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EFFECTS OF BLANCHING AND DRYING ON THE BIOACTIVE COMPOUNDS OF RED BEETROOT (*BETA VULGARIS* L. VAR RUBRA) POWDER

Yohanes Kristianto[1], Arsinah Habibah Habibah Fitriah[2]✉, Nur Rahman[1],
Indri Hapsari[1], Tri Dewanti Dewanti Widyaningsih[2], Siti Narsito Narsito Wulan[2],
Hidayat Sujuti[3]

[1]Department of Nutrition, Polytechnic of Health Ministry of Health
Ijen 77c Street, Malang, East Java, 65112, **Indonesia**
[2]Faculty of Agricultural Technology, Universitas Brawijaya
Jl. Veteran, Ketawanggede, Kec. Lowokwaru, Kota Malang, Jawa Timur 65145, **Indonesia**
[3]Faculty of Medicine, Universitas Brawijaya
Jl. Veteran, Ketawanggede, Kec. Lowokwaru, Kota Malang, Jawa Timur 65145, **Indonesia**

ABSTRACT

Background. Red beetroot is rich in bioactive compounds and antioxidants with numerous health benefits. However, its high moisture content makes it susceptible to decomposition. This study investigated the effects of different drying methods, following blanching pretreatments, on the quality of beetroot powder.

Material and methods. Beetroot samples were pretreated by either water or steam blanching and subsequently dried using vacuum or oven drying. Freeze drying was performed for comparison. Proximate composition, nitrate content, betalain concentration, antioxidant activity (IC_{50}), and color parameters were analyzed using analysis of variance (ANOVA). Principal component analysis (PCA) was conducted to further evaluate the effects of treatments.

Results. Drying methods significantly influenced the bioactive properties of beetroot. Compared with conventional oven drying, vacuum drying yielded powder with higher betalain content (3,478.33 mg/100 g) and stronger antioxidant activity (IC_{50} = 541.73 ppm). Blanching pretreatment also had a significant effect. Steam blanching followed by oven drying produced powder with a nitrate content of 413.23 mg/kg. When steam blanching was combined with vacuum drying, the betalain content increased further to 3,996.81 mg/100 g, significantly higher than that obtained by oven drying, regardless of blanching type. This combination also produced powder with the strongest antioxidant activity (IC_{50} = 493.32 ppm). Blanching and drying treatments both increased the redness (a*) of beetroot powder. Steam blanching followed by vacuum drying resulted in the most intense red color, decreasing yellowness (b*) and lightness (L*) more than water blanching. Freeze-drying preserved high nitrate content, strong antioxidant activity, and good color retention.

Conclusion. Vacuum drying preceded by either steam or water blanching is an effective method for producing beetroot powder with high bioactive compound content.

Keywords: beetroot, drying, blanching, betalain, nitrate, antioxidant

✉arsinah_habibah@student.ub.ac.id; https://orcid.org/0000-0003-1488-9333

INTRODUCTION

Red beetroot is a highly nutritious vegetable rich in vitamins, minerals, and various bioactive compounds, including betalains, phenolics, carotenoids, nitrates, and ascorbic acids. Fresh beetroot contains approximately 115.34 mg/100 g total betalain, 29.66 mg GAE/g total phenolics, 36.37 mg RE/g total flavonoids, and 197.67 mg/100 g nitrate (Hamid and Mohamed Nour, 2018). These bioactive compounds exhibit strong antioxidant activity and contribute to beetroot's reputation as a dietary source of nitrates. Owing to its high nitrate content, beetroot has been associated with several vascular health benefits, including reduced blood pressure, inhibition of platelet aggregation, enhanced endothelial function, and improved exercise performance in both healthy individuals and patients with peripheral arterial disease (Dos S. Baião et al., 2020; Chhikara et al., 2019; Lidder and Webb, 2013). Additionally, beetroot bioactives have demonstrated anticancer potential (Kazimierczak et al., 2014). Betalains, in particular, show promising applications in the food and pharmaceutical industries due to their antioxidant and antimicrobial properties. They can reduce protein oxidation, delay microbial growth, and enhance the color and sensory quality of refrigerated minced beef. Furthermore, betalains have demonstrated antibacterial activity against *Staphylococcus aureus* and *Salmonella enterica* (Chaari et al., 2023a; Chaari et al., 2023b).

