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Research article

Colour, nutritional composition and antioxidant properties of dehydrated carrot (*Daucus carota* var. *sativus*) using solar drying techniques and pretreatments

Jiasmin Akter [a], Jahidul Hassan [a,*], M. Mizanur Rahman [a], Md Sanaullah Biswas [a], Haider Iqbal Khan [b], Md Mijanur Rahman Rajib [a], Mohammed Razu Ahmed [c], Md Noor-E-Azam Khan [a], Md Faisal Ahamed Hasan [a]

[a] *Department of Horticulture, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur, 1706, Bangladesh*
[b] *Department of Crop Botany, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur, 1706, Bangladesh*
[c] *Department of Agricultural Marketing, Ministry of Agriculture, Bangladesh*

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ABSTRACT

Carrot is a seasonal perishable tuberous root vegetable which presents a preservation challenge owing to its elevated moisture content. Recently, carrot processing has received more attention because of its many health-promoting qualities and the reduction of postharvest losses in a cost-effective safe way. This study was designed to sort out the effective solar drying technique including pre-treatment that would retain the color and quality characteristics of dehydrated carrot. Carrot slices were subjected to dry using open sun drying (D1), solar drying long chimney (D2), solar drying short chimney (D3) and box solar drying (D4) techniques with the pre-treatments of ascorbic acid 1 % (C3), citric acid 5 % (C4), potassium metabisulfite 1 % (C5) and potassium sodium tartrate 0.3 % (C6) before drying. Drying characteristics, nutritional attributes, phytochemicals and antioxidant of the dehydrated carrot samples were compared with the fresh sample and untreated (control) sample. Results showed that D4 was a good drying method to preserve nutritional quality with good appearance. Among the pretreatments, C5 and C4 resulted improved nutritional quality retention, enhanced visual acceptability and enriched antioxidant activities. PCA (Principal Component Analysis) and correlation matrix revealed that D4 with C5 retained the maximum amount of vitamin, minerals, total phenolic content, antioxidant and admirable dehydrated carrot color by inactivating enzymatic reaction. Therefore, box solar drying with potassium metabisulfite pretreatment would be very promising for functional carrot drying retaining acceptable color and nutrition composition.

1. Introduction

Carrot (*Daucus carota* var. *sativus*) belongs to the family Apiaceae and originated in Mediterranean region [1]. It is an ancient cool season root vegetable that are cultivated worldwide. This vegetable provides a significant amount of dietary carotenoids (α and β carotene), vitamins (A, B_6, and C), minerals (Ca and K), and edible fiber [2]. Carrot and its products have been increasingly consumed

* Corresponding author.
E-mail address: jhassan@bsmrau.edu.bd (J. Hassan).

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in recent years because they are recognized as a valuable source of natural antioxidants. Additionally, the β-carotene found in carrots, which is a precursor of vitamin A, has been found to have anticarcinogenic properties [3]. In Bangladesh, the cultivated area for carrots is 5085 acres, resulting in a total production of 19246 metric tons [4]. Carrots are very seasonal and are readily accessible at specific periods of the year. This leads to a seasonal glut, which is responsible for substantial postharvest losses and a decrease in the per capita availability of vegetables in Bangladesh. Postharvest decay is the primary factor that limits the shelf life of vegetables, resulting in the deterioration of around 17 % of the world's total production during post-harvest handling [5]. Furthermore, in Bangladesh, the conventional method of farming results in a significant loss of vegetables after harvesting, reaching up to 43 % [3].

Prolonging the shelf life of vegetables can contribute to reducing postharvest losses, thereby improving the situation [3]. Various procedures, including as freezing and drying, are employed to mitigate degradation following harvest. Drying and subsequent storing can improve the longevity or shelf life of carrots. Drying is a crucial technique that not only greatly prolongs the shelf life of food but also expands the range of food options available to customers [6]. Conversely, Bangladesh has consistently maintained an average temperature of 26 °C, with a minimum and maximum range of 15 °C and 34 °C respectively, throughout the year. The average solar radiation ranges from 3.92 to 5.71 kWh/m2, and the annual average rainfall is approximately 2200 mm (mm) [7]. These climatic conditions are thought to be ideal for drying purposes. Dehydrated food materials offer benefits such as the ability to manage product quality, ensure hygienic conditions, and minimize product loss. It is a preservation technique that primarily seeks to extend the lifespan of products by dehydrating food by the circulation of hot air. This reduces the water content to a level that is insufficient for the growth of microbes, enzymatic reactions, and other forms of deterioration [8,9]. In order to prevent the growth of microorganisms, it is necessary to maintain the moisture content and water activity below roughly 10 % and 0.60–0.65, respectively [10], with the specific values dependent on the kind of food. Simultaneously, the flavor and a majority of the nutritional content can be conserved and intensified. Nevertheless, the process of drying can result in thermal harm to desiccated substances, as well as substantial alterations in their physical, chemical, and sensory attributes. Hence, the choice of a suitable drying technique holds significant importance. According to An et al. [11], drying technologies have garnered substantial attention and investment in research and development due to the increasing need for improved product quality, reduced operational costs, and minimized environmental effect. The use of solar drying techniques has some benefits over conventional open-sun drying, including the following: (1) smaller area needed; (2) maintained relatively high quality of dried crop; (3) protection from sudden rain; (4) low capital, equipment, and operating costs; and (6) high final value of dried product. Agricultural crops have been pretreated before drying to assist reduction of some of the undesirable properties. The primary objective of pretreatment is typically to deactivate enzymes such as polyphenol oxidase, peroxidase, and phenolase, as well as to hinder some unwanted chemical interactions that lead to several detrimental alterations in a product [10].

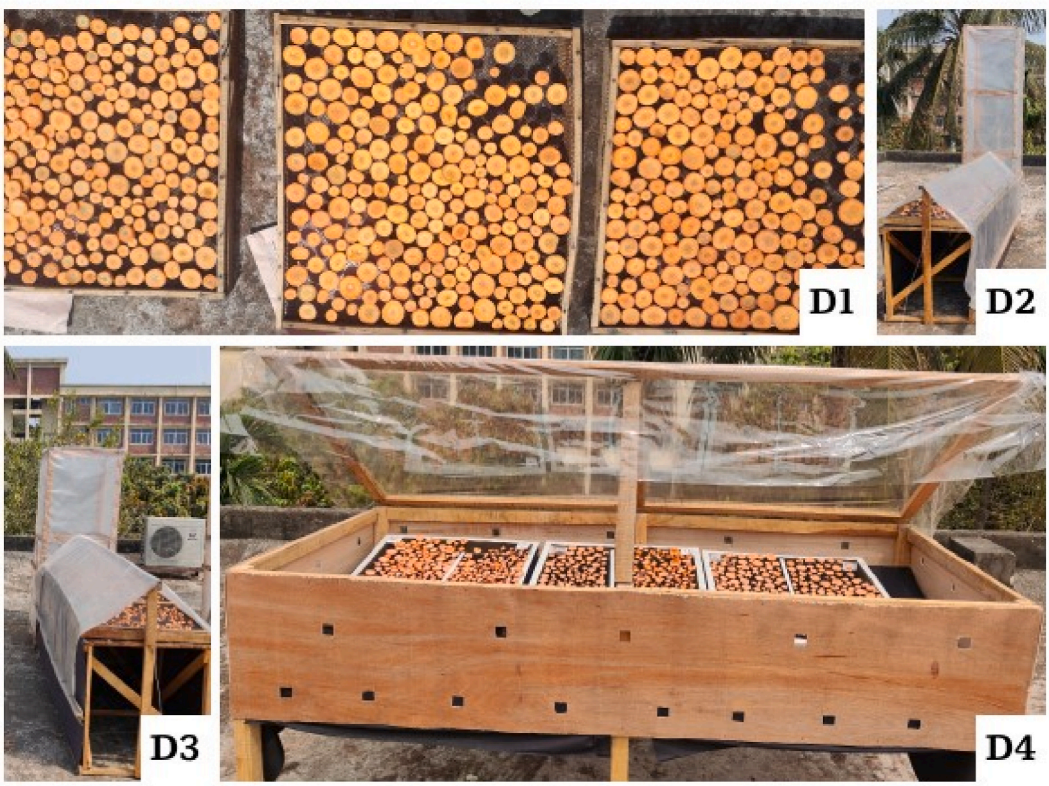

Fig. 1. Different types of solar dryers; D1: Open sun drying (OSD), D2: Solar dryer long chimney (SDLC), D3: Solar dryer short chimney (SDSC), D4: Box solar dryer (BSD).

