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Impact of pretreatment and different drying methods on nutritional and antioxidant properties of Turkey berry fruits (*Solanum torvum*)

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Turkey berry (*Solanum torvum*) is a nutrient-dense indigenous fruit widely consumed in Ghana, but its high moisture content makes it highly perishable. Converting fresh turkey berries into shelf-stable powders could reduce postharvest losses and support year-round availability. This study therefore evaluated drying and pretreatment combinations that best preserve the nutritional and functional quality of turkey berry. A 2 × 4 factorial design was used, involving two pretreatment conditions (unblanched and hot-water blanched) and four drying methods (solar, freeze, convection, and vacuum). Quality attributes assessed included moisture content, proximate composition, energy value, selected minerals (iron, calcium, and phosphorus), vitamin C, total phenolic content, and antioxidant activity. Drying successfully produced shelf-stable powders, reducing moisture from 81.68% in fresh fruits to 4.19%–8.49% in dried samples, with blanched samples generally attaining lower final moisture than unblanched ones. Fresh fruits contained 3.84% protein, 65.46 kcal/100 g energy, and 2.17 mg/100 g iron, while dried powders showed higher proximate and energy values mainly due to nutrient concentration following water removal rather than absolute increases. No single drying method optimised all quality parameters, indicating that the most suitable process depends on the targeted attribute. Freeze drying and vacuum drying generally produced the best powders when nutrient retention and functional quality were prioritised. Blanched freeze-dried samples retained the highest vitamin C, while blanched vacuum-dried samples recorded the highest total phenolic content and antioxidant activity. Overall, drying offers strong potential for turkey berry value addition in Ghana when processing choices are aligned with intended nutritional or functional goals.

KEYWORDS

antioxidant activity, convection oven, freeze drying, proximate composition, solar drying, Turkey berry, vacuum drying

1 Introduction

Turkey berries (*Solanum torvum*) are small green fruits borne on bristly shrubs and are valued for their nutritional and therapeutic importance. Compositional studies have reported the presence of proximate nutrients (protein, fat, carbohydrate/fibre, and ash), vitamin C (2.69–31.54 mg/100 g) and essential minerals such as iron (13.05–208.43 mg/kg), calcium (221.6–43 mg/kg), phosphorus (0.58%), potassium (1.84%), and magnesium

(0.14%–0.32%), although concentrations vary with origin, maturity, and processing conditions (Abraham et al., 2022; Akoto et al., 2015; Agyei-Poku et al., 2025). In Ghana, they are known by several local names, such as “Kwahu-nsusua,” “Abedru,” and “Cantose,” and have been a staple ingredient in traditional dishes for generations. Darkwah (2020) reported that they are widely used in Ghana to help prevent and manage anaemia, based on the perception that they boost blood levels. Despite its nutritional and therapeutic value (Atuna et al., 2022), turkey berry is highly perishable. It is typically sold fresh through informal value chains where cold storage is limited and handling practices are inconsistent (Essilfie et al., 2025). The fruit’s high moisture content hastens physiological breakdown and increases susceptibility to spoilage resulting in postharvest losses especially under the hot, humid conditions prevalent in Ghanaian markets. Developing shelf-stable turkey berry products that maintain nutritional quality is therefore critical for reducing losses and improving year-round availability.

Drying is one of the oldest and most widely used preservation methods for fruits and vegetables, particularly where access to refrigeration is limited. By reducing moisture content and water activity, drying inhibits microbial growth and slows enzymatic and other deteriorative reactions. This extends the shelf life of perishable produce, often from a very short shelf-life to weeks or months depending on product, packaging, and storage conditions (Nyamgero et al., 2025; Moutia et al., 2024). For African leafy vegetables and other indigenous crops, a range of drying technologies, from open sun and improved solar dryers to hot air, infrared, microwave and freeze drying, have been investigated (Hag et al., 2020). These studies have consistently shown that the type of drying method employed can influence the retention of vitamins, minerals, pigments and phenolic compounds. The studies report that mild, low temperature processes such as freeze drying generally provide superior preservation of colour, vitamin C and antioxidant capacity compared with sun or conventional hot air drying (Managa et al., 2020; Alibas and Ipek, 2026). However, solar and other intermediate technologies are often more accessible and affordable for small scale processors than freeze drying. When these solar and intermediate technologies are properly designed and managed, they can deliver better quality end products than traditional open sun drying (Shahat et al., 2016; Muchoki et al., 2025).

Blanching is commonly applied prior to drying of vegetables to inactivate browning and quality degrading enzymes, reduce microbial load, expel trapped gases and modify tissue structure in ways that can accelerate moisture removal (Ijod et al., 2025; Fellows, 2017; Deng et al., 2019). However, hot water blanching can also cause leaching of water-soluble minerals, sugars and vitamins into the blanching medium and thermal degradation of heat sensitive constituents.

Existing research on turkey berry has not yet generated the processing evidence needed to support reliable, nutrition-sensitive value addition in Ghana. Most studies have concentrated on the fresh fruit’s composition, simple household cooking such as boiling, or medicinal uses of extracts (Melila et al., 2021; Asante et al., 2024; Abraham et al., 2022; Kouadio et al., 2020). Where processing has been examined, findings consistently show that turkey berry nutrients and phytochemicals are highly sensitive to heat and handling. For example, boiling can reduce several minerals and

certain phytochemicals, indicating that processing conditions can markedly shift its nutritional profile (Abraham et al., 2022; Kouadio et al., 2020). Drying studies also suggest variability across methods. Meenakshi et al. (2022) compared sun, solar, and cabinet drying of pretreated turkey berry fruits and found that all methods produced powders with similar moisture levels (7.3%–7.5%), with crude fibre ranging from 12.6 to 14.7 g, vitamin C from 3.6 to 5.2 mg, carotenoids around 1130–1140 µg, and iron at about 20.0–20.4 mg. Ash content, however, differed across methods, from 5.6 g in solar-dried samples to 7.0 g in cabinet-dried samples. Phytochemical outcomes also varied, with total flavonoids highest under cabinet drying (about 806.6 mg GAE/100 g) and total phenols were similar under sun and solar drying (about 716 mg GAE/100 g) but lower in cabinet-dried powder (about 604 mg GAE/100 g). More recent work further highlights that blanching and drying can alter bioactive compound extractability and antioxidant activity, reinforcing that phytochemicals respond strongly to these interventions (Helilusiatiningsih et al., 2023; Deka et al., 2024; Barathiraja et al., 2022; Agyei-Poku et al., 2025; Mang et al., 2026).

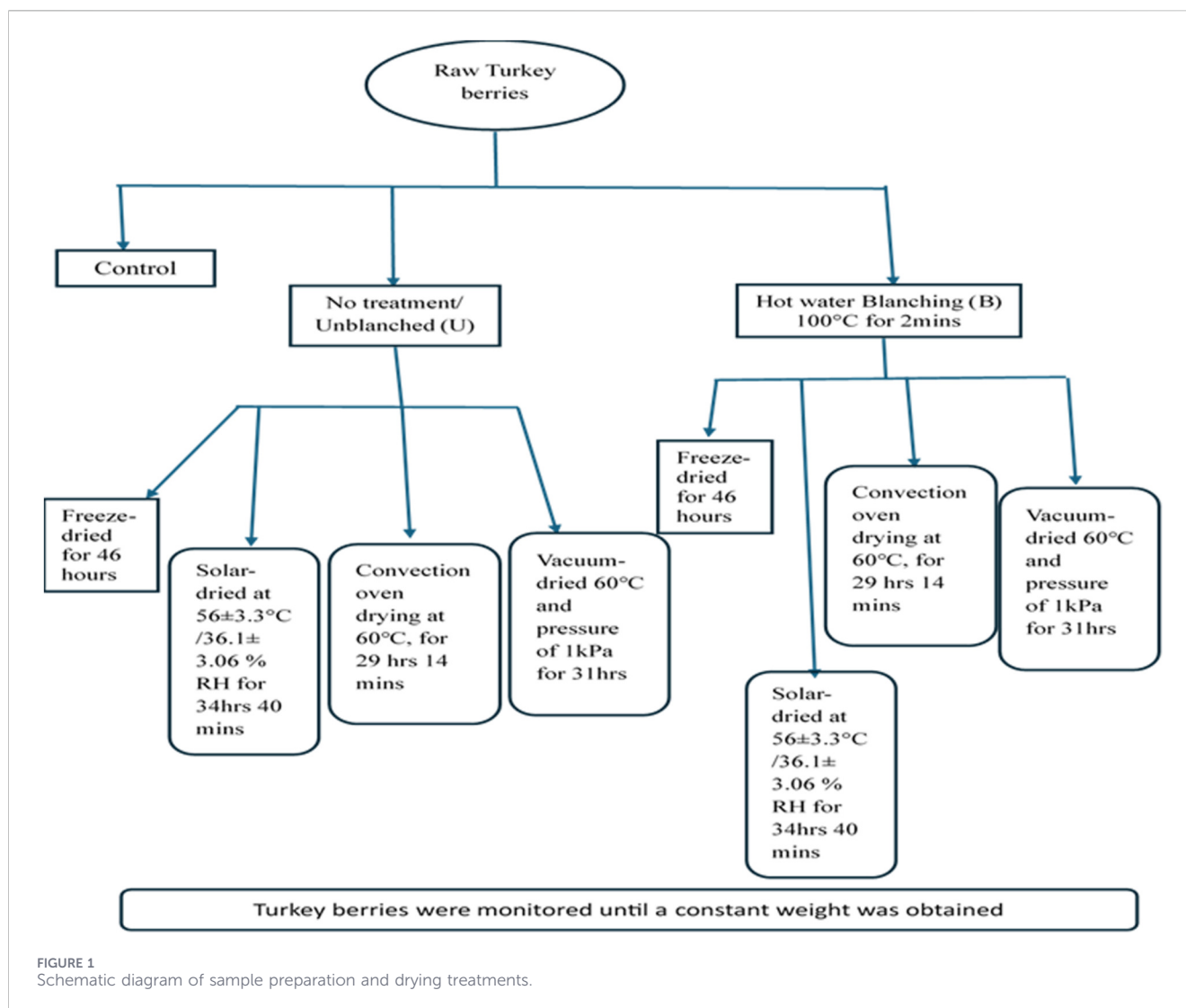
However, the current evidence is fragmented and does not provide decision-ready guidance for processors because it rarely evaluates blanching and drying technologies together across a wide range of practical options. In particular, there is limited comparative evidence on how blanching pretreatment interacts with diverse drying methods, including solar drying, convective oven drying, vacuum drying, and freeze drying, to influence proximate composition, mineral content, vitamin C, total phenolics, and antioxidant activity of turkey berry. This gap limits the ability of small-scale processors, farmer groups, and extension services to design low-cost, evidence-based processing strategies aligned with Ghana’s turkey berry value chains. Without clear data on trade-offs, stakeholders cannot confidently determine when blanching improves drying efficiency and safety but potentially compromises heat-sensitive nutrients. It also cannot determine which drying method offers the best balance between nutrient retention, product stability, energy requirements, and technical feasibility.