Like many vegetables, fresh red beetroot has a high moisture content – up to 92.9% (Abdo et al., 2020) – which makes it highly susceptible to microbial spoilage and enzymatic degradation. To extend its shelf life and preserve nutritional quality, appropriate postharvest handling and processing techniques are required (Sousa-Gallagher et al., 2016). Among these, drying is an effective method for reducing water content and inhibiting microbial growth, enzymatic activity, and physical or chemical deterioration during storage (Russo et al., 2013). The choice of drying method can significantly influence the retention of bioactive compounds and the overall quality of the resulting beet powder. For instance, freeze-drying has been reported to provide good preservation of betalains and polyphenols (Tarasevičienė et al., 2024). However, this method is energy-intensive, time-consuming, and requires substantial capital investment (Assegehegn et al., 2020; Fellows, 2022; Stratta et al., 2020), underscoring the need for alternative drying approaches capable of delivering comparable results.

Drying performance can be further enhanced by pretreatments, such as blanching, which is widely applied to vegetables and has been shown to accelerate air-drying rates and improve the color intensity of dried products (Oshima et al., 2021). Previous studies have shown that blanching before drying improves reconstitution, swelling, and water absorption capacities, foam stability, bulk density, and other functional properties of beet powder (Chaudhary and Kumar, 2020). Moreover, blanching has been found to increase drying efficiency (Mella et al., 2022). To the best of our knowledge, no study has examined the combined effects of steam blanching and vacuum oven drying on red beetroot. Therefore, the objective of this study was to determine the optimal combination of blanching and drying methods for producing beetroot powder with high levels of bioactive compounds and antioxidant activity.

MATERIAL AND METHODS

Raw materials

Fresh red beetroot tubers (*Beta vulgaris* L. var Rubra L.) were obtained from beetroot distributors in Batu City, East Java Province, Indonesia (7°50′58.61″S, 112°28′49.21″E). Tubers were selected based on the following criteria: freshness and integrity; normal, non-deformed shape; harvest age of 90–100 days; individual weight between 200 and 300 g; and absence of visible physical damage. The selected tubers were transported to the experimental laboratory, cleaned of soil and debris, and stored at −20ºC in an ultra-low temperature freezer (ULTRA GUARD™ UF V 500, BINDER GmbH, Germany) until use. Molecular identification of beetroot varieties was carried out at the Variety Identification Laboratory of the Center for Sweetener and Fiber Plant Instrument Standard Testing (Agricultural Instrument Standardization Agency/BSIP Sweetener and Fiber Crops), Ministry of Agriculture. The analysis employed the PCR method using ISSR (Inter Simple Sequence Repeat) marking.

Blanching and drying treatments

The experiment was conducted using different blanching and drying methods as pretreatments prior to powder production. Two drying methods were applied: conventional oven drying and vacuum oven drying. The blanching pretreatments included water blanching, steam blanching, and an unblanched control. Each treatment was replicated three times, resulting in six treatment combinations and a total of 18 experimental units (6 × 3). Additionally, freeze drying was performed separately for comparison.

Fresh red beetroots were peeled and sliced into thin chips measuring approximately 5 × 3 × 0.3 cm (length × width × thickness) using a sharp kitchen knife. Blanching was then carried out according to the experimental design, either in hot water at 100ºC for 30 seconds or in hot steam at the same temperature for 120 seconds (Zhang et al., 2019). Following blanching, the samples were dried using either a vacuum oven (Memmert VO400-Thermoblech, Germany) or a conventional oven (Memmert UFE550, Germany). Vacuum drying was performed at 70°C under 100 millibars pressure for 12 hours, while conventional oven drying was conducted 70°C for 4 hours.

For freeze drying, a separate set of samples was packed in polypropylene/polyethylene zip-lock plastic bags (Plastic Klip, Indonesia; 17 × 11 cm) and frozen at –80°C for 24 hours (Binder, Germany). The frozen samples were then dried using a benchtop freeze dryer (ilShin Biobase TFD 8503, Korea) for 52 hours. All dried beetroot chips obtained from the various drying methods were ground into a powder using a grinder (Philips HR2116, Indonesia) and sieved through an 80-mesh screen (Retsch 5657, Germany) before analysis. The drying process of the red beetroot is illustrated in Fig. 1.