Potassium and sodium hydroxide, potassium carbonate, potassium metabisulphate, methyl and ethyl ester emulsions, citric and ascorbic acids are widely employed pretreatments [12] in many crops for commercial purposes. Several investigations have been conducted to examine the various methods of carrot processing, including air drying [13,14], sun drying [15], convection-microwave drying [16,17], freeze drying [18], solar drying [19,20], and infrared drying [21]. But research findings regarding the effect of combining different degrees of pretreatments before solar drying on nutritional quality, sensory acceptance, and antioxidant characteristics of carrots are scanty. Previous reports have shown that direct sun drying is vulnerable to several obstacles, including contamination by dust and scavenging by animals. Additionally, there is a risk of inadequate or excessive drying, which can compromise the quality and nutritional composition of the dried samples [6,12,22]. Developing a solar dryer and pretreatment method as a cost-effective alternative to existing dryers has the potential to reduce postharvest losses significantly while maintaining the color and nutritional composition of the dried goods. This strategy is still desirable in this context. In the current study, locally made solar drying method for dehydration process was selected over the other sophisticated afore-mentioned methods accounting the expenses and technical knowledge. We assumed that if a solar dryer using locally available materials (wood, bamboo etc.) can be developed that might be effective in maintaining the nutritional qualities of the dried products, it will be handy for farmers and general people of rural areas and remote farming areas. We also expected that farmers who are interested in processing their produce and acting as entrepreneurs would have access to pretreatments. As a result, it has been hypothesized that the proposed different solar drying techniques and pretreatment strategies before drying would be effective to retain color and biochemical attributes of the dehydrated carrot (Supplementary Fig. 1). Taking into account the facts mentioned above, an experiment was conducted to determine the most effective solar drying technique with pretreatment for color retention and quality attributes of the dehydrated carrots.

2. Materials and methods

2.1. Study approach

The study took place at the rooftop open space and Tissue Culture Laboratory of the Department of Horticulture at Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), located in Salna, Gazipur-1706, Bangladesh. The coordinates of the location are 24.02° N latitude and 90.23° N longitude. Three trials of the drying process were conducted concurrently using four different solar drying methods: open sun drying (OSD), long chimney solar dryer (LSD), short chimney solar dryer (SSD), and box type solar dryer (BSD). These methods were labelled as D1, D2, D3, and D4 accordingly (Fig. 1). The open sun drying (OSD) was followed the drying process done in a tray made of 2 ft^2 wooden frame enclosed with perforated black net ware. The tray containing carrot slices, each with a thickness of 5 ± 0.2 mm, was exposed to direct sunlight for the purpose of drying in an open sun drying method. In chimney based solar dryer, the chimney was prepared at 6 ft height for long (LSD) and 3 ft height for short chimney (SSD) and the air flow desk chamber at 6 ft length 3 ft width was prepared for both types of chimney dryers that was covered with thin black polythene sheet where the tray was placed during the drying operations. The one part of this air flow desk chamber remained open to access air flow (inlet) and another part was attached with the chimney to pass the hot air (outlet). The air used for drying would be heated with the sunlight while passing through the white polythene sheet covered tunnel and outlet this hot air through the long and short chimney. In box solar drier (BSD), the box is made up of wood board (1.4 ft height, 7 ft length and 3 ft width) and the box is elevated 1.8 ft from the surface of the ground upon a wood stand. There were several holes (1 $inch^2$) in length directions (total 12 of which 6 holes in each side of the box) and width sides (total 6 holes of which 3 holes in each side of the box) of the box to ensure the inlet and outlet of air flow (Fig. 1). The inside of the dryer is coated with polythene sheet in black color that efficiently absorbs solar radiation that comes in while the dryers were enclosed with the white polythene sheet so that solar radiation is transmitted through it which make an environment like a greenhouse.

Five identical plates of fresh carrot slices were prepared for each drying cycle, and each plate contained a 500 g sample. The starting weigh of each plate, which contained fresh carrot slices with a thickness of 5 ± 0.2 mm, was recorded using an electric weighing device (model: GX4000; range: 0.01–4100 g; supplier: A&D Co., Japan). The moisture content (%) in the fresh carrot was determined by subjecting it to an oven at 100 °C for 18 h until the weight of the sample reached a constant level [6]. These parameters provided the benchmark of drying period for all the dryers to dehydrate the sample with the maximum reduction of the moisture (%). The 1st plate of the fresh sample (C1) was utilized for color and physical appearance evaluation by panelists; nutrition composition estimation and antioxidant activity (AA) determination purposes. This information served as the baseline indicators for comparing the drying methods generated dehydrated samples qualities to the fresh one denoted as C1. The leftover four plates of fresh carrot slices were dried using the proposed OSD (D1), LSD (D2), SSD (D3) and BSD (D4) drying methods with or without pretreatment. Four different pre-drying treatments, designated as C3, C4, C5, and C6, were applied to the slice samples before drying. These treatments included ascorbic acid (AA 1 %), citric acid (CA 5 %), potassium metabisulfite (KMS 1 %), and potassium sodium tartrate (KT 0.3 %). For each treatment, the three plates of fresh slices were used covering three replications and another plate was used without pretreatment (control) denoted as C2.

A study was done to assess the effects of four distinct solar drying techniques on the color, nutritional composition, and bioactive components of dried carrots. The study followed a randomized complete block design (RCBD) with two factors and three replications. The solar drying procedures and pretreatments were designated as factor-A and factor-B, respectively, with four and six treatment levels each. The total duration of this study (both drying and chemical analyses) was February to June 2021 where the drying experiment was conducted for eight days from 14 March 2021–21 March 2021. The carrot slices were dehydrated until they reached a desirable moisture content of 13–14 % (wet basis), which is the ideal moisture level for safely storing carrots [6]. During the drying period the temperature range was 30–44 °C and relative humidity was 22–32 %. The required drying time was varied from 8 to 21 h.

2.2. Sample preparation and pretreatment

Fresh carrot (BU carrot 1 variety) was acquired from the research field of Horticulture department, BSMRAU, Salna, Gazipur-1706, during February to March 2021. The carrots exhibited a consistent and uniform size, shape, and maturity stage, while also being devoid of any signs of mechanical damage, insect infestation, or pathogenic infection. Upon reaching the laboratory, the carrots underwent a process of cleansing using tap water. The tuberous air-dried carrot root samples were cut into slice with sharp knife (Elite, Platinum, China) to achieve a thickness of 5 ± 0.2 mm and the slices were soaked with 1 % ascorbic acid (C3), 5 % citric acid (C4) (lemon juice), 1 % potassium metabisulfite (C5) and 0.3 % potassium sodium tartrate (C6) for 10 min before drying.

2.3. Drying process of carrot

The carrot slices (500 g) that had been pretreated beforehand were evenly distributed across three trays in each dryer, representing three replications. They were then subjected to four distinct drying procedures, as seen in Fig. 1. The drying process continued until the carrot lost a moisture level of 85–86 % (wet basis) [6]. Carrot slices of 5 ± 0.2 mm in thickness were placed on a square shape mesh tray (tray made up of wooden frame with black net ware in thin layers and each slice kept apart from each other. The tray was exposed directly to sunlight for the purpose of drying in an open sun drying method. In chimney based solar dryer for both long and short chimney, the tray was placed on the thin black polythene sheet covered horizontally placed air flow desk chamber. The one part of this air flow desk chamber remained open to access air flow (inlet) and another part was attached with the chimney to pass the hot air (outlet). The air used for drying would be heated with the sunlight while passing through the white polythene sheet covered tunnel and outlet this hot air through the long and short chimney. In box type solar drier, there was several holes in all sides of the box to ensure the inlet and outlet of air flow (Fig. 1). Temperatures, humidity and weight change of the carrot slices were recorded at three (3) hours interval from 09:00 a.m. to 5:00 p.m. in each drying day using a digital weight machine, thermometer and hygrometer. The thermometer and hygrometer sensors were placed throughout the drier chamber to accurately gauge the temperature and humidity levels of the heated air that enters the drying chamber. The same methodology was also employed to gauge the ambient temperature and humidity on each day of the drying process under open sun drying conditions. Ultimately, the performance of the various solar dryers was assessed in comparison to the open sun drying method.

2.4. Evaluating the nutritional and phytochemical quality of dehydrated carrot

2.4.1. Moisture content (%)

The moisture content of the dried samples was determined using both the wet basis (Equation (1)) and dry basis methods (Equation (2)) [6]. The fresh and dehydrated carrot samples were weighed using a top pan electric balance to determine their initial and final masses. The moisture content was determined by calculating the ratio of the difference in mass between the initial and final carrot samples to the mass of the fresh sample.

$$\text{Moisture content wet basis } (\%) = \frac{\text{Ww}}{\text{Ww} + \text{Wd}} \times 100 \tag{1}$$

where,

Ww + Wd = initial weight.
Ww = weight of water.
Wd = weight of dry matter

$$\text{Moisture content dry basis } (\%) = \frac{\text{MCwb}}{(100 - \text{MCwb})} \times 100 \tag{2}$$

where,

MCwb = Moisture content at wet basis.

2.4.2. Determination of pH

Twenty (20) g carrot sample was blended by using a grinder and the resultant juice was used for pH determination using a digital pH meter (SD 300 pH).

2.4.3. Determination of total soluble solids (TSS)

The hand refractometer (Model: Atago N1, Japan) was used to determine the total soluble solids (°Brix) of both fresh and dehydrated carrot samples. A little amount of carrot juice extracted from 1 g of fresh and rehydrated sample was poured on to the refractometer's prism. The concentration of soluble solids was then measured and recorded as degrees Brix (°Brix).