This study therefore, was needed to generate comparative, Ghana-relevant evidence on the combined effects of two pretreatment conditions (blanching and non-blanching) and four drying technologies (freeze drying, solar drying, convective oven drying, and vacuum drying) on the nutritional and phytochemical quality of turkey berry. By identifying the most suitable pretreatment–drying combinations, the work aims to support practical value addition that improves year-round availability of shelf-stable turkey berry products, strengthens smallholder-oriented processing, and better serves urban consumers seeking convenient nutrient-dense foods.

2 Materials and methods

2.1 Fruit collection

Fresh turkey berries were obtained from the Madina market in the Greater Accra region of Ghana. To limit farm-to-farm heterogeneity, turkey berries were sourced from a single vendor.



Only physiologically mature and undamaged fruits were selected. Samples were transported in clean ventilated sacks and processed within 4 h (240 min) of purchase.

2.2 Experimental design

A 2×4 factorial experiment (four drying methods and two pre-treatments) was conducted. This design produced eight treatment combinations, which resulted in eight data points. The study was conducted in three replicates and the fresh turkey berry fruits were used as control.

2.3 Sample preparation and drying process

Whole turkey berries were washed and divided into three portions. One portion was kept fresh and used as the control. The second portion received no pre-treatment (Unblanched -U), while the third was blanched in hot water (B) at 100 °C for 2 min. Each of the U and B samples were subsequently divided into four sub-portions: the first one was freeze-dried for 46 h in an Infitek Freeze dryer (model: LYO60B-2S), the second portion was solar-dried at

56 °C $\pm$ 3.3 °C and 36.1% $\pm$ 3.06% RH for 34 h 40 min by arranging the fruits in a single layer on clean drying trays and loaded into the dryer. Samples were dried under sunlight hours only. During non-sunlight periods (sundown to sunrise), the samples were retained in the solar dryer and covered in polyethylene bags overnight to reduce moisture uptake from ambient air and prevent contamination. Solar drying resumed the next day and continued until constant weight was obtained. Samples were turned or gently mixed at regular intervals. The third portion was dried in an Infitek convection oven (Model: DON-H140) by placing the berries in a single layer in a tray and dried at a temperature of 60 °C, for 29 h 14 min. The fourth and final portion was arranged on trays and dried in an Infitek vacuum oven (Model:DOV90H) at a temperature of 60 °C and pressure of 1 kPa for 31 h. The drying process was monitored until a constant weight was obtained (Figure 1). The entire experiment was conducted in triplicate.

At the end of drying, the samples were milled into powder using an Infitek hammer mill (Model: HWM-TA110, Sieve size: 0.8 mm). The powders were then sealed in airtight bags to minimise moisture reabsorption.

2.4 Determination of quality parameters

2.4.1 Determination of the proximate composition of Turkey berries

The proximate composition of turkey berries was determined using standard procedures outlined by the Association of Official Analytical Chemists (AOAC International, 2005).

2.4.1.1 Moisture content

The moisture content was determined using AOAC method 925.10. Approximately 2.0 g of the sample was accurately weighed into a clean, dry crucible of known weight. The crucible and its contents were placed in a hot air oven and dried at $105^{\circ}\text{C} \pm 2^{\circ}\text{C}$ for 24 h to a constant weight. The crucible was transferred to a desiccator to cool for about 30 min after drying and reweighed.

Moisture content (%) was calculated using the formula:

$$\text{Moisture Content (\%)} = [(W_1 - W_2) / (W_1 - W_0)] \times 100$$

Where:

W_0 = weight of empty crucible.

W_1 = weight of crucible + initial fresh sample.

W_2 = weight of crucible + dried sample.

2.4.1.2 Protein content

Protein content was determined using AOAC method 920.87. Approximately 2.0 g of sample was weighed into a Kjeldahl digestion flask. Concentrated H_2SO_4 (25 mL) and a selenium catalyst tablet were added, and the mixture was digested on a block heater until a clear, colourless solution indicated complete digestion. The digest was cooled, quantitatively transferred to a 100 mL volumetric flask, and made up to volume with distilled water.

For distillation, 25 mL of 4% boric acid containing two drops of mixed indicator (methyl red/bromocresol green) was placed in a 250 mL conical flask, and the condenser tip was immersed below the liquid surface. The distillation unit was pre-flushed with boiling distilled water and the steam trap emptied. An aliquot (10 mL) of the digest was introduced into the distillation apparatus, followed by 15 mL of 40% NaOH to liberate ammonia, which was steam-distilled into the boric acid receiver (turning bluish-green on contact).

After 5 min of distillation, the receiver was removed and titrated with 0.1 N HCl to a faint pink endpoint. All determinations were performed in triplicate, with a reagent blank run for correction. Nitrogen content was calculated from the titration, and crude protein was obtained using the factor 6.25:

$$\text{Crude protein (\%)} = \text{Nitrogen (\%)} \times 6.25$$

2.4.1.3 Crude fat

Crude fat content was determined according to AOAC method 922.06 using Soxhlet extraction with petroleum ether (40°C – 60°C). Following extraction, the solvent was evaporated, and the lipid residue was dried to constant weight, cooled in a desiccator, and weighed for gravimetric determination of crude fat.

The crude fat content was calculated as follows:

$$\text{Crude Fat (\%)} = [(W_2 - W_1) / W_s] \times 100$$

Where:

W_1 = weight of empty flask.

W_2 = weight of flask with extracted fat.

W_s = weight of sample.

2.4.1.4 Total ash

Ash content was measured using the dry ashing method (AOAC 923.03). Two (2) grams of (fresh and dried) turkey berries was weighed and spread evenly into a crucible and incinerated in a muffle furnace for 4–6 h at a constant temperature of 550°C until a light grey ash was obtained, indicating the removal of all organic matter. It was then cooled in a desiccator and weighed. Ash was calculated as follows:

$$\text{Total Ash (\%)} = [(W_2 - W_1) / W_s] \times 100$$

Where:

W_1 = weight of empty crucible.

W_2 = weight of crucible + ash.

W_s = weight of sample.

2.4.1.5 Carbohydrate content

The carbohydrate content was estimated by difference. The percentage of carbohydrates was calculated using the following formula:

$$\begin{aligned} \text{\% Carbohydrate} &= 100 - [\text{Moisture (\%)} + \text{Crude Protein (\%)} \\ &\quad + \text{Crude Fat (\%)} + \text{Ash (\%)}] \end{aligned}$$

2.4.1.6 Energy

The energy value was calculated using the Atwater conversion factors of 4 kcal/g for protein, 9 kcal/g for fat and 4 kcal/g for carbohydrate. Metabolisable energy (ME) was computed according to:

$$\begin{aligned} \text{Energy (kcal/100 g)} &= (4 \times \text{protein}) + (9 \times \text{fat}) \\ &\quad + (4 \times \text{carbohydrate}) \end{aligned}$$

where protein, fat and carbohydrate are in g/100 g of sample.

