <i>Persea americana</i>	6164.67	13384.0	10944.4	9731.3	478.0	24133.9	244.1	1626.1	98	78	87	88	100	58	60	80	81	Very high
HD <i>Persea americana</i>	6260.85	17084.3	12577.2	11000.0	289.3	19568.3	192.5	1824.7	100	100	100	100	61	47	47	89	80	Very high
MHD <i>Persea americana</i>	5938.19	14767.0	12287.0	10751.7	358.5	19304.4	342.7	807.4	95	86	98	98	75	46	84	40	78	Very high
MD <i>Persea americana</i>	3465.49	8715.3	8083.3	6547.6	383.6	9946.2	197.2	2043.3	55	51	64	60	80	24	48	100	60	High
FD <i>Citrus limon</i>	692.79	873.0	1270.0	191.0	123.5	24467.3	406.6	143.9	11	5	10	2	26	58	100	7	27	Moderate
<i>Persea americana</i>	2071.23	4852.5	2836.4	2656.8	81.8	5329.7	75.1	143.5	33	28	23	24	17	13	18	7	20	Low
MHD <i>Citrus limon</i>	419.77	648.5	1076.9	197.7	113.6	28190.2	141.8	114.3	7	4	9	2	24	67	35	6	19	Low
MD <i>Musa acuminata</i>	375.71	773.2	925.6	185.7	22.2	41836.2	36.2	136.0	6	5	7	2	5	100	9	7	17	Low
HD <i>Citrus limon</i>	381.61	924.9	994.8	208.3	157.4	26111.1	68.5	58.6	6	5	8	2	33	62	17	3	17	Low
FD <i>Musa acuminata</i>	542.32	1323.7	1205.2	216.7	34.6	31889.9	53.1	107.9	9	8	10	2	7	76	13	5	16	Low
FD <i>Carica papaya</i>	290.39	826.6	920.7	69.0	90.2	13701.5	84.5	440.2	5	5	7	1	19	33	21	22	14	Low
MHD <i>Musa acuminata</i>	334.45	678.7	824.2	147.3	22.2	34635.8	17.8	45.0	5	4	7	1	5	83	4	2	14	Low
MD <i>Hylocereus polyrhizus</i>	228.96	314.5	634.4	48.3	149.0	11603.9	25.4	714.3	4	2	5	0	31	28	6	35	14	Low
MHD <i>Hylocereus polyrhizus</i>	174.36	228.1	525.1	5.0	147.1	12974.5	36.6	642.3	3	1	4	0	31	31	9	31	14	Low
HD <i>Carica papaya</i>	179.63	760.7	877.7	84.3	178.4	10483.3	19.2	538.7	3	4	7	1	37	25	5	26	14	Low

(Continued)

TABLE 4 (Continued)

Fruit samples	FRAP (mg Fe ²⁺ /100 g DW)	DPPH (mg AAE/100 g DW)	TPC (mg GAE/100 g DW)	Tannin (mg TAE/100 g DW)	Flavonoids (mg QE/100 g DW)	Polysaccharides (mg PE/100 g DW)	Ascorbic acid equivalents (mg AAE/100 g DW)	Anti-glycation (mg AG/100 g DW)	Relative %								AI ^a (%)	Category
									FRAP	DPPH	TPC	Tannin	Flavonoids	Polysaccharides	AAE	Anti-glycation		
MD <i>Carica papaya</i>	241.37	894.3	968.3	43.0	109.2	10923.2	40.4	632.2	4	5	8	0	23	26	10	31	13	Low
MHD <i>Carica papaya</i>	291.95	933.5	1000.3	53.7	96.7	13821.9	27.7	550.3	5	5	8	0	20	33	7	27	13	Low
HD <i>Musa acuminata</i>	93.08	146.1	287.9	26.0	26.5	32417.8	12.7	141.4	1	1	2	0	6	77	3	7	12	Low
MD <i>Citrus limon</i>	284.81	328.5	925.9	188.3	96.9	19072.8	17.4	79.0	5	2	7	2	20	46	4	4	11	Low
FD <i>Hylocereus polyrhizus</i>	203.21	185.0	605.2	72.1	86.9	13257.0	27.7	443.7	3	1	5	1	18	32	7	22	11	Low
HD <i>Hylocereus polyrhizus</i>	179.63	234.3	678.5	76.0	89.5	12391.1	44.1	340.7	3	1	5	1	19	30	11	17	11	Low
<i>Carica papaya</i>	69.56	189.5	176.8	20.6	28.2	2301.3	28.9	7.2	1	1	1	0	6	6	7	0	3	Low
<i>Citrus limon</i>	67.70	33.9	211.2	27.4	9.7	4014.6	6.9	99.3	1	0	2	0	2	10	2	5	3	Low
<i>Musa acuminata</i>	33.44	40.2	95.7	16.9	6.7	3926.6	8.6	80.4	1	0	1	0	1	9	2	4	2	Low
<i>Hylocereus polyrhizus</i>	23.58	21.6	44.8	3.9	10.2	662.2	3.8	18.5	0	0	0	0	2	2	1	1	1	Low

The relative percentage value was calculated based on the highest value in each assay.
^aAverage value of the relative percentages from eight assays. Each fruit peel sample was classified into very high (76–100%), high (51–75%), moderate (26–50%), and low (0–25%) AI species.
AAE, ascorbic acid equivalents; AG, aminoguanidine; AI, antioxidant index; DPPH, 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity; DW, dry weight; FD, freeze drying; FRAP, ferric reducing antioxidant power; GAE, gallic acid equivalent; HD, hot air oven drying; MD, microwave drying; MHD, microwave-assisted hot air oven drying; PE, polysaccharide equivalent; QE, quercetin equivalent; TAE, tannic acid equivalent; TPC, total phenolic content.

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