2.4.4. Determination of total sugar

The total sugar content in the fresh and dehydrated carrots were analyzed by Bertrand's method [23]. Exactly 5 mL of the extract solution were prepared from 1 g of blended sample taken in a 50 mL of conical flask and 2 drops of 4 N HCl was added to it. Then the flask was heated for 30 min on a sand bath for hydrolysis then 10 mL of Bertrand A (40 g $CuSO_4.5H_2O$ dissolved in 1 L of distilled

water) and Bertrand B (200 g sodium potassium tartrate and 150 g of NaOH were dissolved in 1 L of distilled water) solution was added into the cooled solution. After adding the solution, the conical flask was again placed on sand bath and heated for 30 min and kept overnight undisturbed for cooling. The supernatant was decanted and discarded carefully by keeping precipitation. The precipitation was washed 3 times with distilled water until green color was present. Then Bertrand C (50 g ferric sulphate and 115 mL H_2SO_4 were dissolved in 1 L of distilled water) solution was added to the precipitation (Cu2O). Finally, the solution was titrated with 0.4 % potassium permanganate (KMnO4) solution. The total sugar (mg/100 g DW) was calculated comparing tabulated values. Before calculation, dilution factor of 0.4 % KMnO4 was determined.

2.4.5. Determination of ascorbic acid

The ascorbic acid concentration in fresh and dehydrated carrot was measured using a modified titration method [24]. 5 mL of each extract solution, derived from 1 g of blended sample powder from both the fresh and dehydrated samples, were transferred into a 50 mL conical flask. Subsequently, the extract solutions were supplemented with 5.0 mL of KI solution (5 %), 2 mL of glacial acetic acid, and 2 mL of starch solution (2 %). Afterwards, each solution was titrated against KIO_3 (0.001 N) using a burette until the emergence of a blue hue, which signifies the outcome of the reaction. Each of the tested samples underwent three repetitions of titration. The data were documented, organized, and computed for the determination of ascorbic acid (mg/100 g DW) in each sample (Equation (3)).

$$\textit{Ascorbic acid content}\ \text{mg} \Big/ 100\ \text{g}\ \ \text{DW} = \frac{\text{T} \times \text{F} \times \text{V} \times 100}{\text{v} \times \text{W}} \tag{3}$$

where,

DW = Dry weight (for fresh sample, mg/100 g fresh weight [FW])
T = titrated volume of 0.001 N KIO_3 (mL)
F = 0.088 mg of ascorbic acid per mL of 0.001 N KIO_3
V = total volume of sample extracted (mL)
v = volume of the extract (mL) titrated with 0.001 N KIO_3

2.4.6. Determination of β – carotene

The β–carotene content was assessed using a modified UV scanning technique. The initial sample (1 g) was homogenized using a mortar and pestle, and then incorporated into a solution of acetone and hexane (4:6) in a 10 mL volume. The mixture was thoroughly mixed. Subsequently, the sample underwent filtration using a Whatman 42 filter with a particle retention capacity of 2.5 μm, and was then transferred into a test tube. The sample's optical density was evaluated using a spectrophotometer (PD-303 UV Spectrophotometer; APEL Co.) at four different wavelengths: 663 nm, 645 nm, 505 nm, and 453 nm. The β-carotene content (mg/100 g DW) was calculated using the formula provided in reference (Equation (4)) [25].

$$\beta - \text{carotene mg/100 g DW} = 0.216\ (\text{OD663}) + 0.452\ (\text{OD453}) - 1.22\ (\text{OD645}) - 0.304\ (\text{OD505}) \tag{4}$$

where,

DW = Dry weight (for fresh sample, mg/100 g fresh weight [FW])
OD = Optical density at particular wave length.
0.216; 0.452; 1.22; 0.304 = absorption coefficient of the respective absorbance.

2.4.7. Determination of mineral content

The mineral content (potassium, sodium, calcium, magnesium) was measured using an Atomic Absorption Spectrophotometer (AAS), following the protocols outlined by Abbas et al. [26] with some adjustments. For this purpose, 10 g of dried sample were pulverized to create a powder. Then, 0.5 g of the sample powder were placed in a 50 mL conical flask. Next, a mixture of HNO_3 and $HClO_4$ (Nitric – perchloric acid) in a ratio of 5:1 was added to the flask. The mixture was then digested using a sand bath. The final step of the digestion process involved filtration using a Whatman 42 filter paper with a particle retention size of 2.5 μm. The filtered solution was then diluted with distilled water to reach a final volume of 100 mL in a 100 mL volumetric flask. To determine the mineral content, a 10 mL sample extract was placed in a 50 mL volumetric flask and then diluted with distilled water to get a total volume of 50 mL. Subsequently, the levels of potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg) were quantified using an atomic absorption spectrophotometer (AAS) with the model PinAAcle 900H manufactured by PerkinElmer. The mineral concentration was quantified use the subsequent equation (5):

$$\%\ \text{mineral (DW)} = \frac{\text{sample reading} \times \text{final volume} \times \text{dilution factor}}{\text{sample weight}} \tag{5}$$

where,

DW = Dry weight.

2.4.8. Determination of crude protein

Protein was determined through Kjeldahl method by using equation (6) [27] -

$$\text{Nitrogen } \% = \frac{\text{sample titre} - \text{blank titre} \times \text{normality of acid} \times 14 \times 100}{\text{sample weight} \times 1000} \quad (6)$$

The protein percentage was determined by using equation (7) to the total nitrogen percentage.

$$\text{Protein (DW) } \% = \text{Nitrogen } \% \times 6.25 \quad (7)$$

where,

DW = Dry weight.

6.25 = constant factor

2.4.9. Analysis of total phenolic, total flavonoid and antioxidant activity

The total phenolic compounds and antioxidant activity content in the dehydrated and fresh samples were analyzed by extraction of 1 g powdered sub-sample with 25 mL methanol. The sample was placed in water bath at 30 °C for 2.5 h and centrifuged at 6000 rpm for 15 min. The supernatants were decanted and filtrated by Whatman 42 filter paper into test tube covered with foil paper and stored at 4 °C until the samples were analyzed.

The Folin–Ciocalteu technique [6] with some modifications was employed to estimate the total phenolic content (TPC). For the analysis, 0.5 mL of the sample extracts were mixed vigorously with 2.5 mL of the Folin–Ciocalteu reagent, and the resulting solution was kept at a controlled temperature for 10 min. Next, 2 mL of a solution containing 7.5 % sodium carbonate was added to the mixture. The resulting mixture was then incubated at a temperature of 30 °C for a duration of 1 h. The absorbance of diluted sample extracts was calibrated against a known quantity of gallic acid (a polyphenolic molecule). The sample and the gallic acid standard were analyzed for absorbance at a wavelength of 760 nm using a UV-VIS spectrophotometer (PD-303 UV Spectrophotometer; APEL Co.), with methanol blank as the reference. The TPC values were quantified as mg of gallic acid equivalents per 100 g of dry weight (mg GAE/100 g DW).

Total flavonoid content (TFC) was determined by aluminum chloride colorimetric method [28] with some modifications. Here, similar methanolic sample extract was used as working sample, that were previously used for total phenolic content determination. Diluted extract solution of 100 μL was put into an Eppendorf tube with the addition of 400 μL methanol. Initially, 100 μL of 10 % $AlCl_3.6H_2O$ was added and then 100 μL of 1 M sodium acetate was added. The reaction was allowed to incubate for a duration of 40 min, and the absorbance of the reaction mixture was measured at a wavelength of 420 nm relative to a blank solution of methanol. The TFC values were quantified as mg of quercetin equivalents per 100 g of dry weight (mg QE/100 g DW).

The antioxidant activity of both fresh and dehydrated carrots was assessed using the DPPH radical scavenging test. This assay relies on quantifying the capacity of antioxidants to scavenge the stable radical. The experiment was carried out following the methodology outlined in Refs. [28,29], with certain adjustments. The previously made sample extract was utilized to determine the antioxidant activity. To conduct the antioxidant test, we obtained extracts from both the fresh and dehydrated samples, as well as solutions of ascorbic acid, at various concentrations ranging from 20 to 200 μg/mL. These extracts and solutions were then mixed with 3 mL of methanol. Subsequently, a volume of 1 mL of methanolic DPPH solution were added. The reaction mixture was incubated in a dark location for 30 min, and the absorbance was measured at a wavelength of 517 nm using a spectrophotometer, with the blank (control) as the reference. The radical scavenging activity was determined using the formula (Equation (8)) described in Ref. [30] and represented in units of micrograms per millilitre (μg/mL).

$$\% \text{ scavenging activity} = \frac{A0 - A1}{A0} \times 100 \quad (8)$$

where,

A0 = Absorbance of control.

A1 = absorbance of sample

Inhibition concentration (IC_{50}) used to indicate antioxidant capacity and was determined from the graph that plotted % radical scavenging activity against concentration of extract for standards and test sample. Lower IC_{50} value corresponds with a higher antioxidant activity [31]. IC_{50} was expressed by equation 9 –

$$IC_{50} = \frac{y - b}{a} \quad (9)$$

where.

Y is replaced by 50 in the above equation.

Value of a and b was found from regression line plotted for each sample separately.