2.4.2 Minerals and vitamin C determination

The mineral composition of the dried turkey berries [phosphorus (P), calcium (Ca) and iron (Fe)], was determined using the dry ash extraction method as described by the Association of Official Analytical Chemists (AOAC International, 2005).

2.4.2.1 Sample ashing and mineral extraction

Approximately 2 g of each dried and finely ground sample was placed in a clean, pre-weighed porcelain crucible and incinerated in a muffle furnace at 550°C for 5 h until a white or light gray ash was obtained. After cooling, the ash was dissolved in 5 mL of 1 N nitric acid, filtered, and made up to a known volume with distilled water for analysis.

2.4.2.2 Iron

Iron content was measured using the method described by Achikanu et al. (2013). The ash solution was treated with a

reducing agent and complexed with 1,10-phenanthroline to form a reddish-orange ferrous complex. Absorbance was measured spectrophotometrically at 510 nm, and iron concentration was calculated using a standard curve prepared from known concentrations of ferrous ammonium sulfate hexahydrate.

2.4.2.3 Calcium

Calcium was determined simultaneously by the complexometric ethylenediaminetetraacetic acid (EDTA) titrimetric method (AOAC 984.27). Titration was carried out in the presence of murexide indicator at pH 12. The endpoint was indicated by a distinct colour change, and the concentration was calculated based on the volume of EDTA used.

2.4.2.4 Phosphorus

Phosphorus content was determined by vanadomolybdate yellow colorimetric spectrophotometry (AOAC 965.17). An aliquot of the digested sample solution was treated with ammonium vanadate and ammonium molybdate reagent, forming a yellow complex. Absorbance was measured using a Jenway electronic spectrophotometer at 420 nm. The concentration of phosphorus was quantified using a standard calibration curve of known phosphate concentrations prepared from monopotassium dihydrogen phosphate (KH_2PO_4).

2.4.2.5 Vitamin C

Vitamin C (ascorbic acid) was determined by the titrimetric method according to (AOAC International, 2007). Twenty grams of the fresh fruit was blended (powders were mixed with oxalic acid) and the volume made up to 100 mL with 0.4% oxalic acid in a volumetric flask. The resulting solution was filtered and 5 mL of the filtrate and 15 mL 0.4% oxalic acid was pipetted into a conical flask and titrated with the standard redox dye (2, 6-dichlorophenol indophenols) in the burette until the solution turned pink and remained at that colour for 10 s. This colour change indicated that all the ascorbic acid in the solution had been used up and therefore, there was no electron available to reduce the 2, 6-dichlorophenol indophenols. The vitamin C content was calculated using the following formula;

$$\text{Ascorbic acid (mg/100 g)} = \text{Titre} \times \text{Dye equivalent} \times \text{dilution factor}$$

2.4.3 Total phenolic content

The total phenolic content (TPC) of turkey berries was determined using the Folin–Ciocalteu method, as described by Odabasoglu et al. (2005) with slight modifications. For the assay, 100 μL of each gallic acid standard or sample extract was mixed with 500 μL of distilled water and 100 μL of Folin–Ciocalteu reagent. The reaction mixture was allowed to stand for 6 min at room temperature. Then, 500 μL of distilled water and 1 mL of 7% sodium carbonate solution were added. After incubation for 90 min, the absorbance was measured at 760 nm using a Shimadzu spectrophotometer (Model UV-1800 240V IVDD).

The total phenolic content was calculated and expressed as milligrams of gallic acid equivalents per gram of extract (mg GAE/g) using the formula:

$$\text{TPC (mg GAE/g)} = (X \times V) / M$$

Where:

X = Concentration of phenolics determined from the calibration curve (mg/mL).

V = Volume of extract used in the assay (mL).

M = Mass of extract used (g).

2.4.4 Determination of antioxidant activity

The total antioxidant activity of the turkey berry samples was evaluated using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical scavenging assay, following the method described by Brand-Williams et al. (1995) with slight modifications. Oxidized DPPH, when dissolved in methanol, yields a deep purple hue that becomes discoloured upon reduction by antioxidant compounds. To prepare the sample extract, 2.5 g of turkey berries was homogenised in 50 mL of methanol and filtered using Whatman No. 42 filter paper to obtain a clear extract.

A 0.002% DPPH solution in methanol was prepared, and its absorbance was measured at 515 nm using a spectrophotometer (Model: TR 515, The Tintometer Limited, United Kingdom). For the antioxidant activity test, 3 mL of the DPPH solution was mixed with the sample extract and allowed to react in the dark for 15 min. The absorbance of the reaction mixture was then recorded at 515 nm.

The percentage inhibition of DPPH radicals by the sample was calculated using the following formula:

$$\text{Inhibition (\%)} = [(A - B) / A] \times 100$$

Where:

A = Absorbance of the DPPH solution without sample (control).

B = Absorbance of the DPPH solution after reaction with the sample extract.

2.5 Statistical analysis

All data analyses were performed using the SAS software version 9.4 (SAS Institute Inc., Cary, NC, United States). The GLM procedure in SAS was used to determine the effects of drying method and pretreatment as well as their interactions on the proximate composition, total phenolic content, antioxidant properties, vitamin C and mineral content of turkey berries. GLM was used to analyze the two factor factorial experimental design because it is more robust than ordinary ANOVA as it is able to deal with a combination of categorical and continuous factors as predictors. When significant effects were observed, treatment means were compared using Tukey's Honestly Significant Difference (HSD) test.

3 Results and discussion

This study shows that processing methods, especially the combination of drying methods and pretreatment (hot water blanching), significantly alters the proximate profile, energy density, mineral content, vitamin C, total phenolic content and antioxidant activity of turkey berry powders. The most direct effect of drying was the sharp reduction in moisture (from about 82% in

TABLE 1 Effect of pretreatment and drying methods on the proximate composition of turkey berry fruits on as-is basis (wet basis).

Pre-treatment	Drying method	Moisture (%)	Protein (%)	Total fat (%)	Ash (%)	Carbohydrate (%)	Energy (kcal/100 g)
Fresh (control)		81.68 ± 0.60 ^a	3.84 ± 0.06 ^e	0.20 ± 0.01 ^b	1.30 ± 0.02 ^s	12.11 ± 0.07 ^f	65.46 ± 0.70 ^f
Unblanched (U)	Solar dry (SD)	7.33 ± 0.03 ^c	15.47 ± 0.39 ^d	2.97 ± 0.05 ^c	6.01 ± 0.04 ^d	68.26 ± 0.30 ^b	361.68 ± 0.28 ^c
	Freeze dry (FD)	7.83 ± 0.08 ^c	16.35 ± 0.19 ^{cd}	3.06 ± 0.06 ^{bc}	5.79 ± 0.07 ^e	66.94 ± 0.34 ^{bc}	361.01 ± 0.41 ^c
	Convection dry (CD)	8.49 ± 0.09 ^b	16.25 ± 0.22 ^{cd}	3.18 ± 0.07 ^b	5.69 ± 0.06 ^{cd}	66.40 ± 0.03 ^{cd}	359.58 ± 0.54 ^d
	Vacuum dry (VD)	7.57 ± 0.12 ^c	17.74 ± 0.10 ^b	4.04 ± 0.12 ^a	5.49 ± 0.16 ^f	65.35 ± 0.29 ^{de}	367.58 ± 0.52 ^b
Blanched (B)	Solar dry (SD)	5.45 ± 0.16 ^e	20.01 ± 1.27 ^a	1.57 ± 0.04 ^s	6.81 ± 0.02 ^b	66.17 ± 1.43 ^{cd}	358.82 ± 0.36 ^d
	Freeze dry (FD)	4.19 ± 0.01 ^f	15.23 ± 0.12 ^d	2.50 ± 0.02 ^e	6.33 ± 0.10 ^c	71.77 ± 0.21 ^a	370.49 ± 0.56 ^a
	Convection dry (CD)	4.72 ± 0.06 ^f	20.97 ± 0.08 ^a	2.70 ± 0.02 ^d	7.04 ± 0.04 ^a	64.57 ± 0.12 ^c	366.43 ± 0.30 ^b
	Vacuum dry (VD)	6.69 ± 0.02 ^d	17.06 ± 0.14 ^{bc}	1.81 ± 0.05 ^f	6.95 ± 0.04 ^{ab}	67.49 ± 0.13 ^{bc}	354.49 ± 0.40 ^e

Values are reported as mean ± standard deviation (n = 3). ^{a-f}Means with the same letter in the same column are not significantly different at α = 0.05.

the fresh control to below 9% in all dried treatments). This reduction therefore, concentrated macronutrients and minerals when results were expressed on a wet basis. This concentration effect is widely reported for fruits and vegetables and is a major reason dried powders appear to have higher nutritional content (per 100 g) than fresh samples. Beyond concentration, the significant drying method and blanching interactions observed for most indices in our dataset indicate that pretreatment changes both drying kinetics and compositional outcomes, which is consistent with broader evidence that blanching modifies tissue permeability and enzyme activity. Blanching done prior to dehydration significantly enhances drying efficiency by reducing processing time by 15%–42%, and also facilitates extraction of bioactive compounds thereby significantly increasing the value of some phytochemicals (Sharma et al., 2025).