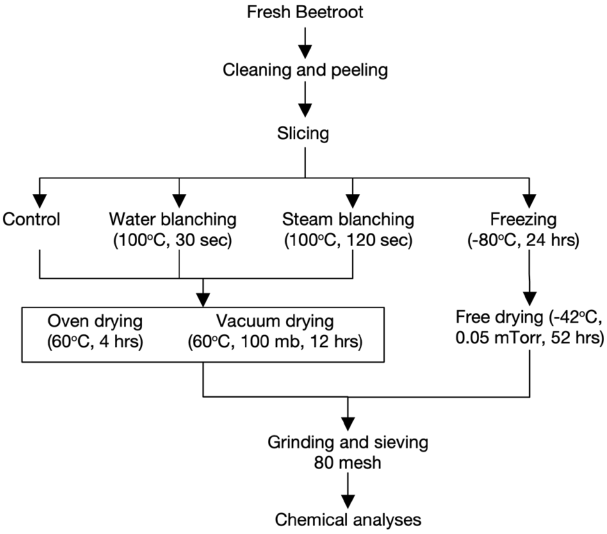


Fig. 1. Steps in red beetroot powder processing

Beetroot powder analyses

The red beetroot powder was analyzed for proximate composition, mineral content, nitrate, betalain, and antioxidant levels. The proximate and mineral analyses were conducted in the Food Quality and Safety Laboratory, Faculty of Agricultural Technology, Brawijaya University. Moisture and ash contents of the powder were determined using thermogravimetric and dry ashing methods, respectively. Antioxidant activity was measured using the DPPH assay (Nurmazela et al., 2022). Nitrate content was analyzed spectrophotometrically with a Shimadzu UVmini-1240 at wavelengths of 220 nm and 275 nm (Yumaitelia, 2018). Betalain content was determined according to the method of Slavov et al. (2013). The total energy was estimated using the Atwater factors, as follows: Energy content = Protein (%) × 4 + Carbohydrate (%) × 4 + Fat (%) × 9 (Hamid and Mohamed Nour, 2018).

Color parameters were measured and expressed as L^*, a^*, and b^* values according to the CIELAB color system. In this system, L^* represents lightness (ranging from 0 = black to 100 = white), a^* represents the red–green axis (positive values indicate redness, negative values indicate greenness), and b^* represents the yellow–blue axis (positive values indicate yellowness, negative values indicate blueness (Gupte, 2010; Nadal et al., 2014).

Statistical analysis

Results were reported as means ± standard deviations. Differences in means among the treatment groups were analyzed using the analysis of variance (ANOVA). When a statistically significant difference was detected, Tukey's post hoc test was applied. Statistical analyses were performed using JASP software (version 0.19.2; JASP Team, 2024) at a 95% confidence level. The chemical properties of beetroot samples, based on pretreatment before drying, were further evaluated by principal component analysis (PCA) using the R statistical computing environment (version 4.5.1; R Core Team, 2025).

RESULTS AND DISCUSSION

ISSR identification of red beetroot DNA from five samples showed that all samples exhibited 45% similarity (Fig. 2). The BDG1 and BDG3 samples showed 71% similarity and were classified in the same group, while BDG2, BT2, and BT1 showed 68% similarity and were grouped together. The red beetroot variety tested was identified as the Boro variety, introduced from the Netherlands by Bejo Zaden B.V., and belonging to the species *Beta vulgaris* (Astuti et al., 2021). The sample has the genealogy Ms-Eg-01-04-05-09 (♀) × 0T-01-05-20-1 S-60-20-36 (♂) and is recognized as a hybrid variety. The ISSR identification of the red beetroot tuber variety is presented in Fig. 2.

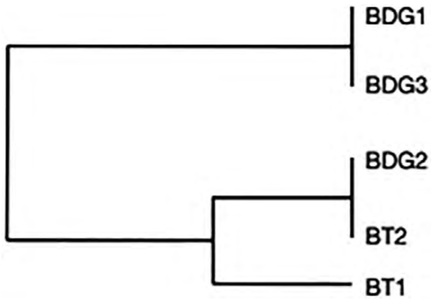


Fig. 2. Dendrogram of beetroot samples identification

The tubers were nearly round (obovate) and uneven in shape, measuring 7–9 cm in length and 6–9 cm in width, and weighing 140–240 g per bulb. The tuber color was reddish-purple (RHS 60 A), and the taste was somewhat sweet.