2.4.10. Color retention confirmation by enzyme inactivation test

The color retention agents which were extensively studied to retain the color of horticultural products through inactivating the enzymatic activities responsible for discoloration. It has been hypothesized that the two most heat resistant enzymes, peroxidase (POD) and polyphenol oxidase (PPO), might be deactivated to retain the color of the dehydrated samples. Therefore, the peroxidase (POD) test was done to confirm whether the drying was adequate with or without pretreatment to retain the acceptable color of the dehydrated carrots. In this study, the protocol was followed as per [32] with some modifications. 1 g of dried sample powder was taken and grinded in mortar pestle with addition of 5 mL of distilled water. Additionally, 10 mL distilled water was added and kept for 2 h at room

temperature. The mixture was centrifuged at 6000 rpm for 10 min before filtration using Whatman filter paper. Filtered working sample extract of 5 mL was taken in a test tube and adding 10 mL distilled water. Then added 1 mL of 0.5 % guaiacol and 1 mL of 0.08 % of hydrogen peroxide. Afterwards, the reaction was closely observed for 3.5 min. If there was any color (brown) developed within 3.5 min then it has been decided that the sample is not adequately retain its color after drying with pretreatment meanwhile if there was no color developed after 3.5 min and the solution remain clear then the sample is successfully retained its color with the respective drying technique with color retention pretreatment.

To further investigate the role of the PPO enzyme in generating color change in dried carrots, we also performed an enzyme activity test. The method suggested by Zhou [33] was employed to quantify the variation in absorbance at 408 nm for evaluating the activity of the PPO enzyme using a spectrophotometer (APEL, UV-VIS Spectrophotometer, PD – 303 UV, PD 33-3-OMS-101 b, Japan). The blank sample consisted of 3 mL of sample solution in the same buffer as the standard reaction. The standard reaction, on the other hand, consisted of 0.3 mL of PPO solution and 2.7 mL of 14 mg/mL catechol in 0.1 mol/L phosphate buffer with a pH of 6.0. A unit of PPO activity was defined by comparing the original value to the change in absorbance of 0.001 per minute, and expressed in percentage.

Moreover, the color parameters of the fresh and dehydrated carrots were evaluated using the Minolta CR-400 colorimeter (Minolta Conica, Japan) following the CIE L*, a*, b* system by the design coordinates (where L* indicates lightness; a* red-green axis; and b* as blue-yellow axis) and D65 was used as the standard illuminant. On the basis of the estimated L*, a*, b* coordinates, ΔE between the fresh and dried sample was calculated according to equation (10) [34]:

$$\Delta E = \sqrt{(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2} \tag{10}$$

where, ΔE is the total color difference, ΔL* is the lightness difference between fresh and dried carrot, Δa* is the greenness difference between fresh and dried carrot, and Δb* is the yellowness difference between fresh and dried carrot.

2.5. Statistical analyses

The experiment was conducted using a two-factor randomized complete block design (RCBD) with three replications. Factor- A includes 4 levels of drying techniques factor-B includes 6 levels consists of 4 types of pretreatment agents, control (without pretreated) and fresh sample. Experiment data were analyzed using R (version 4.1.2) program. Analysis of variance (ANOVA) and Duncan's Multiple Range Test (DMRT) were used to compare differences between the treatments at the 95 % confidence level of each variable. Correlation matrix and cluster analysis were conducted to determine the relationships among the nutritional contents of the dried carrots that were tested. Subsequently, principal component analysis (PCA) was conducted to illustrate the relationships among the estimated correlated nutritional qualities of the dried carrots in the reduced dimensions of newly derived factors, which were labelled as Dim1 (Dimension 1 or PC1) and Dim2 (Dimension 2 or PC2). The selection of the number of additional variables was based on the eigenvalues, which indicate the entire amount of variance that can be accounted for by a specific principal component. In this methodology, only components (factors) with an eigenvalue greater than 1.00 were taken into account for interpretation. The emphasis was placed on analysing the factor loadings of the independent variables (dryers' type and pretreatments) and the contribution of each of the studied dependent variables (nutritional composition) to the overall variations. The outcomes of PCA are presented in a tabular format (Table 3), displaying factor loadings that indicate the correlations between the characteristics of the dependent variable and the factors Dim1 and Dim2. Additionally, a graphical representation in the form of an ellipse plot is provided, illustrating the factor scores of drying methods and pretreatments in the Dim1 (PC1)-Dim2 (PC2) coordinate system. The factor loadings and contributions of each dependent variable were determined using various R packages (agricolae, facatominer, factoextra, ggplot2, corrplot) in version 4.1.2 of the program. The data were presented as the average of three measurements ± standard deviation (SD).

Table 1
Proximate composition of dehydrated carrots affected by drying methods and pretreatments.

Drying method[y]	Moisture content (MC DW) %	P^H	TSS (° Brix)	Total Sugar (mg/100g DW)	Protein (%)
D1	6.03 ± 0.4b	4.65 ± 0.7a	7.42 ± 1.2b	24.84 ± 5.8b	13.59 ± 16.4a
D2	5.97 ± 0.3b	4.71 ± 0.7a	7.32 ± 0.8b	21.00 ± 5.3d	13.57 ± 16.4a
D3	6.68 ± 0.6a	4.66 ± 0.5a	7.42 ± 1.5b	22.96 ± 5.3c	11.59 ± 17.1c
D4	6.49 ± 0.5a	4.55 ± 0.7b	8.50 ± 1.6a	26.39 ± 4.9a	13.02 ± 16.4b
Pretreatments [x]					
C1 (Fresh)	85.00 (MC FW)[z]	5.72 ± 0.2a	6.27 ± 0.0e	21.73 ± 0.1e	48.67 ± 0.1a
C2	7.66 ± 0.2d	4.21 ± 0.3d	7.99 ± 0.8c	28.70 ± 3.2a	5.62 ± 3.2d
C3	6.54 ± 0.7 ab	4.46 ± 0.4c	7.87 ± 1.6c	23.16 ± 4.5d	5.19 ± 1.2e
C4	6.66 ± 0.6a	4.17 ± 0.2d	8.65 ± 1.7a	19.03 ± 3.4f	8.22 ± 1.4b
C5	6.22 ± 0.2c	5.08 ± 0.5b	6.86 ± 0.8d	25.55 ± 6.6b	6.06 ± 3.7c
C6	6.39 ± 0.3bc	4.20 ± 0.2d	8.37 ± 0.9b	24.64 ± 7.5c	3.89 ± 1.9f

[y] D1; open sun drying, D2; solar drying long chimney, D3; solar drying short chimney, D4; box solar drying.

[x] C1; fresh sample, C2; control (without pretreatment), C3; ascorbic acid (1 %), C4; citric acid (5 %), C5; potassium metabisulfite (1 %), C6; potassium sodium tartrate (0.3 %).

[z] the moisture content of fresh sample (C1) was measured in fresh weight (FW) basis, DW = Dry weight, Data presented as means ± SD in each column followed by different letters are significantly different at 95 % confidence level using DMRT.

3. Results

3.1. Proximate composition of dehydrated carrots

The proximate composition of dried carrot samples was analyzed and the findings are displayed in Table 1. Significant variations ($p < 0.05$) were observed in the concentration of proximate parameters in the dehydrated products when comparing 4 drying procedures and 4 pretreatments to both the fresh sample and the control sample (without pretreatment). All the examined dryers, regardless of whether they underwent pretreatment or not, dried carrot slices to a moisture content of 5–7% on a dry basis.

Regardless of the drying techniques employed, the dried goods exhibited a considerable increase in both TSS (Total Soluble Solids) and total sugars compared to the fresh sample. The increase in the concentration were more noticeable in the carrot samples dried under the D4 drying methods and that was 8.50 (°Brix) and 26.39 (mg/100 g DW) respectively. The highest protein content was found in the D1 (13.59 %) and D2 (13.57 %) dried sample while the next best protein content (13.02 %) was observed in D4 drying methods with the lowest pH (4.55). The minimum TSS (7.32 °Brix) and total sugar (21.00 mg/100 g DW) with the maximum pH (4.71) was reported in the D2 drying method. In terms of pretreatments, the highest TSS (8.65 °Brix) and the lowest pH (4.17) was recorded when pretreated with C4. The lowest TSS was observed in C1 (6.2 °Brix). C4 treated sample also recorded 2nd higher (8.22 %) protein content followed by C5 (6.06 %) treated sample compared to other pretreatments (Table 1). Meanwhile, the highest total sugar (28.70 mg/100 g DW) was found in untreated control sample followed by the C5 treated sample.

3.2. Vitamins and mineral content of dehydrated carrots

The vitamins and mineral compositions of the fresh as well as the dehydrated carrot samples showed variations due to the drying methods and pretreatments effect (Table 2). The highest concentrations of K (0.37 %), Na (0.23 %), and Mg (0.08 %) were seen in the D2 dehydrated sample while D3 had the highest concentration of Ca (0.08 %) (Table 2). Meanwhile, the lowest observed concentration of K (0.33 %) was found in D4 and Na (0.19 %) in D3 that showed statistically identical levels to D4. Furthermore, D2 exhibited lower concentration of Ca (0.06 %), which was consistent with the levels observed in D1. Similarly, D4 displayed lower Mg (0.07 %), which was identical to the results obtained from D3 and D1. Considering the pretreatments effect, the sample treated with C5 exhibited the highest levels of K (0.43 %) and Na (0.24 %) while the maximum quantity of Ca (0.08 %) was seen in C2, which was the same as C6.