3.1 Proximate composition

3.1.1 Moisture content

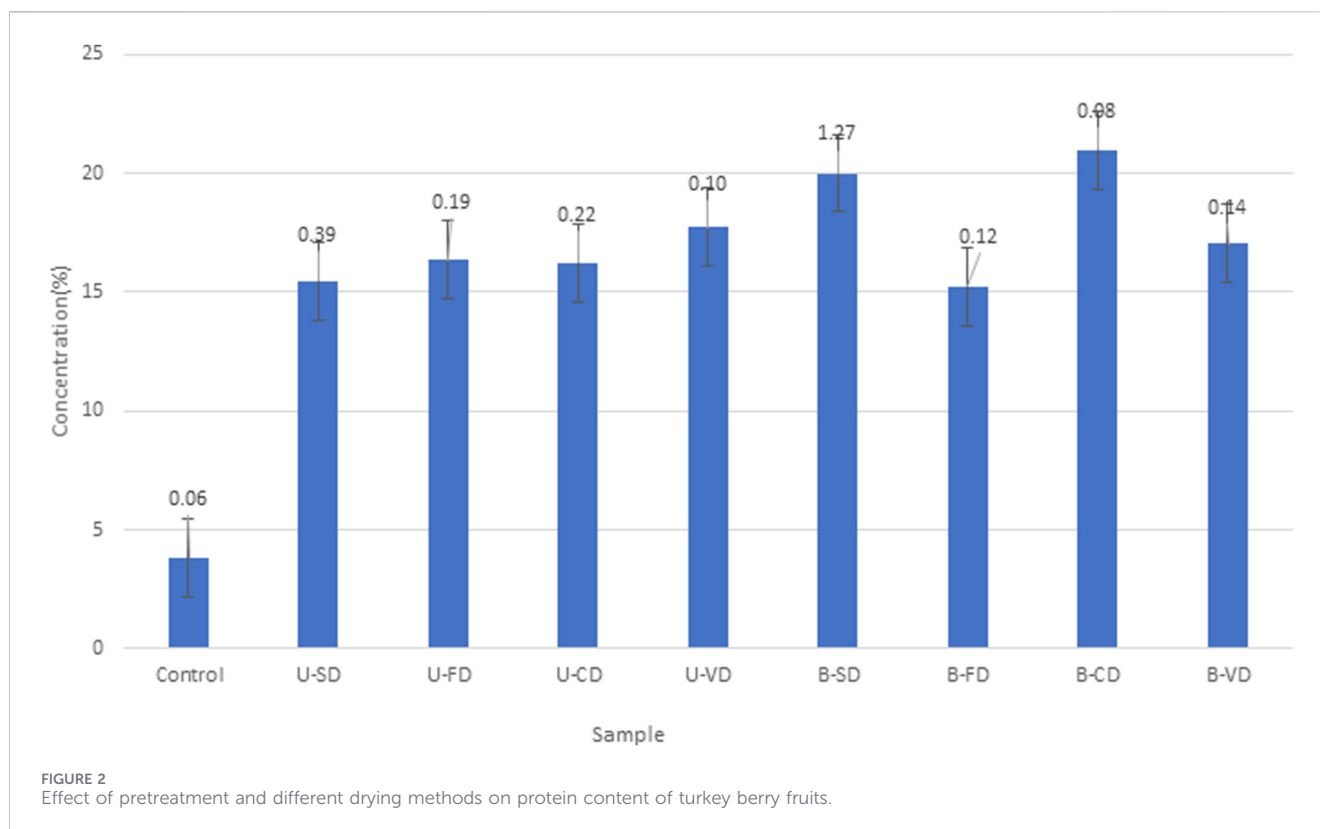
The fresh turkey berries (control) had a moisture content of 81.68% (Table 1), which was significantly higher than any dried sample (p < 0.05). After drying, moisture levels dropped to single digits in a range of 4.19% ± 0.01% to 8.49% ± 0.09% which is beneficial for shelf stability and prevention of microbial growth (Nyangena et al., 2020). Among the drying methods, U-CD recorded the highest moisture content. It was also observed that blanching prior to drying resulted in more thorough moisture removal from the fruits. In particular, B-FD had the lowest moisture (4.19%), a value significantly lower than its unblanched counterparts (7.83%). Blanched samples generally showed reduced final moisture compared to unblanched samples dried by the same method. All drying methods yielded low residual moisture (between 4% and 8%), which is low enough to prevent microbial spoilage compared to the fresh berries. Blanching prior to freeze drying produced the lowest moisture content. This is consistent with reports that, the ice sublimation under low pressure during freeze-drying creates porous structures and enables efficient water removal (Dziki, 2020; Zambrano et al., 2019). In contrast, convection (hot-air) drying

without blanching retained the highest moisture among the dried samples. This is plausible because hot-air drying can be limited by surface hardening and internal diffusion resistance in intact tissues while blanching mitigated these barriers by disrupting cell membranes (Wang et al., 2024; Zang et al., 2024). These trends agree with reports that thermal pretreatments accelerate drying by improving moisture diffusion (Sharma et al., 2025). Overall, combining blanching with freeze or convection drying enabled more thorough dehydration, an important factor for shelf stability.

3.1.2 Protein content

Drying had a significant effect on protein content (expressed as % of sample weight). The control contained only 3.84% protein on as-is basis (Table 1), due to dilution by water, and the dried berries had 15%–21% protein. The highest protein concentrations (20.97% and 20.01%) were observed in berries that were blanched then dried with hot-air (B-CD) or solar methods (B-SD) respectively (Figure 2). These higher concentrations could be explained that blanching likely inactivated endogenous enzymes (proteases, oxidases) that could otherwise degrade or alter proteins during prolonged drying, thereby improving protein retention in the high-heat methods (Sharma et al., 2025; Deng et al., 2019; Hadidi et al., 2019; Xiao et al., 2017).

These values, though not significantly different from each other, were significantly higher (p < 0.05) than the freeze dried and vacuum dried samples. This could suggest that blanching prior to higher-temperature drying could assist in preserving or concentrating proteins. In contrast, the lowest protein levels among dried samples were found in blanched freeze-dried (B-FD) samples (15.23%) and unblanched solar-dried (U-SD) (15.47%) samples. Blanching produced differing effects depending on the drying method that was used. In CD and SD samples, it was observed that blanching significantly increased protein content from 16.25% to 20.97% for CD and from 15.47% to 20.01% for SD. In contrast, for gentler methods like freeze and vacuum drying, blanching slightly reduced the protein content. Freeze-drying and vacuum drying are relatively gentle processes, so the protein values in the blanched and



unblanched samples tended to stay very similar. That pattern is consistent with the idea that, at lower product temperatures and under reduced oxygen exposure, enzyme-driven quality changes are less likely to progress compared with higher-temperature hot-air drying (Owusu-Kwarteng et al., 2017; Obembe and Ojo, 2021). It is however important to note that the higher protein percentages in the dried samples were mainly due to the lower moisture content which highlights that drying concentrates nutrients rather than creating them.

3.1.3 Fat content

From the results obtained, fresh turkey berries are naturally very low in fat (0.20% as-is basis) (Table 1). After drying, the measured total fat content increased in all samples (on a weight percentage basis) due to water loss. The higher fat percentages observed in dried samples likely reflect concentration plus differences in lipid extractability after cell disruption (Lekjing et al., 2024). The U-VD sample recorded the highest fat content (4.04%). Reduced pressure processes are often discussed in terms of limiting oxygen exposure and oxidation, which can protect lipids and other oxidation-sensitive constituents during dehydration. This aligns with reports that reduced-oxygen drying environments can better retain labile constituents like unsaturated fats (Deng et al., 2019; Vega-Gálvez et al., 2025; Ninčević Grassino et al., 2025). In comparison, the sample that had the lowest fat among dried treatments was the B-SD sample (1.57%), which was followed closely by B-VD sample (1.81%). These results showed that blanching before drying, led to a reduction in fat content for every drying method ($p < 0.05$). Blanching before vacuum drying

reduced the fat content from 4.04% down to 1.81%. The reduction in fat fraction in blanched dried samples is consistent with the possibility of lipid loss during blanching through leaching of surface-associated lipids or removal of lipid-containing exudates (Tadesse et al., 2023). Blanching-related nutrient loss is well documented for water-soluble components and, in some matrices, can also affect lipid-associated fractions depending on tissue integrity and processing conditions (Sharma et al., 2025).