Chemical composition of fresh red beetroot

The analysis of fresh red beetroot revealed a high moisture content of 93.89 g per 100 g, slightly higher than the literature values, which range from 87.6 g (Kemenkes, 2020) to 92.12 g (Aulia and Sunarharum, 2020). The energy content was 20.77 Kcal. The contents of carbohydrates, protein, and fat were 3.18 g, 1.81 g, and 0.09 g, respectively. The analysis also showed a notably higher vitamin C level (43.99 mg) compared with the 10 mg reported by Kemenkes (2020). Regarding bioactive compounds, the nitrate (NO_3^-) concentration was 3,700 mg/kg, substantially higher than the 1,306 mg/kg reported by Raczuk et al. (2014) and 2,816 mg/kg by Ekart et al. (2013). Red beetroot was selected for this study because it contains higher levels of nutrients – particularly betalains – than yellow beetroot varieties (Bárta et al., 2020; Sokolova et al., 2024). Differences between the present findings and the literature values may be attributed to several factors, including the developmental stage of the harvested root (Srivastava and Bala, 2019). Among the minerals analyzed, iron (1.94 mg) and calcium (109.21 mg) were higher than the reported literature values of 1.0 mg and 27 mg, respectively. In contrast, potassium was considerably lower (27.80 mg) than 404.9 mg, and sodium (13.86 mg) was slightly lower than 28.5 mg. The ash content was 1.03 mg, consistent with the 1.1 mg reported by Kemenkes (2020).

Moisture content of red beetroot powder

Drying of red beetroot produced powders with moisture contents ranging from 9.98% to 13.78%. Conventional oven drying resulted in significantly lower moisture content ($p < 0.05$) compared with other methods. The blanching pretreatment also had a marked effect on the final moisture content. The lowest value was obtained from oven drying combined with water blanching, whereas the highest occurred with vacuum drying without blanching (Table 1).

The moisture levels observed in this study are comparable to those reported by Aulia and Sunarharum (2020), who obtained 13.63% moisture in beetroot powder produced by cabinet drying at 68°C for 8 hours after blanching. According to the National Food and Drug Authority No. 17 of 2019, the moisture content of health supplement products must not exceed 10% (BPOM, 2019). The beetroot powder produced through oven drying following water blanching treatment in this study met this requirement. Maintaining a low moisture level in dried foods is essential to suppress microbial growth and prevent deterioration during storage.

Overall, conventional oven drying produced powders with lower moisture content than vacuum drying,

Table 1. Moisture, nitrate, betalain, and antioxidant contents of beetroot powder

Methods	Pre-treatment	Moisture (%)	Nitrate (mg/kg)	Betalain (mg/100 g)
Oven drying	Control	12.53 ±0.11ab	162.71 ±13.09 b	1,587.28 ±57.81c
	Steam blanching	12.62 ±1.21ab	413.23 ± 4.95 d	2,677.92 ±28.26b
	Water blanching	9. 98 ±0.69a	295.10 ±21.83 c	2,009.85 ±195.88bc
Vacuum drying	Control	13.78 ±0.99b	81.24 ±7.06 a	2,481.14 ±243.54b
	Steam blanching	12.15 ±0.99ab	270.95 ±18.39 c	3,996.81 ±269.89a
	Water blanching	12.34 ±1.03ab	368.42 ±26.77 d	3,957.04 ±366.62a

Notes: Values are presented as means ± standard deviation. Values with different notation letters within the same column indicate significant differences (Tukey, $p < 0.05$).

except in the case of steam-blanched samples. In this study, vacuum drying was performed in batch mode due to equipment constraints. Each sample was dried for 3 hours in a vacuum oven, placed in a desiccator for 1 hour, and then returned to the oven for another 3 hours. This intermittent procedure allowed partial reabsorption of moisture from ambient air during transfer, thereby increasing final moisture content. In contrast, conventional oven drying was conducted continuously for 4 hours, allowing for more complete water evaporation and yielding lower final moisture content.

Blanching pretreatment significantly enhanced drying efficiency. The most pronounced reduction in moisture was achieved through water blanching followed by conventional oven drying. Blanching prior to drying improves drying performance in fruits and vegetables, as blanched samples exhibit higher drying rates than unblanched ones (Oshima et al., 2021; Sarkar et al., 2021). The elevated temperature during blanching likely causes cellular damage in the beetroot tissues, facilitating water release during drying.