Table 2
Vitamins and mineral composition of dehydrated carrots affected by drying methods and pretreatments.

Drying method[y]	β-carotene (mg/100g DW)	β-carotene reduction %	Ascorbic acid (mg/100g DW)	Ascorbic acid reduction %
D1	0.79 ± 0.2d	30.70	4.46 ± 5.2d	67.39
D2	0.82 ± 0.2b	28.07	4.82 ± 4.4b	64.76
D3	0.80 ± 0.2c	29.82	6.59 ± 5.8a	51.83
D4	0.86 ± 0.1a	24.56	4.64 ± 4.1c	66.08
Pretreatment [x]				
C1 (Fresh)	1.14 ± 0.02a	–	13.68 ± 0.2a	–
C2	0.64 ± 0.1e	43.86	1.43 ± 2.5f	89.54
C3	0.83 ± 0.05b	27.19	1.79 ± 1.9e	86.92
C4	0.74 ± 0.1c	35.09	4.29 ± 3.0c	68.64
C5	0.82 ± 0.05b	28.07	9.85 ± 2.8b	27.99
C6	0.73 ± 0.06d	35.96	3.72 ± 3.8d	72.81

Drying method[a]	Potassium (%)	Sodium (%)	Calcium (%)	Magnesium (%)
D1	0.35 ± 0.06c	0.22 ± 0.02b	0.06 ± 0.01c	0.07 ± 0.01b
D2	0.37 ± 0.05a	0.23 ± 0.02a	0.06 ± 0.01c	0.08 ± 0.01a
D3	0.36 ± 0.04b	0.19 ± 0.08c	0.08 ± 0.02a	0.07 ± 0.02b
D4	0.33 ± 0.1d	0.19 ± 0.9c	0.07 ± 0.01b	0.07 ± 0.01b
Pretreatment [b]				
C1 (Fresh)	0.35 ± 0.00c	0.18 ± 0.00d	0.05 ± 0.00c	0.06 ± 0.00d
C2	0.36 ± 0.1b	0.24 ± 0.09a	0.08 ± 0.03a	0.09 ± 0.02a
C3	0.32 ± 0.03e	0.19 ± 0.04c	0.06 ± 0.01b	0.07 ± 0.01c
C4	0.33 ± 0.02d	0.19 ± 0.07c	0.06 ± 0.01b	0.07 ± 0.01c
C5	0.43 ± 0.04a	0.24 ± 0.09a	0.05 ± 0.01c	0.08 ± 0.01b
C6	0.31 ± 0.06f	0.23 ± 0.05b	0.08 ± 0.01a	0.07 ± 0.01c

[y] D1; open sun drying, D2; solar drying long chimney, D3; solar drying short chimney, D4; box solar drying.

[x] C1; fresh sample, C2; control (without pretreatment), C3; ascorbic acid (1 %), C4; citric acid (5 %), C5; potassium metabisulfite (1 %), C6; potassium sodium tartrate (0.3 %). Vitamins were estimated in fresh sample as mg/100g of fresh weight (FW) and in dehydrated sample as mg/100 g dry weight (DW). Data presented as means ± SD in each column followed by different letters are significantly different at 95 % confidence level using DMRT.

[a] D1; open sun drying, D2; solar drying long chimney, D3; solar drying short chimney, D4; box solar drying.

[b] C1; fresh sample, C2; control (without pretreatment), C3; ascorbic acid (1 %), C4; citric acid (5 %), C5; potassium metabisulfite (1 %), C6; potassium sodium tartrate (0.3 %). Minerals in fresh and dehydrated samples were determined in dry weight (DW). Data presented as means ± SD in each column followed by different letters are significantly different at 95 % confidence level using DMRT.

Table 3
Factor loadings and score for the first two principal components (Dim1 and Dim2) of dried carrot at different condition.

Loadings[z]	Dim1	Dim2
Temperature	0.88	−0.02
Humidity	−0.88	−0.06
MCwb	0.85	−0.02
MCdb	0.84	−0.04
Total required time	−0.77	−0.04
Drying rate	0.40	−0.30
pH	0.09	0.79
β-carotene	0.36	0.32
Vitamin C	0.09	0.69
TSS	−0.05	−0.53
Reducing sugar	−0.09	−0.75
Total sugar	−0.33	0.02
Na	−0.73	0.30
K	−0.38	0.64
Ca	−0.35	−0.20
Mg	−0.77	0.29
IC_{50}	0.16	0.89
Phenol	−0.63	−0.51
Flavonoid	−0.66	0.14
Protein	−0.06	−0.39

[z] MCwb; moisture content wet basis, MCdb; moisture content dry basis; TSS; total soluble solid, Na; sodium, K; potassium, Ca; calcium, Mg; Magnesium, IC_{50}; 50 % inhibition capacity of antioxidant.

Additionally, C2 had the highest concentration of Mg (0.09 %). In contrast, the C6 sample had the lowest concentration of potassium (0.31 %), whilst the C1 (Fresh) sample had the lowest levels of sodium (0.18 %), magnesium (0.06 %), and calcium (0.05 %). However, the C5 treated sample had a calcium content equivalent to that of C1 (Table 2). All the drying methods caused significant ($p < 0.05$) differences in β-carotene and ascorbic acid content those were found in reduction trend in the dehydrated carrot samples compared to the fresh sample (Table 2). The results revealed that D4 retained the maximum (0.86 mg/100 g DW) β-carotene and D3 drying method retained the maximum ascorbic acid (6.59 mg/100 g DW). D1 drying method losses the maximum β-carotene (30.70 %) and ascorbic acid content (67.39 %). It was also evident that carrot slices pretreated with C5 retained the highest ascorbic acid (13.85 mg/100 g DW) with retaining higher amount of (0.82 mg/100 g DW) β-carotene compared to untreated control sample. However, the control (untreated) sample lost the maximum amount of β-carotene (43.86 %) and ascorbic acid content (89.54 %) contents respectively (Table 2).

3.3. Bioactive compounds and antioxidant activity of dehydrated carrots

Different drying methods showed variable effects on total phenolic content (TPC) and total flavonoids content (TFC) of carrot samples (Fig. 2). All the drying methods give an increasing (54.51–67.92 GAE/100 g DW) trend of TPC after drying except for the D4 drying method compared to the fresh sample. Among the pretreated sample it has been revealed that C5 treated sample was able to retain the maximum (68.22 mg GAE/100 g DW) and C6 retained the lowest (39.42 mg GAE/100 g DW) quantity of TPC compared with the other treated sample (Fig. 3).

On the other hand, TFC was in decreasing trend due to the drying methods and pretreatment effects except in D1 and D2 compared to fresh sample (Fig. 2). Among the drying methods, D1 led to the highest (40.33 mg QE/100 g DW) TFC retention followed by D2

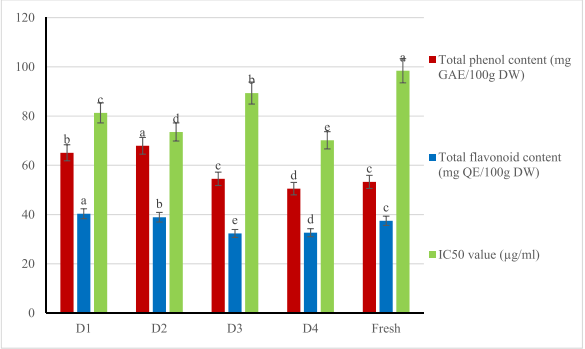

Fig. 2. Effect of drying methods on Bioactive compounds and Antioxidant Activity.

(38.90 mg QE/100 g DW) and D3 led to the lowest (32.32 mg QE/100 g DW). Among the pretreatment effects C3 (36.64 mg QE/100 g DW) and C5 (36.38 mg QE/100 g DW) pretreated sample retained the higher quantity of TFC and C6 retain the lowest (33.52 mg QE/100 g DW) quantity of TFC compared to fresh sample (Fig. 3).

In the present study, antioxidant activity of dehydrated and fresh carrot was determined using DPPH assay. In the result of DPPH test, D1 reported higher (81.29 μg/mL) IC_{50} value which represents the lower antioxidant activity while D4 showed the lowest (70.17 μg/mL) IC_{50} value that implies the highest antioxidant activity (Fig. 2). Regarding the pretreatment effect on the IC_{50} it has been observed that the highest antioxidant activity with the lowest IC_{50} value (40.24 μg/mL) was observed for the C5 (Fig. 3). Whereas, the lowest antioxidant activity with the highest (182.13 μg/ml) IC_{50} value was observed in (C6). From this finding, it has been observed that the DPPH scavenging ability had relationship (either positive or negative) with TPC and TFC.

3.4. Color retention confirmation by enzyme inactivation test

Clearly distinct variations among the treatments were observed during the reaction with POD enzyme inactivation test. Interesting visualization was experienced among the drying methods, where D1 showed brown color, D2 and D3 showed less brown color whereas D4 showed clear solution with no brown color (Fig. 4 A). From this finding it can be confirmed that D4 was able to retain the color of the dehydrated carrot slices by inactivating enzyme. Similar trend of result in color retention was noticed when C3, C4, C6 treated sample dried under D1, D2, D3 drying methods exhibited deep brown to light brown color (Fig. 4 B). But most importantly, no color developed when C5 treated sample dried in D4 while tested in the enzyme inactivation test.