3.1.4 Ash content

The ash content of the control was 1.30% (Table 1), however this value significantly increased after the samples were dried. This increase is a reflection of mineral concentration as water and other volatiles are removed. Blanching (pretreatment) of the berries before drying increased the ash content in all samples, thus, blanched dried samples had significantly higher ash percentages compared to unblanched ones. According to studies, hot water blanching causes mineral leaching into the water and thus reduces ash content (Sarkar et al., 2021; Sharma et al., 2025). However, in our study, hot-water blanching resulted in higher ash percentages in the final powders compared to the unblanched one. Since the blanched dried powders recorded more ash, it could be explained that blanching removed other soluble solids such as sugars, acids to a greater extent, than minerals, thus, effectively raising the mineral content of dry matter (Adedeji et al., 2025). A similar “relative increase” in ash was recorded by Sharma et al. (2025), when blanching reduced non-mineral components preferentially. Another possible factor is that blanching improved drying efficiency and uniformity, reducing handling losses of minerals. Follow-up analyses of the blanching water for leached

minerals would help confirm whether blanching enhanced mineral retention or simply caused proportionate shifts (Deng et al., 2019). Among the dried powders, ash ranged from 5.49% to 7.04%, peaking in B-CD (7.04%) and reaching its lowest value in U-VD (5.49%). Similar results were obtained by Grassino et al. (2024) in their study evaluating the effect of different drying processes on the chemical and texture profile of *Cucurbita maxima* pulp. Xiao et al. (2017) and Adedeji et al. (2025) explain that hot-water blanching has been associated with leaching of nutrients and in this study, it could be that there was leaching of non-mineral solids, which made ash appear higher as a fraction of the remaining dry matter.

3.1.5 Carbohydrate and energy content

In the control samples, carbohydrates made up 12.11% (due to dilution by water), whereas in dried samples, the carbohydrate content, ranged from about 64.6% to 71.8%. Blanching with freeze drying yielded the highest carbohydrate content of 71.77%. In terms of energy content, the dried berries recorded roughly 5–6 times more energy per 100 g, with values ranging from 354–370 kcal/100 g compared to the control. Despite this overall recorded higher energy content, there were significant differences in energy content among the dried treatments ($p < 0.05$). The highest caloric value was found in the B-FD samples (370.49 kcal/100 g). In their study on the impact of three drying methods on the properties of *Citrus reticulata* Blanco cv. Dahongpao powder, Li et al. (2023) reported that freeze-drying, which uses low temperature and low pressure preserves heat-sensitive substances and can retain more soluble sugars while hot-air drying can promote sugar browning reactions. The high carbohydrate content (and energy density) in the blanched freeze-dried samples could be attributed to the gentle, low-temperature nature of freeze drying which minimizes thermal degradation or volatilization of sugars and organic acids, while the blanching also inactivates enzymes that could otherwise break down or oxidize sugars (Adetoro et al., 2021; Managa et al., 2020). Therefore combining blanching and freeze drying best preserved the soluble solids (natural sugars, etc.) that contribute to carbohydrate-by-difference and calories. By contrast, the blanched convection-dried samples had one of the lower carbohydrate percentages among dried samples. This may be due to a combination of blanching effects and the harsher convective drying conditions. Prolonged heat exposure can induce Maillard browning and sugar degradation, or greater loss of sugar-rich components, thereby lowering measured carbohydrates (Deng et al., 2019). The lowest carbohydrate percentage observed was in the B-CD sample.

3.2 Mineral content (Fe, Ca, P) and vitamin C

The effect of pretreatment and drying method on the mineral content (Ca, Fe and P) and Vitamin C of blanched and unblanched fresh and dried turkey berry fruits on as-is basis (wet basis) is shown in Figures 3–6.

The results of the mineral and vitamin C analysis confirm that both drying method and blanching pretreatment are key determinants of micronutrient retention in turkey berries. Dehydration inherently concentrates minerals and other solids, while pretreatments can alter tissue permeability and enzyme activity, creating method-specific nutrient outcomes. In

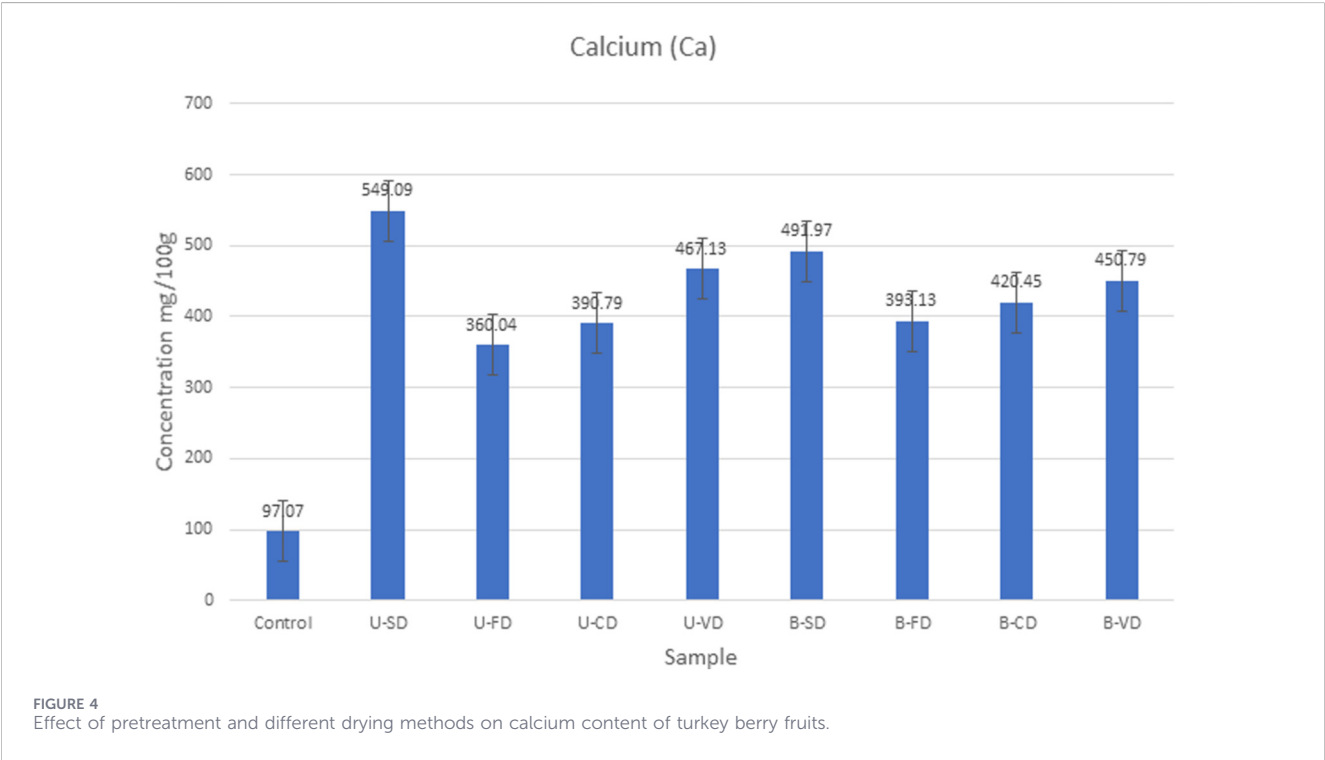
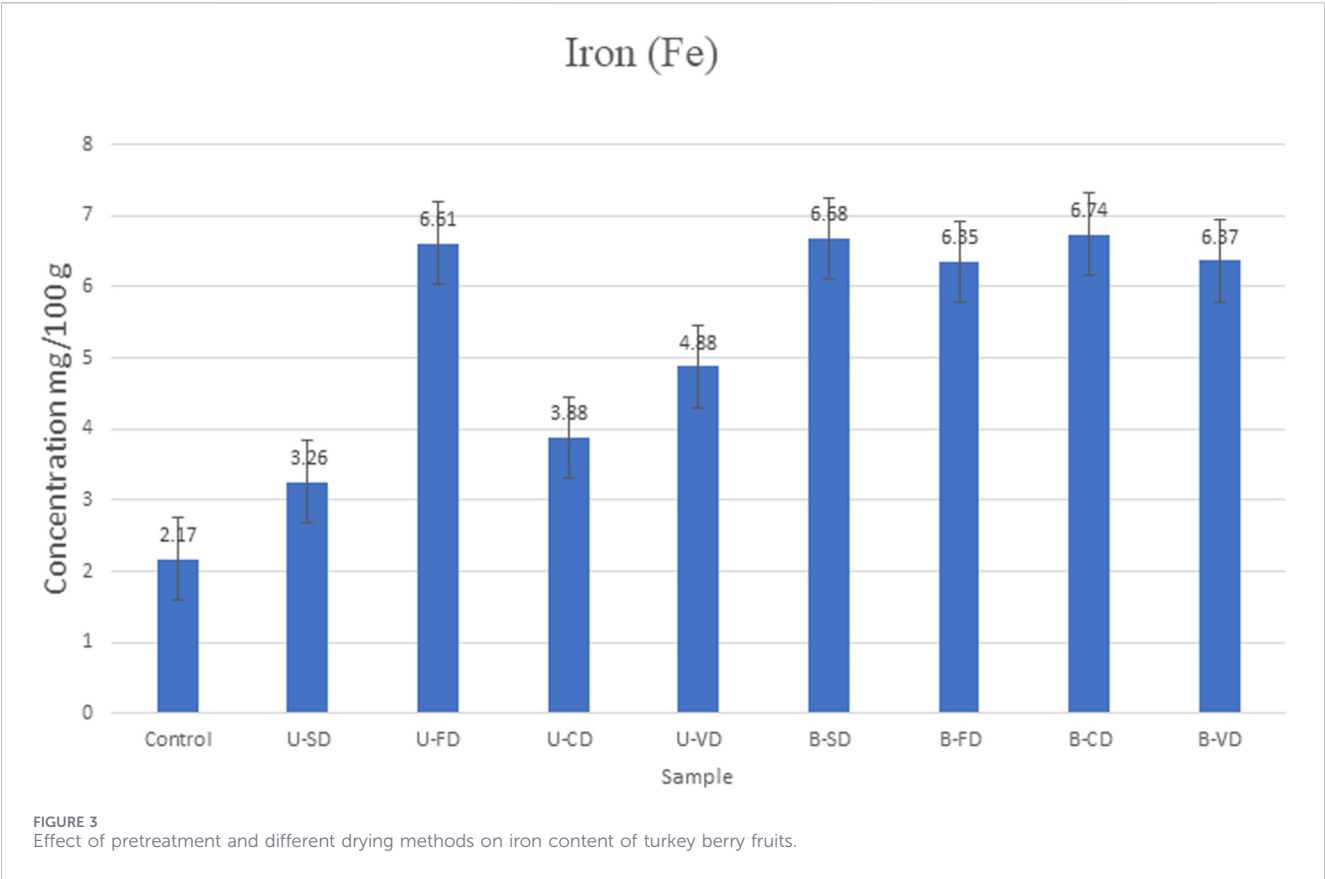
particular, hot-water blanching is well known to cause leaching of water-soluble nutrients (minerals and vitamin C) into the blanch water, and it also inactivates enzymes that would otherwise accelerate nutrient breakdown (Fellows, 2017; Sharma et al., 2025). Our findings reflected this dual nature although in some cases blanching improved stability of a nutrient during drying, and in others it caused upfront losses, underscoring the need to optimize blanching conditions for each nutrient.