In contrast, freeze drying produced beetroot powder with a higher moisture content (17.89 ±2.49%). By comparison, Vasconcellos et al. (2016) reported a lower value of 11.4% for red beetroot chips freeze-dried at −20°C for 48 hours. Other studies have observed that freeze-dried beetroot tubers retain more moisture than those processed by microwave, vacuum, hot air, or solar drying. Although freeze drying requires longer processing times, moisture levels as low as 7.0% can be achieved after approximately 22 hours and 20 minutes of drying (Liu et al., 2024). During freeze drying (lyophilization), several critical process parameters must be precisely controlled to achieve optimal results. The process is effective only when performed within specific temperature and pressure ranges that allow the frozen product to be heated without melting the ice. Sublimation occurs exclusively under conditions below the triple point of water (0.01°C, 610.5 Pa) (Orrego et al., 2023).

Nitrate content of red beetroot powder

Drying red beetroot tubers into powder generally reduces their nitrate content. In the present study, nitrate levels decreased from 3,700 mg/kg in fresh beetroots to between 81.24 and 413.23 mg/kg after processing. Conventional oven drying produced higher nitrate levels than vacuum drying, with the greatest nitrate content observed in samples dried in the oven following steam blanching pretreatment. The difference in nitrate content between powders produced by oven and vacuum drying was statistically significant ($p < 0.05$).

The effect of drying method on nitrate concentration was significantly influenced by blanching ($p < 0.05$). Blanching pretreatment enhanced nitrate retention in beetroot powder compared with unblanched samples ($p < 0.05$). As shown in Table 1, nitrate content was lower for vacuum-dried samples with water blanching than for vacuum-dried samples with steam blanching. Steam blanching yielded the highest nitrate content (413.23 mg/kg), although the difference from water blanching was not significant ($p > 0.05$). The lower nitrate content of water-blanched samples may be attributed to the water solubility of nitrate (EFSA, 2008), which facilitates leaching losses during the drying process.

The nitrate reductions observed in this study are consistent with most previous findings. Although Hamid and Mohamed Nour (2018) reported increased nitrate levels after sun, oven, or freeze drying, the majority of studies indicate a decline. Handling and processing steps such as storage, washing, peeling, and heating generally reduce nitrate content (EFSA, 2008). Vasconcellos et al. (2016) found that heat application during beetroot powder production markedly lowered nitrate levels, with concentrations varying across products: beetroot juice (12,252.9 mg/kg), spray-dried powder (2,031.2 mg/kg), freeze-dried powder (1,683.5 mg/kg), and steamed tubers (1,649.7 mg/kg). Reductions in nitrate content have also been reported for other vegetables, including beetroot leaves, parsley, cabbage, carrots, and tomatoes. For instance, boiling vegetable powders in water at 90°C for 15 minutes decreased nitrate levels by 4.09%–13.41% (Salehzadeh et al., 2020).

Nitrate loss in red beetroot after washing and boiling (unpeeled) was approximately 10%, increasing to 23% in previously stored beetroots. Storage at room temperature before processing also influences nitrate levels, as stored roots undergo moisture loss and rehydration during boiling, promoting greater nitrate leaching (Ekart et al., 2013). Nitrates derived from vegetables exhibit high bioavailability in humans. The acceptable daily intake (ADI) established by the Joint FAO/WHO Expert Committee on Food Additives (JECFA) is 0–5 mg/kg body weight for sodium nitrate and 0–3.7 mg/kg body weight for nitrate ions (JECFA, 2002).

In this study, freeze-dried beetroot powder contained 1203.33 ± 35.17 mg/100 g of nitrate – higher than levels obtained using other drying methods. In contrast, Hamid and Mohamed Nour (2018) reported a lower value of 261.09 mg/100 g. Nitrate content in beetroot is also influenced by climatic and agricultural factors. Beetroots grown at temperatures above 30°C generally accumulate less nitrate than those grown in cooler climates, while the use of nitrogen-rich fertilizers can also impact nitrate content (Dos Santos Baião et al., 2016). Seasonal variations are also evident: red beetroots harvested in spring in Europe had nitrate levels of 3,612 mg/kg compared with 2,434 mg/kg in autumn-harvested samples (Ekart et al., 2013).

Betalain content of red beetroot powder

Drying of beetroot yielded betalain contents ranging from 1,587.28 to 3,996.81 mg/100 g of powder. Vacuum drying resulted in higher betalain retention than conventional oven drying ($p < 0.05$). Furthermore, steam blanching led to a substantial increase in betalain content compared with water blanching ($p < 0.05$). The betalain contents of the beetroot powders are presented in Table 2.