Furthermore, the PPO inactivation test results is shown in the Supplementary Table 1. The PPO relative activity (%) exhibited substantial variation ($p < 0.05$) in response to changes in drying and pretreatment methods. As observed, the highest (100 %) PPO activity in fresh sample (C1). However, among the dryers the PPO relative activity (%) was higher (83.2 %) in OSD (D1) while the lower (19.6 %) in BSD (D4) drying techniques. Meanwhile, the remarkable reduction in the PPO activity (6.3 %) was noticed in the 1 % KMS pretreated (C5) dehydrated carrot samples compared to the untreated control (C2) sample where maximum (95.3 %) PPO relative activity was recorded. Therefore, from these findings it has been revealed that C5 treated carrot could retained the best color when dried in the D4.

The validity of this result was further supported by the color analysis of the dehydrated carrots. The color of carrot slices underwent a notable alteration due to the drying process, which was influenced by the specific drying procedures employed and the impact of pretreatments (see Supplemental Table 1). All drying procedures resulted in the darkening of carrots, as indicated by a decrease in the L* coordinate relative to the fresh sample. However, the D4 dried samples exhibited the greatest L* value among the different drying methods. This process is also evident in the decrease of green color in dried carrots using various drying techniques, as demonstrated by a considerable increase in the a* value compared to the fresh sample. Concurrently, there is a decreasing pattern in the value of b* throughout the various drying techniques, which suggests a decline in the yellow color intensity of the dried carrots. The decrease was found in the D4 sample, followed by D3, and the lowest decrease was observed in D2. The L*, a*, and b* values showed a consistent pattern in the pretreated dried carrots. The C5 treated samples exhibited superior color compared to the untreated (control) and fresh samples. Regarding the ΔE parameter (total color difference), it was observed that the color of all the samples, which underwent dehydration by various drying methods and pretreatments, differed significantly from the color of the fresh carrot. As per the interpretation suggested by the International Commission of Illumination (CIE), a ΔE value greater than 3.5 indicates a noticeable color difference. This difference was observed in the dried samples of D4 and C5, with the smallest difference between the dried and fresh samples. The largest difference was observed in the samples dried in the open sun (D1) without any pretreatment (C2).

3.5. Correlation coefficient analysis

Pearson's correlation was employed to assess the interrelationships among the 20 variables examined in both pretreated and untreated dehydrated carrots, including MCwb, MCdb, temperature, relative humidity, total time required, drying rate, β-carotene, Vitamin C, pH, TSS, IC50, reducing sugar, total sugar, protein, total phenol, total flavonoid, Mg, Na, K, and Ca. The correlation matrix

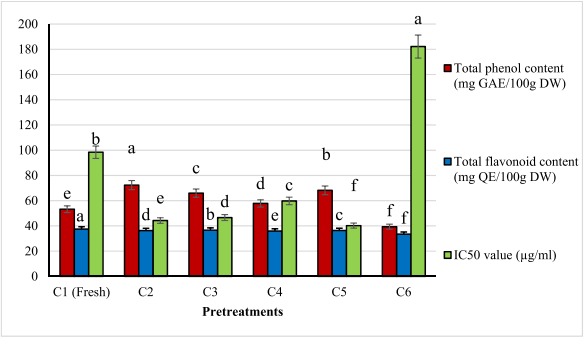

Fig. 3. Effect of pretreatments on Bioactive compounds and Antioxidant Activity.

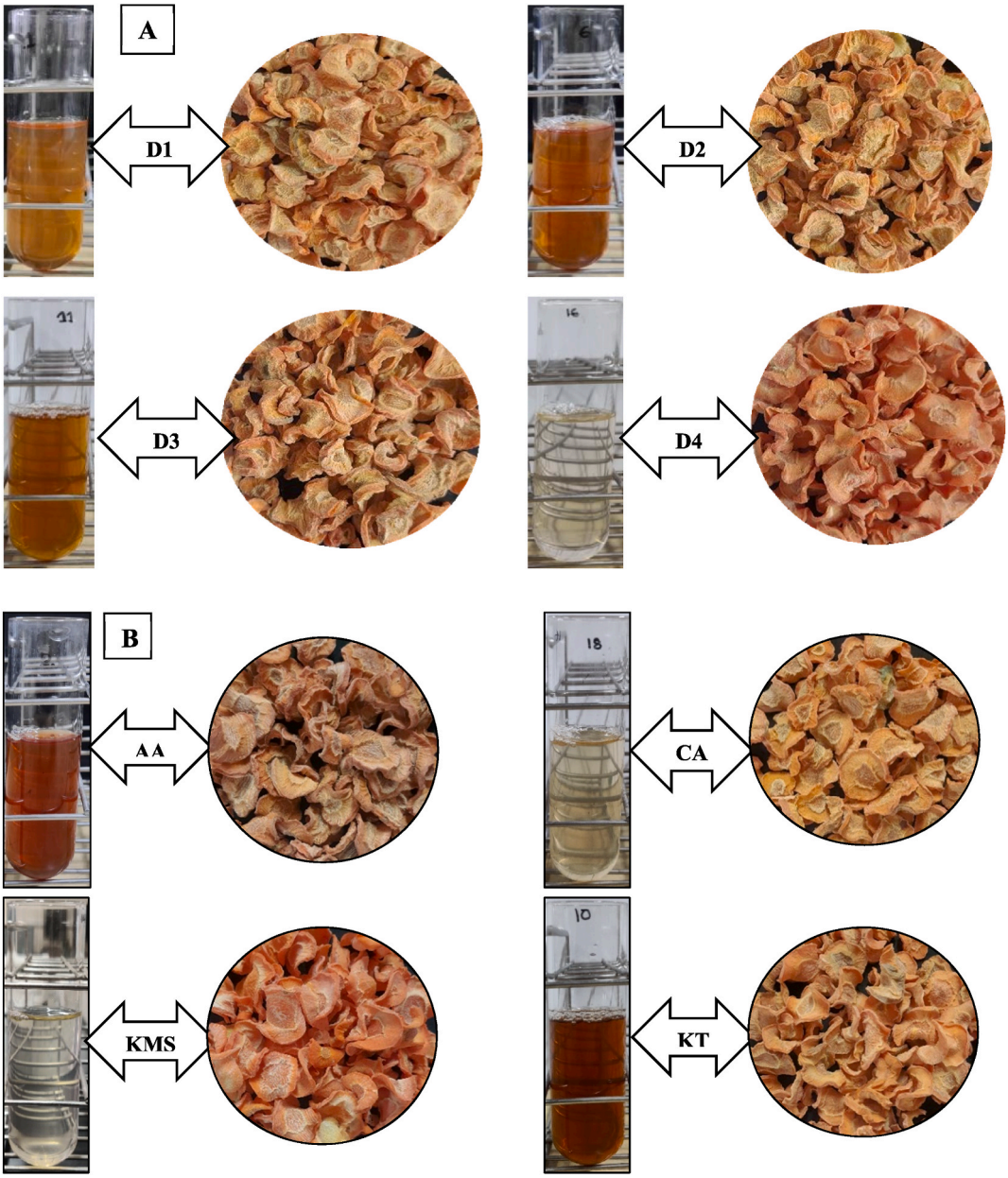

Fig. 4. Enzyme inactivation test confirmed color retention in the dehydrated carrot following (A) different drying methods (D1 = open sun drying, D2 = solar drying long chimney, D3 = solar drying short chimney, D4 = box solar drying), and (B) pretreatments (AA = ascorbic acid (1 %), CA = citric acid (5 %), KMS = potassium metabisulfite (1 %), KT = potassium sodium tartrate (0.3 %)).

displayed significant positive and negative correlations among the 20 variables examined (Fig. 5). The correlation study among the 20 variables (dependent) revealed that temperature and relative humidity showed strong negative correlation (R2 = −0.90) that denoted increase in temperature during the carrot drying process bringing about a decrease in relative humidity. A substantial positive association between temperature and the moisture contents of wet and dry bases (MCwb and MCdb) was also observed (R2 = 0.85, 0.86), demonstrating that as temperature rises during carrot drying, both the dry matter content and the moisture content of the dry base increase. Total required time showed negative correlation (R2 = −0.61) with temperature that indicated increase in temperature helped in a decrease in total required time. Meanwhile, there was a strong positive correlation (R2 = 80) between vitamin C and IC_{50} which means that increase in vitamin C content brings about an increase in antioxidant activity. Considering the antioxidant features, IC_{50} had a moderately strong negative correlation (R2 = −0.60) with total phenolic content. This relationship showed that increase in total phenolic content bring a decrease in IC_{50} (increase antioxidant). There is a moderately positive correlation (R2 = 0.56) between total phenolic and total flavonoid content which showed increase in total phenolic bring about an increase in total flavonoid content.