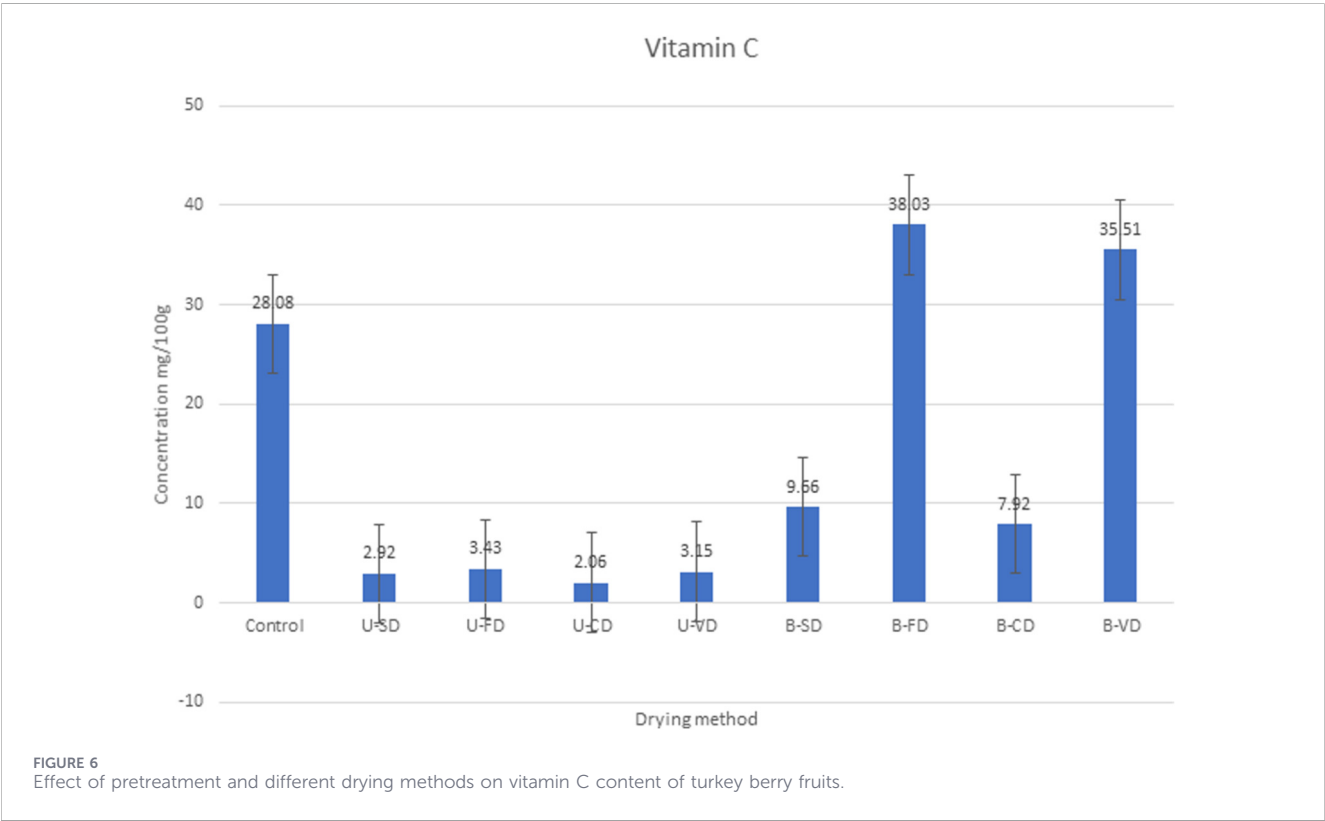
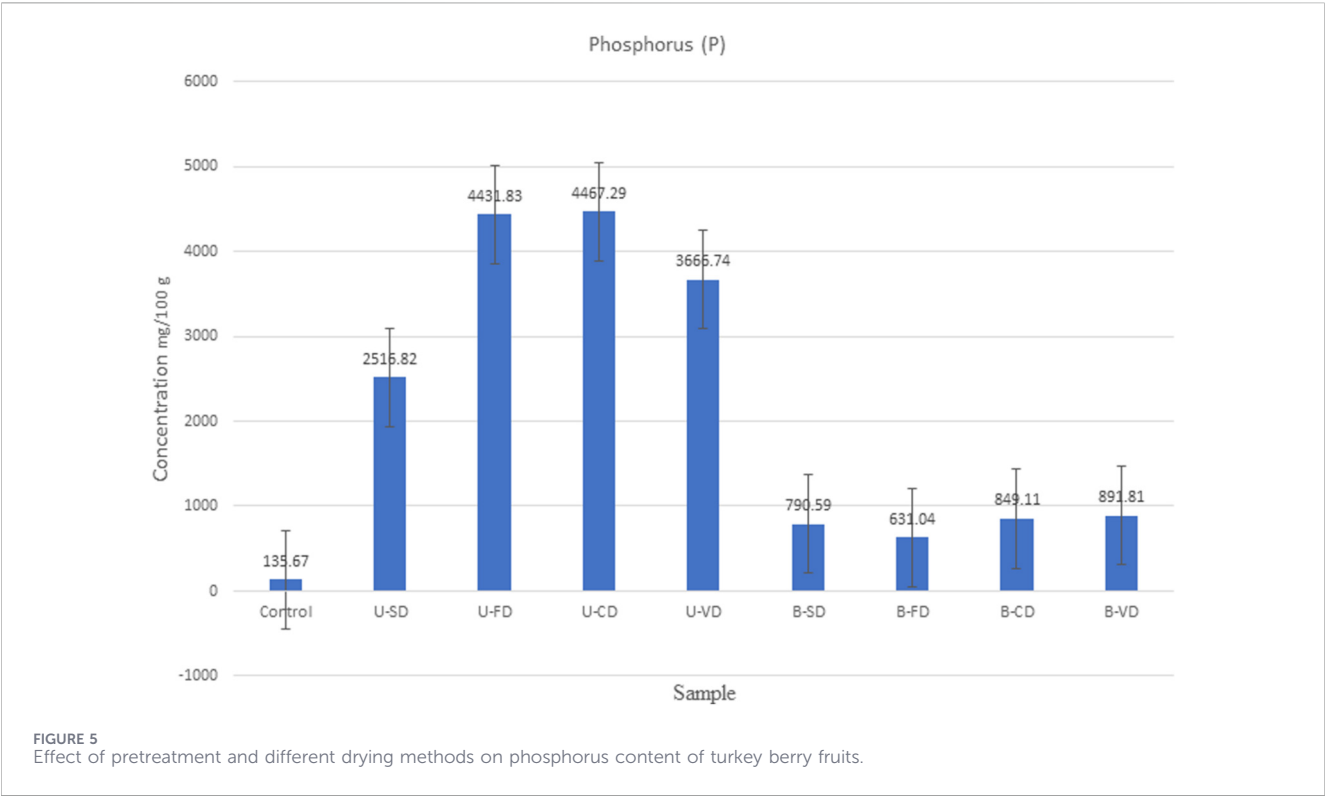
3.2.1 Iron (Fe)