The betalain levels obtained in this study are consistent with previously reported values, such as 2,469.07 mg/100g of beetroot powder (Kaur et al., 2021). Variability in betalain concentration across studies may be attributed to differences in beetroot cultivars, processing conditions, and sample preparation methods. For instance, six beetroot cultivars grown in the South Bohemian region exhibited betalain levels ranging from 1.38 to 16.78 mg/g dry matter (Bárta et al., 2020). Preparation methods, particularly peeling, can also markedly affect betalain content, as beetroot skin contains 10% to 50% more betalains than the flesh (Vaitkevičienė et al., 2022; Zin et al., 2022). The superior betalain content in vacuum-dried samples likely reflects the effect of reduced air pressure, which minimizes compound degradation and improves overall quality compared to conventional oven drying. Reducing the atmospheric pressure inside the drying chamber lowers the boiling point of water, enabling faster and more efficient drying at lower temperatures. In contrast, air drying relies on heat transfer through contact with indirectly heated surfaces (Orrego et al., 2023). It is also probable that vacuum ovens facilitate drying under controlled conditions that suppress the loss of aroma, volatile compounds, and nutrients, while simultaneously preventing protein denaturation and browning.

Betalains are water-soluble nitrogen-containing pigments derived from a core structure known as betalamic acid (4-(2-oxoethylidene)-1,2,3,4-tetrahydropyridine-2,6-dicarboxylic acid) (Pereira et al., 2022). Temperature plays an important role in the stability of betalains during food processing and storage. Betalains begin to degrade at temperatures above 50°C (Rodríguez-Mena et al., 2023). Several enzymes, including peroxidase, polyphenol oxidase, and glucosidase, are also capable of degrading betalains (Rodriguez-Amaya and Carle, 2021). This likely explains the higher betalain content observed in beetroot powders that underwent blanching prior to drying. Blanching beetroots without peeling has also been reported to help retain betalain content (Kaur et al., 2021).

Antioxidant activity of red beetroot powder

The antioxidant activity results are expressed as IC_{50} values (Fig. 3). The IC_{50} represents the concentration of an antioxidant-containing substance required to reduce 50% of the initial DPPH radicals; a lower IC_{50} indicates greater DPPH scavenging potency and thus stronger antioxidant activity (Olugbami et al., 2014). The DPPH (2,2-diphenyl-1-picrylhydrazyl) assay is widely used for evaluating antioxidant activity due to its simplicity, accuracy, and cost-effectiveness. DPPH, a free radical, exhibits a color transition from deep purple to light purple and eventually to pale yellow when it reacts with antioxidant compounds (Baliyan et al., 2022). Red beetroot is a rich source of antioxidants, including betaine, betalains, polyphenols, phenolics, saponins, flavonoids, vitamins, and nitrates. Among these, betanin shows superior free radical-neutralizing capacity compared to anthocyanins (Chen et al., 2021).

Beetroot powder produced by vacuum drying exhibited significantly stronger antioxidant activity ($p < 0.05$) compared to powder produced by conventional oven drying. Blanching pretreatment also influenced antioxidant activity: steam blanching resulted in greater antioxidant activity than water blanching. The strongest antioxidant activity (IC_{50} 493.32 ± 38.75 ppm) was obtained from vacuum drying combined with steam blanching pretreatment.