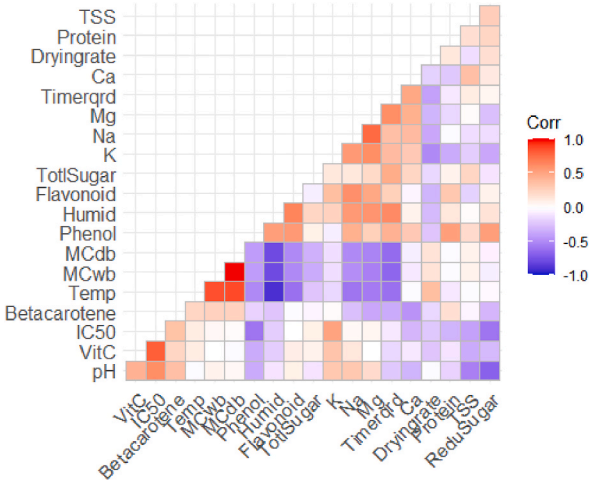

Fig. 5. Correlation coefficients for 20 variables of dried carrot.

pH and reducing sugar had a negative correlation (R2 = −0.68) that means decrease in pH value increases reducing sugar content as observed from D4 and C5 before. Temperature and total flavonoid also had a negative correlation (R2 = −0.61) that suggested that increase in temperature decreases the total flavonoid content of the dehydrated carrot.

3.6. Cluster analysis

Cluster analysis showed that the studied 20 variables were divided into some most significant clusters with remarkable contributions in the quality evaluation of the dehydrated carrot. Based on the degree of divergence 20 variables were grouped into two main clusters namely cluster (I) and cluster (II) (Fig. 6). Cluster (I) was further divided into 2 sub cluster and cluster (II) divided into 3 sub cluster (Fig. 6). The cluster (I) including 8 variables and they are MCwb, MCdb, temperature, drying rate, β-carotene, pH, IC_{50}, Vitamin C (40 % variable) and the cluster (II) including 12 variables and they are reducing sugar, TSS, protein, K, total sugar, Ca, total phenol, total flavonoid, relative humidity, total time required, Mg, Na (60 % variable).

3.7. Principal component analysis

The results illustrated in the previous sections indicate that the nutrient composition of dehydrated carrots was significantly

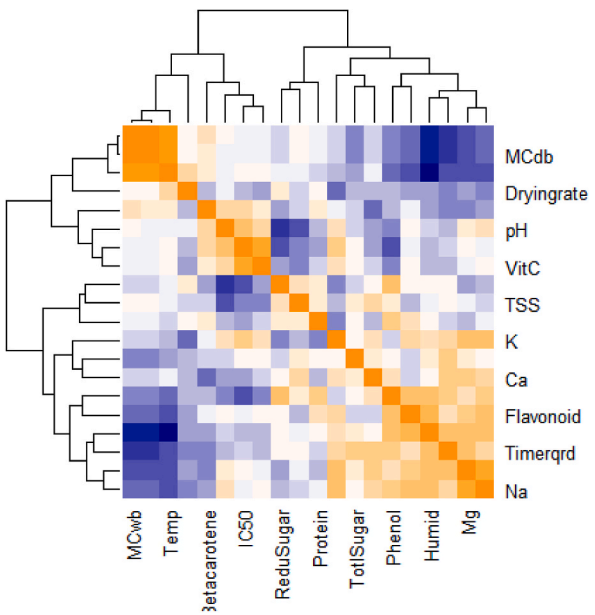

Fig. 6. Distribution of 20 variables of dried carrot into two clusters.

affected by drying methods and pretreatments. Nevertheless, a simple visual examination is insufficient to correctly identify discrepancies between drying techniques and the choice of pretreatment. Hence, the nutrient contents of all the samples of dried carrots were analyzed using principal component analysis (PCA) in order to examine the relative variability and facilitate the selection of appropriate drying procedures and pretreatments. PCA streamlined the intricate data by converting the multitude of interrelated factors into a reduced set of variables to identify the most salient characteristics. The biplot (Figs. 7 and 8) visually represented the correlations, both similarities and differences, between various indices using Dim 1 (PC1) and Dim 2 (PC2). The two primary components (Dim1 and Dim2) accounted for 52.1 % of the overall variance in the data. The factor loadings and scores for the first two principal components (Dim1 and Dim2) of dry carrot under various conditions are provided in Table 3. The higher positive scores along with Dim1 correspond to temperature (0.88), MCwb and MCdb (0.85, 0.84) while moderate positive score was characterized for β-carotene (0.36), drying rate (0.40) and IC_{50} (0.16) and lower score for vitamin C (0.09) and pH (0.09). The higher negative scores along Dim1 corresponds to humidity (−0.88), total time required (−0.77), Mg (−0.77), total phenolic content (−0.63) and total flavonoid (−0.66) and the lower was characterized for TSS (−0.05), protein (−0.06). On the contrary, the higher positive score along Dim2 corresponds to pH (0.79), vitamin C (0.69), IC_{50} (0.89) and lower for total flavonoid (0.14), TSS (0.02). The higher negative scores along the Dim2 characterized for reducing sugar (−0.75), TSS (−0.53), total phenolic content (−0.51) and lower for temperature (−0.02), total required time (−0.04). Therefore, pH, β-carotene & vitamin C and IC_{50} might be consider as major positive contributors, while TSS, reducing sugar, total phenol and protein might be considered as major negative contributors during drying of carrot.

The selection of the most successful drying processes and pretreatments was influenced by these variables. Results from the biplot of the drying methods (Fig. 7) revealed that D4 methods located in a distinct position in relation to the Dim1 and Dim2 followed by D3 where most of the variables were showing strong positive correlation to each other while D2 was overlapped with the D1 that indicates the variations in the studied variables were lower and shown lower correlation with each other. Meanwhile, in order to identify the best pretreatment for retaining the nutritional composition, PCA-biplot was performed again without fresh sample to avoid the influence of fresh samples nutrients. As observed in Fig. 8, C4 pretreatment could be distinguished than others with positive correlation among the variables considering both the dimensions of the biplot. However, the rest of the studied pretreatments D2, D3 and D5 interact with each other with different nutritional compositions and those positioned to the negative side of the Dim1 and Dim2 that made clear different than D4 and D1 control (without treatment).

4. Discussion

Alterations in nutritional composition may happen throughout the process of dehydration. The concentration of the proximate composition varied significantly due to all drying procedures, regardless of whether pretreatments were utilized or not. The carrot slices dried using the D4 (box dryer) method exhibited superior outcomes in terms of their proximate composition compared to the other drying methods (Tables 1 and 2). These factors may be attributed to the elevated temperature and decreased drying duration. For instance, accelerated dehydration from the high temperature and short drying time may have resulted in an excessive amount of moisture being removed from the goods, which could account for the rise in total sugar, TSS, and pH when compared to fresh samples (Table 1). The D4 solar dryer, with its greater temperature and shorter drying time, yielded more favorable outcomes compared to sun drying (Supplementary Table 1). Previous research on mangoes and pineapples [6,11] have also documented similar findings. There was an interlink between reduction of sample slice moisture and greater percentage of TSS. Significant decrease in moisture content increases the TSS content. Chavan [35] also reported similar result in banana. Abd-Allah [36] observed that the rise in TSS in tomatoes is caused by the loss of water during the dehydration process and the movement of solutes prior to dehydration. Moreover, during the drying process, the increase in total sugars might be relevant to the impact of drying temperature on the reducing and non-reducing

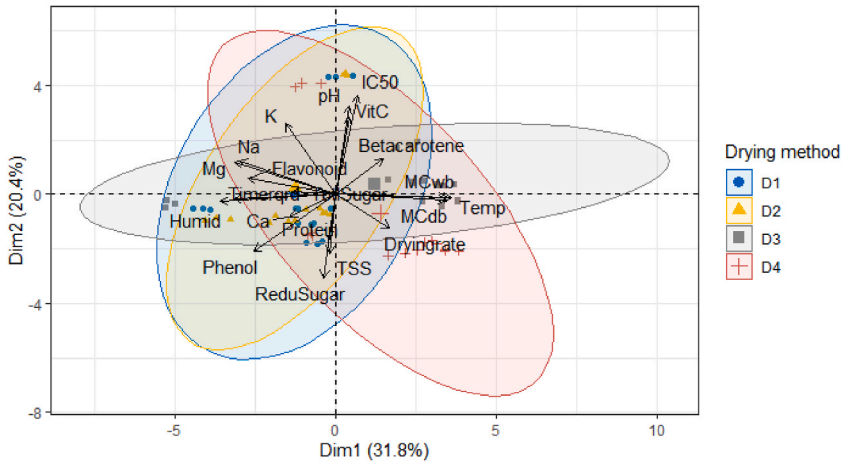

Fig. 7. Biplot diagram of principal component analysis of dried carrot using different drying methods.