The Fe content ranged from 2.17 ± 0.15 mg/100 g in the control samples to 6.74 ± 0.03 mg/100 g in the dried samples (Figure 3). Higher Fe values were obtained in all unblanched dried samples compared with the control. Among drying methods, U-FD samples showed higher Fe than other samples after drying. This trend is consistent with reports that freeze-drying can yield higher retained iron than solar or hot-air drying in plant materials, with solar drying often producing the lowest Fe values (Asante et al., 2024). Similar results have been reported by Kabeer et al. (2023) in their study of the effect of different drying techniques on the nutrient and physiochemical properties of ripe Nendran banana powder. They observed that freeze-dried products retain iron levels closer to the raw material than higher-temperature methods. In our study, Fe was quantified after mineralisation by dry ashing (muffle furnace at 550 °C for 5 h) followed by dissolution of the ash in nitric acid prior to instrumental measurement. This method targets total inorganic Fe in the mineral residue and minimises matrix-related interferences from sugars, proteins, and pigments. Thus, differences in Fe are more likely linked to processing effects on mineral retention or distribution within the tissue. Blanching had a notable influence on Fe where blanched samples showed equal or higher Fe content than unblanched samples under the higher-temperature drying methods. Blanching prior to drying increased the measured content of Fe under most drying methods. Blanching before convection drying boosted Fe from about 3.9 to 6.7 mg/100 g, and similarly from about 3.3 to 6.7 mg in solar drying. Although mineral behaviour during blanching is matrix- and method-dependent, increases in measured Fe after blanching plus dehydration have been reported. Increased Fe content was observed after moringa leaves were steam blanched (Wickramasinghe et al., 2020) and where optimised water blanching combined with cabinet drying retained higher iron (Neelavathi et al., 2025). Blanching of fruits and vegetables is a standard step to inactivate polyphenol oxidase and related oxidative enzymes. This step limits oxidative changes during subsequent drying and storage that can promote browning reactions and stronger binding of minerals within oxidised pigment complexes (Moon et al., 2020; Ijod et al., 2024). U-FD samples had the highest Fe content among all the unblanched samples. In contrast, U-SD and U-CD samples recorded lower Fe values (3.26 ± 0.11 and 3.88 ± 0.07 mg/100 g respectively) than the samples dried using freeze drying or vacuum drying. These differences show that gentler drying methods like freeze-drying better preserve Fe content relative to higher-temperature methods in the absence of pretreatment.

3.2.2 Calcium (Ca)

Calcium followed a similar trend of increased concentration upon drying (Figure 4). All dried samples showed Ca levels





several-fold higher than the control due to moisture loss. Similar trend was observed by [Kouadio et al. \(2020\)](#) in their study of the proximate composition and phytochemical properties of fresh and boiled turkey berries. The highest Ca level was observed in U-SD samples (549.09 ± 2.72 mg/100 g). Relatively higher Ca levels were also recorded in U-VD samples (467.13 ± 0.96 mg/100 g) when compared to U-CD and U-FD samples. The effect of blanching on Ca varied with drying method. Blanching showed mixed effects on

Ca across drying methods, which is plausible because blanching can promote mineral leaching into the blanch water, yet the extent is matrix- and condition-dependent, and Ca may be less affected than other minerals in some products (Korus, 2022; Sharma et al., 2025). Blanching caused slight Ca losses in some cases while in some other situations, blanching slightly improved Ca values. SD samples recorded a decrease in Ca content (from 549.09 ± 2.72 mg to 491.97 ± 2.63 mg/100 g) after blanching. On the other hand, slightly higher Ca values were obtained for B-FD and B-CD samples. Although the blanching effect on Ca was not uniform, all blanched treatments still recorded significantly higher Ca than the control on as-is basis. In practical terms, ensuring adequate blanch conditions or possibly using a calcium-retaining pretreatment solution may help retain more Ca while still obtaining the benefits of blanching.

3.2.3 Phosphorus (P)

Phosphorus exhibited the most pronounced change with blanching. Like Fe and Ca, P in the turkey berries that were studied was concentrated by drying. U-CD and U-FD samples had the highest P levels (4467.29 ± 76.69 and 4431.83 ± 32.25 mg/100 g) (Figure 5), which are more than 30 times the P in control (135.67 ± 0.52 mg) on as-is basis. U-VD and U-SD samples yielded slightly lower P content. However, blanching prior to drying caused a dramatic reduction in phosphorus content with all drying methods. B-FD berries contained only 631.04 ± 2.01 mg phosphorus compared to the U-FD samples (4431.83 mg). Similarly, phosphorus levels in CD samples decreased from 4467.29 mg in the unblanched samples to 849.11 ± 2.10 mg/100 g with blanching. Hot-water blanching reduces phosphorus, and longer blanching causes larger P losses (time/intensity effect) (Muchoki et al., 2025). Fadupin et al. (2017), showed that blanching for 30 min or more significantly reduced phosphorus in green leafy vegetables, demonstrating the classic time-dependent leaching loss pattern. Korus (2022) in his study on the effect of pre-treatment and drying methods on the content of minerals, B-group vitamins and tocopherols in kale leaves, reported that blanching reduced minerals and explicitly stated that blanching drives losses of water-soluble compounds (minerals), with the extent influenced by time and factors like vegetable:water ratio and contact surface. Among blanched samples, VD recorded the highest P levels (892 mg/100 g), whereas FD recorded the least amount of phosphorus (631 mg/100 g). Overall, to maximize P retention, it is important to avoid the water-blanching step. Our findings agree with this trend where for all the dried samples, the blanched ones has significantly lower P. The consistency of this effect highlights that phosphorus is highly water-soluble and readily lost in the blanching step. According to Sharma et al. (2025), other methods like steam or microwave blanching could be used to prevent leaching or the severity of blanching could be minimized by using shorter blanch times, lower temperature and smaller water to fruit ratio.

3.2.4 Vitamin C content

Vitamin C was the most sensitive nutrient measured in this experiment, highly sensitive to both drying method and

pretreatment, and it varied dramatically with treatments. Fresh turkey berry (control) had a moderate vitamin C content (28.08 ± 0.08 mg/100 g) (baseline), but all drying methods without blanching drastically reduced vitamin C content ($p < 0.05$), especially in unblanched, high-heat dried samples (Figure 6). These samples had very low vitamin C levels, which aligns with the well-established fact that vitamin C is highly prone to thermal and oxidative degradation (Managa et al., 2020; Daghan et al., 2018). Freeze-drying, preserved vitamin C levels slightly better than the other drying methods for the unblanched samples (3.43 ± 0.11 mg/100 g). The highest vitamin C levels in our study were recorded when blanching was combined with the most gentle drying methods (B-FD and B-VD samples) (Figure 6). These retained significantly more vitamin C than any other dried treatments. This finding is in line with other studies which showed that freeze drying best preserved vitamin C in fruits, followed by vacuum or other oxygen-limited drying methods, whereas hot-air and sun drying caused drastic vitamin C loss (Muchoki et al., 2025; Managa et al., 2020). Two mechanisms could explain this observed results. Blanching could have inactivated ascorbic acid oxidase and other enzymes that could rapidly degrade vitamin C, ensuring that the blanched fruits no longer lost vitamin C enzymatically during the handling and early drying stages (Sharma et al., 2025). Additionally, freeze drying and vacuum drying provide low-temperature, low-oxygen environments, thus slowing the chemical oxidation of ascorbic acid during drying (Deng et al., 2019). In a few treatments the percentage of vitamin C in the dried product was higher than in the fresh samples, but this is a result of nutrient concentration when water was removed. This does not mean that more vitamin C was produced during drying (Deng et al., 2019). Our results also echo findings from recent work on turkey berry and related *Solanum* species, which indicated that pretreatments (like boiling or chemical dips) and controlled drying can preserve certain nutrients and phytochemicals, but the outcomes depend on specifics of the process (Abraham et al., 2022; Deka et al., 2024).

3.3 Total phenolics and antioxidant activity

The effects of pretreatment and drying methods on the antioxidant activity and total phenolic content of blanched and unblanched fresh and dried turkey berries on as-is (wet basis) is shown in Table 2.