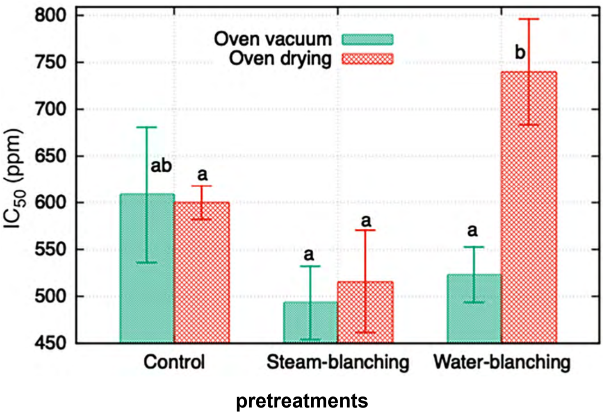


Fig. 3. Effect of pretreatment and drying on antioxidant activity

The high antioxidant activity observed in beetroot powder subjected to vacuum drying and steam blanching may be attributed to the efficient heat transfer achieved during steam blanching. This process accelerates the inactivation of oxidative enzymes, thereby minimizing the loss of antioxidant compounds during subsequent drying (Tanongkankit et al., 2010). In contrast, unblanched samples exhibited weaker antioxidant activity because the enzymes in the cells remained active, leading to the loss of antioxidant compounds through enzymatic reactions (Hossain et al., 2010). The inactivation of enzymes and the low moisture content of the product can help preserve its antioxidant activity. Freeze drying resulted in the strongest antioxidant activity in beetroot powder (IC_{50} 38.70 ±45.98 ppm). This is likely due to the low processing temperature, which favors the retention of antioxidant compounds naturally present in beetroots, such as betalains. Betalains in beetroot have been shown to strongly correlate with antioxidant activity ($R^2 = 0.99$) as measured by the DPPH method (Bucur et al., 2016). Since betalains degrade at temperatures above 50°C (Rodríguez-Mena et al., 2023), processing beetroot at freezing temperatures allows for greater preservation of these compounds.

Color of red beetroot powder

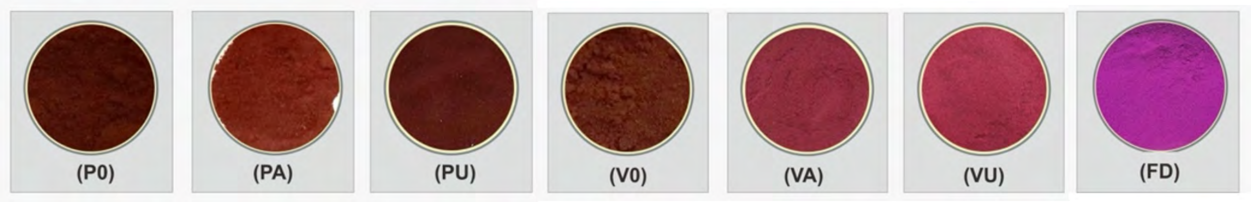
Conventional oven drying resulted in slightly higher brightness in beetroot powders compared to vacuum oven drying; however, the difference was not statistically significant ($p > 0.05$) (Table 2). Vacuum oven drying significantly ($p < 0.05$) increased the redness intensity of the beetroot powder compared with conventional drying. In contrast, the vacuum method caused a significant ($p < 0.05$) decrease in the yellowness of the powder. The effects of drying and blanching pretreatments on beetroot powder color are presented in Fig. 4.

Blanching is commonly performed before processing operations such as drying, freezing, and canning. It serves to inactivate enzymes, reduce browning reactions, eliminate microbes, and improve both drying performance and final product quality. Water blanching as a pretreatment significantly ($p < 0.05$) increased

Table 2. Color difference of beetroot powders

Methods	Pretreatment	Brightness (L*)	Redness (a*)	Yellowness (b*)
Drying oven	Control	36.39 ±0.15abc	11.70 ±0.79a	5.56 ±0.02b
	Steam blanching	35.78 ±0.23a	14.18 ±1.49ab	5.04 ±0.18a
	Water blanching	36.89 ±0.42c	14.18 ±2.77ab	4.93 ±0.15a
Vacuum oven	Control	36.01 ±0.34ab	12.83 ±1.49a	5.57 ±0.27b
	Steam blanching	35.69 ±0.31a	18.41 ±2.34b	4.60 ±0.07a
	Water blanching	36.66 ±0.17bc	14.34 ±1.49ab	4.66 ±0.25a

Values represent mean ± standard deviation. Different letters within the same column denote significant differences at $p < 0.05$.

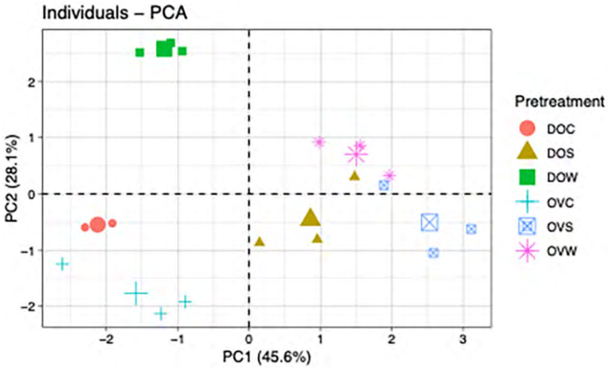


PO – drying oven without blanching pretreatment; PA – drying oven preceded by water blanching; PU – drying oven preceded by steam blanching; VO – vacuum oven without blanching treatment; VA – vacuum oven preceded by water blanching; VU – vacuum oven preceded by steam blanching; FD – freeze drying

Fig. 4. Color of beetroot powders produced by different drying methods

the lightness of the beetroot powder. Steam blanching followed by vacuum oven drying produced the highest red intensity compared with the same blanching treatment applied before conventional drying. Water blanching with different drying methods resulted in similar increases in redness. The combined effects of drying and blanching on powder redness were statistically significant ($p < 0.05$). Blanching methods generally decreased the yellowness (b*) of the powder ($p < 0.05$). The reduction in yellowness caused by vacuum oven drying was more pronounced than that of conventional drying. Among all samples (Fig. 4), beetroot powder produced from freeze-drying displayed a distinctively bright magenta or deep pink hue, characterized by the highest levels of brightness (L*), redness (a*), and yellowness (b*). The measured values for freeze-dried powder were L* = 47.01 ± 0.53, a* = 20.34 ± 0.17, and b* = 22.81 ± 0.02.

The characteristic red color of beetroot is attributed to betalains, which include betacyanins (red pigments) and betaxanthins (yellow pigments) (Chandran et al., 2014). The ratio of betacyanin to betaxanthin determines the overall hue – higher betacyanin content produces a deeper red color. Betacyanin has been reported to account for approximately 88.26% of total betalains (Tarasevičienė et al., 2024). The stability of these pigments is influenced by temperature, oxygen, pH, light exposure, chelating agents, water activity, and other chemical compounds (Martins et al., 2017). Previous research indicates that thermal treatment during beetroot drying enhances redness (La et al., 2015; Tarasevičienė et al., 2024). The deep pink hue observed in freeze-dried beetroot powder is likely due to superior retention of pigments and cellular structure achieved through low-temperature processing. This result aligns with findings that freeze drying produces beetroot powder with optimal color – showing higher brightness, redness, and yellowness – compared with vacuum drying, heat pump drying, microwave drying, and microwave–vacuum drying (Liu et al., 2022).



DOC – Drying oven control; DOS – Drying oven with steam blanching; DOW – Drying oven with water blanching; OVC – Oven vacuum control; OVS – Oven vacuum with steam blanching; OVW – Oven vacuum with water blanching.

Fig. 5. PCA of the first and second principal components

Principal component analysis (PCA) showed that three components accounted for 83.2% of the total data variation. The first principal component explained 45.6% of the variance, while the second explained 28.1%, indicating that three components were sufficient to capture most of the variation. As shown in Fig. 5, samples subjected to blanching pretreatments behaved differently from unblanched controls. Pretreatment using water blanching followed by conventional oven drying produced markedly different results, yielding beetroot powder with lower moisture content and reduced antioxidant capacity, likely due to extensive leaching of bioactive compounds during blanching. PCA also confirmed that vacuum oven drying preceded by steam blanching produced a distinct effect from other treatments, resulting in powder with the strongest antioxidant activity.

CONCLUSIONS

This study examined the combined effects of drying and blanching methods on the nitrate content, betalain concentration, antioxidant activity, and color of beetroot powder. The drying method applied during beetroot processing had a significant impact on its bioactive composition. Compared to conventional oven drying, vacuum drying of red beetroot produced powder with a higher betalain content (3,478.33 mg/100 g), stronger antioxidant activity (IC$_{50}$ = 541.73 ppm), and lower nitrate content (127.56 mg/kg). Blanching the beetroot as a pretreatment before drying also significantly affected its bioactive content. Steam blanching, when combined with oven drying, yielded the highest nitrate content; however, this method produced significantly lower ($p < 0.05$) betalain levels compared to steam blanching followed by vacuum drying. The latter approach also resulted in the strongest antioxidant activity among the red beetroot powders. Freeze-drying produced beetroot powder with higher nitrate content, the strongest antioxidant activity, and better color retention. Both drying and blanching significantly ($p < 0.05$) increased the redness (a*) of beetroot powder, with the highest red intensity observed in samples processed by vacuum oven drying preceded by steam blanching. However, this combination reduced yellowness (b*) more than vacuum drying following water blanching, and also decreased lightness (L*).

ETHICAL STATEMENT

This work did not involve the use of animals or human subjects.

COMPETING INTEREST

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

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DECLARATIONS

Data statement

All data supporting this study has been included in this manuscript.

Ethical Approval

Not applicable.

Competing Interests

The authors declare that they have no conflicts of interest.

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