Drying had a significant effect on the measured phytochemicals of turkey berry in this study. All dried samples showed higher total phenolic content (TPC) and antioxidant activity than the fresh fruit on a per-100 g as-is basis (Table 2). This is a common observation in dried plant materials because removal of water concentrates phenolic compounds, and the drying process can also enhance extractability of bound phenolics from the cell matrix (Managa et al., 2020). In our study, the fresh berries had the lowest TPC and antioxidant readings, whereas any form of drying, resulted in significantly higher TPC levels. Similar trends have been reported in leafy vegetables and fruits where dehydration increases the concentration of phenolics and can even increase the amount that solvents can extract, due to breakdown of cell walls (Deng et al., 2019). Additionally, moderate thermal processing may release phenolics from insoluble complexes or induce the formation of new

TABLE 2 Effect of pretreatment (blanching) and drying methods on the antioxidant activity and total phenolic content of turkey berry fruits on as-is basis.

Pre-treatment	Drying method	Total phenolic content (mg GAE/g)	Antioxidant activity (%)
Fresh (control)	-	5.21 ± 0.42 ^f	52.07 ± 0.85 ^e
Unblanched (U)	Solar dry (SD)	12.82 ± 0.41 ^e	93.50 ± 0.45 ^a
	Freeze dry (FD)	20.16 ± 0.30 ^b	92.32 ± 0.09 ^c
	Convection dry (CD)	15.27 ± 1.63 ^c	92.16 ± 0.04 ^c
	Vacuum dry (VD)	16.84 ± 1.58 ^c	93.11 ± 0.24 ^b
Blanched (B)	Solar dry (SD)	14.53 ± 0.61 ^d	93.73 ± 0.07 ^a
	Freeze dry (FD)	20.54 ± 0.32 ^b	93.21 ± 0.13 ^b
	Convection dry (CD)	15.72 ± 1.27 ^c	90.32 ± 0.29 ^d
	Vacuum dry (VD)	21.15 ± 0.13 ^a	94.07 ± 0.16 ^a

Values are reported as mean ± standard deviation (n = 3). ^{a-f}Means with the same letter in the same column are not significantly different at α = 0.05.

antioxidant derivatives, thereby increasing the measured TPC and antioxidant capacity despite some heat degradation of sensitive compounds (Deka et al., 2024). This phenomenon likely contributed to the consistently high antioxidant values we observed in dried turkey berry powders.

Among unblanched dried samples, U-FD recorded the highest total phenolic content (20.16 ± 0.30 mg GAE/g), followed by the U-VD samples (16.84 ± 1.58 mg GAE/g), then U-CD (15.27 ± 1.63 mg GAE/g) and finally U-SD produced the least amount of total phenolic content. Antioxidant activity was high across all unblanched dried powders with U-SD samples recording the highest activity (93.50% ± 0.45%) and U-CD samples comparatively produced the lowest values (92.16% ± 0.04%). Blanching altered total phenolic content and antioxidant activity in a method-dependent manner which is consistent with the significant interaction term in the ANOVA table (Table 3). For total phenolic content, the highest overall value was observed in B-VD berries (21.15 ± 0.13 mg GAE/g) (Table 2). B-FD berries also recorded high total phenolic content (20.54 ± 0.32 mg GAE/g). The relatively higher TPC values could be a result of the low temperature protection of phenolic compounds observed during processing. This matches the findings of Managa et al. (2020) for night shade berries, where they observed that freeze-dried samples retained more phenolic metabolites and antioxidant activity than those dried with heat. The highest TPC and antioxidant activity were observed in the B-VD samples. Vacuum drying operates at reduced pressure, often with mild heat, which limits oxygen exposure and slows oxidative reactions (Sharma et al., 2025). This could suggest that there was minimal loss of phenolics with blanching when samples were freeze dried. In contrast, blanching slightly reduced total phenolic content under convection drying although the figure was not significantly different from the unblanched samples (unblanched 15.27 ± 1.63 mg/g and blanched 15.72 ± 1.27 mg GAE/g). For B-SD berries, the total phenolic content (14.53 ± 0.61 mg GAE/g) were significantly different from the U-SD ones (12.82 ± 0.41 mg GAE/g).

Drying method was a major determinant of how much total phenolic content and antioxidant activity were recorded. Our results showed significant differences among the methods, aligning with literature that the balance of temperature,

oxygen, and time in drying influence bioactive retention (Managa et al., 2020). It is remarkable that drying using the solar dryers produced relatively high antioxidant activity in our turkey berry samples. Typically, sun/solar drying is expected to cause larger losses of vitamins and phenolics due to long exposure to air, light, and fluctuating temperatures. Yet, the solar-dried powders still showed strong antioxidant values that was slightly lower than the values obtained for freeze or vacuum dried samples. In some food matrices, extended drying can induce the generation of novel antioxidant compounds (e.g., browning products or polymerized phenolics) that compensate for the degradation of the original antioxidants (Muchoki et al., 2025). Thus, while solar drying is generally harsher, its ultimate impact on antioxidant activity can vary. Our data suggest that turkey berry's antioxidant levels were still high even after solar dehydration. This is a promising alternative for small scale processors who utilize such low-cost drying options. However, care must be taken since other nutrients like vitamin C were severely depleted by this method.

3.4 Statistical significance and data reliability

The dataset for all the indices measured shows clear and consistent treatment effects. The two-way ANOVA showed that drying method was the main source of variation (Table 3).

The proximate composition, mineral and vitamin C, and phytochemical datasets all showed clear, statistically robust treatment effects, with drying method consistently emerging as the dominant source of variation. For proximate indices, two-way ANOVA indicated very large drying-method effects across all parameters, particularly moisture and energy (Table 3), while blanching (pretreatment) also influenced several indices, significantly affecting moisture, protein, total fat, and ash but not carbohydrate and energy. Importantly, the drying method × blanching interaction was significant for all proximate indices, confirming that the impact of blanching depended on the drying technique used. Model performance further supported the reliability of these results, with excellent fit ($R^2 = 0.9935\text{--}0.99998$). Similarly, two-way ANOVA confirmed strong treatment effects for minerals

TABLE 3 Analysis of variance (ANOVA) for the effects of pretreatment, drying method, and their interaction on the proximate composition, minerals, vitamin C, antioxidant activity and total phenolic content of turkey berry fruits.

Source	F-value											Total phenolic content
	Moisture	Protein	Total fat	Ash	Carbo hydrate	Energy	Iron	Calcium	Phosphorus	Vitamin C	Antioxidant activity	
Drying method	70960.1*	481.14*	1865.67*	2202.27*	6752.67*	237158*	996.06*	17773.5*	1467.18*	7337.33*	135.74	7988.50*
Pretreatment	839.78*	98.71*	2453.12*	1194.94*	13.09	0.23	3752.84*	8.57	8857.91*	25085.1*	20.58*	0.19
Drying method x pretreatment	63.84*	72.43*	302.14*	53.57*	62.43*	708.20*	717.31*	544.51*	224.01*	3921.11*	5.90*	20.43*
Mean	14.88	15.88	2.45	1.289	61.01	329.51	5.22	402.27	2042.32	14.53	15.81	88.28
Model R-squared	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.97	0.99
Model coefficient of variability (CV)	1.44	2.89	2.36	0.07	0.85	0.14	1.44	0.56	3.80	2.12	5.85	0.40
Root mean square error (RMSE)	0.21	0.46	0.06	5.71	0.52	0.47	0.075	2.24	77.56	0.31	0.93	0.35

Asterisk (*) indicates significance at $p < 0.05$.

and vitamin C, with drying method having highly significant effects on Fe, Ca, P, and vitamin C (very large F-values; $p < 0.05$) (Table 3), while blanching significantly influenced Fe, P, and vitamin C but not Ca. The drying method $\times$ blanching interaction was significant for all four nutrients ($p < 0.05$), reinforcing that pretreatment responses varied by drying approach. Antioxidant activity and total phenolic content followed a similar interaction-driven pattern: drying method had a highly significant effect on antioxidant activity, blanching alone was not significant, but the drying method $\times$ blanching interaction was significant, showing that blanching effects depended on the drying method (Table 3). For total phenolics, blanching and the interaction term were both significant, and model performance remained strong ($R^2 = 0.974$ for total phenolics; 0.999 for antioxidant activity).

4 Conclusion

This study showed that shelf-stable turkey berry powders can be produced through solar, convection, vacuum, and freeze drying. Blanching generally enhanced drying efficiency, while the quality of the powders was influenced by the combined effect of pretreatment and drying method. Phosphorus levels were lower in blanched dried powders, whereas vitamin C was better retained when blanching was combined with freeze or vacuum drying. Total phenolic content and antioxidant activity were higher in dried powders than in the fresh control, with the highest functional quality recorded in blanched samples dried by vacuum or freeze drying. Overall, the results indicate that the most appropriate processing method depends on the particular nutritional or functional quality attribute desired in turkey berry powder production.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GE: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review and editing. AA: Investigation, Writing – original draft. FA: Data curation, Writing – review and editing. MA: Data curation, Writing – review and editing. RK-A: Data curation, Writing – review and editing. RB: Data curation, Writing – review and editing.

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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.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frfst.2026.1776480/full#supplementary-material>

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