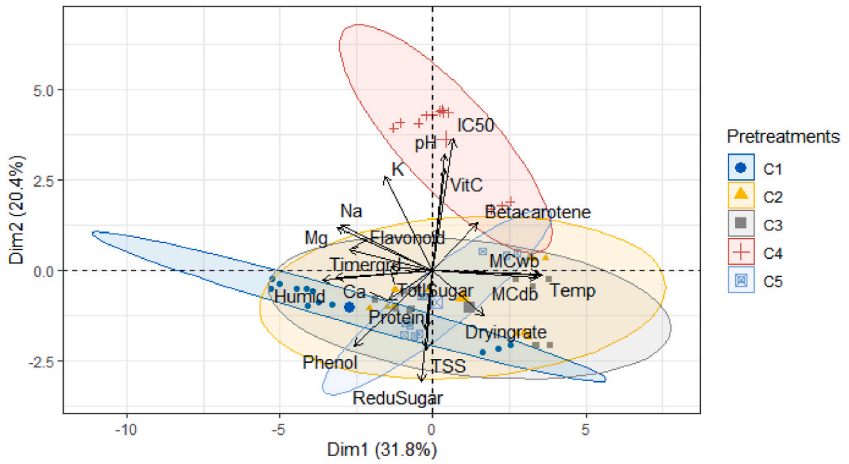

Fig. 8. Biplot diagram of principal component analysis of dried carrot using different pretreatments.

sugars. It was verified that drying at 70 °C caused a greater decrease of reducing sugars while increase in non-reducing sugars compared to the lower temperatures [37]. As shown in our investigation, the D4 sun drier recorded the maximum temperature of 44.34 °C (Supplementary Table 1), which could correspond to an increase in the total sugar content of the dried carrots. Furthermore, during drying the oxidation of the reducing sugars also occurs, and hence the amount of reducing sugars was expected to decrease with a consequent increase in the non-reducing sugars that led to increase the total sugars content [37].

It was noted that the mineral element content in the dehydrated carrot after pretreatment rose significantly compared to the fresh sample (C1) in all three drying processes, as shown in Table 2. The rise in moisture loss, combined with a significant increase in the amount of dried carrot material, may be the cause of this increase [6]. Moisture content is reduced in the D2 drying procedure, likely due to severe desiccation. This is the main reason for the observed rise in dry matter and mineral content, as seen in Tables 1 and 2 George [38], documented a significant positive association between the dry matter and mineral elements, as well as the moisture content. Nevertheless, the D1 approach resulted in the highest depletion of β-carotene and ascorbic acid in the dried carrot, as indicated in Table 2. This is likely due to the carrots being completely exposed to unregulated thermal UV radiation while being dried in the open sun. Furthermore, a comparable outcome was documented for mangos and pineapples [6], as well as for dried chilies [39]. According to Li [40], vitamins such as β-carotene and vitamin C are extremely susceptible to UV radiation, high temperature, and oxidative degradation. Thus, the decrease of β-carotene occurs as a result of stimulated oxidation processes. This study examines the effects of different solar drying techniques and pretreatments at different degrees on the proximate composition of dehydrated carrots. These effects mostly arise from the distinct molecular structures of the components involved. For example, the highest amount of β-carotene degradation in all three drying methods, with the exception of box drying, can be attributed to factors such as temperature, oxygen exposure, and lipoxygenase activity. This phenomenon can be explained by the prolonged exposure of carrots to high temperatures, which leads to the oxidation of their highly unsaturated carotenoid by lipoxygenase. Furthermore, the conversion of *trans*-carotenoids to less pigmented *cis*-forms by isomerization is another factor that contributes to the fading of color in carrots [41]. The observed decrease in carotene degradation during box drying can potentially be attributed to reduced oxidation, which is responsible for the degradation of β-carotene. This reduction in oxidation can be attributed to the faster dehydration and shorter drying time associated with box drying, as well as the limited availability of oxygen throughout the drying process [41]. Meanwhile, during the drying process, the three isomers of vitamin C, specifically D-ascorbic acid, L-isoascorbic acid, and D-isoascorbic acid, undergo oxidation and hydrolysis processes as a result of the presence of temperature, oxygen, and water content. Thus, it has been noted that L-ascorbic acid can undergo oxidation to produce L-dehydroascorbic acid at temperatures lower than 60 °C. L-dehydroascorbic acid can be subsequently transformed into L-ascorbic acid. Nevertheless, when L-dehydroascorbic acid undergoes additional oxidation and hydrolysis, it undergoes a transformation into 2,3-Diketo-L-gulonic acid, leading to the loss of its functionality. As a result, the efficacy of vitamin C diminishes. It is important to note that this process is irreversible and occurs at temperatures exceeding 60 °C [42]. Hence, based on the present data, it may be inferred that the vitamin C content may have been preserved in the dehydrated carrot subjected to box drying, along with the use of a 1 % KMS pretreatment.

Furthermore, bioactive compounds are prone to deterioration due to several causes including enzymes, thermal treatment, pH, oxidation, light, and hydrolysis. Several studies have documented that the total phenolic content (TPC) in different plant species exhibits erratic fluctuations throughout various drying processes [11]. Our investigation found that the drying process leads to changes in the quantities of total phenolic compounds (TPC) as compared to the fresh sample. These alterations occur as a result of the heat extraction of antioxidant molecules that were previously complexed or polymerized [43]. In a study by Kasunmala [44], it was found that heat treatment has the ability to supply energy that can disrupt the connection between phenolics and insoluble polyesters, leading to a potential improvement in polyphenol bio-accessibility. The losses incurred by TPC were a result of the heat destruction of chemicals and the activation of oxidative enzymes during the drying process. The drying process may have improved the effectiveness of oxidative enzymes, specifically polyphenol oxidase and peroxidase, leading to a decrease in phenolic compounds [45]. As stated by

Kumar et al. (46), the application of any drying technique results in the breakdown of cellular structures, leading to an increased susceptibility of phenolic compounds located outside the organelles to degradation. Consequently, a decrease in the levels of these compounds is observed in the dehydrated products. Li [40] reported that higher temperature had the remarkable effect on decreasing the TPC in carrots. The phenolic compounds are very sensitive to high temperatures causing reduction in these bioactive components confirmed by the previous findings [34,46,47]. However, the total phenolic content (TPC) was increased in the dried carrots of all the drying methods (D1, D2, D3) and pretreatments (C3, C4, C5) with the exception of the samples of D4 and C6 compared to the fresh and untreated sample in the current study (Figs. 2 and 3). The primary factor contributing to the inconsistent findings can be attributed to the variations in the molecular compositions of the three phenolic substances, namely polyphenols, flavonoids, and glycosides. Glycosides exhibit greater reducibility in comparison to phenols and flavonoids, and are more prone to the effects of temperature and oxygen concentration. Phenols and flavonoids exhibit lesser reducibility in comparison to glycosides, resulting in their decreased susceptibility to temperature and oxygen concentration [48]. However, our finding was in contrast to evidence of [49,50] where they reported a decrease of TPC with the increase in temperature (70–80 °C) and drying durations. Meanwhile, the present findings are concurrent with the observations of [34] where they reported a considerable increase of TPC was obtained with the drying temperature and time regimes variations. These findings align with the observations made by Nyangena et al. (51), who reported an elevation in polyphenolic concentration in dried mango samples compared to fresh ones. The greater quantities of phenolics found in dried fruits can be linked to the creation of Maillard reaction products. These products have the potential to facilitate the generation of novel phenolic complexes from their precursors when exposed to higher temperatures [51,52]. Additionally, they found that the impact of temperature on the identified TPC (total phenolic content) was both significant and unclear when considering various drying methods. This is because certain TPC compounds, such as feruloyl-dicaffeoylquinic acid and procyanidin, exhibited an increase at 70 °C but a decrease at 80 °C compared to the fresh sample. Regarding (+)-catechin, there was an inverse relationship between the quantity and the temperature [34].

Meanwhile, the total phenolic content (TPC) was reduced in the dehydrated sample of D4 due to the fast-drying process and high temperatures, which could lead to the binding of phenols to proteins and ultimately result in a decrease in TPC. Moreover, the variation of TPC (increase or decrease) may be due to the differences of environmental conditions of the dryers, which can modify the chemical structure of the cellular phenols of the dried sample [11]. Regarding TFC, the dehydrated sample exhibited either a growing or decreasing pattern in relation to the differences in dryers and pretreatments. The observed increases may be attributed to the creation of oxidized compounds, resulting in an overestimation of TFC. Conversely, the losses experienced by TFC may be attributed to the interaction between temperature and drying period. Another study [11] also found that using shorter time and less powerful heating during ginger drying is more effective in conserving flavonoids, which aligns with the findings of the present investigation on D4 dehydrated items. In addition, it can be elucidated that certain flavonoids are formed as oxidation products of phenols under high temperature conditions. As a result, there is a phenomenon where the number of flavonoids retained is higher at high temperatures than at low temperatures [48].

In this investigation, the Folin-Ciocalteu (F–C) method was employed to evaluate the variations in total phenolic content (TPC) between different drying procedures and pretreatment samples in comparison to the fresh samples. The TPC was determined using methanolic extracts. Nevertheless, during the methanol extraction process, the inclusion of various phytochemicals in the extracted sample, such as ascorbic acid, tyrosine, formic acid, and acetic acid, significantly impacted the accuracy of the results. Conversely, the presence of glucose, HMF (5-hydroxymethylfurfural), furfural, and vitamin-B12 did not have any adverse effects on the determination of phenolic compounds [53]. Hence, there exists a potential for the Total Petroleum Hydrocarbon (TPC) identified in this study to surpass the true quantity. The rise in total phenolic content (TPC) may also have an influence on the increase in antioxidant activity. This can be attributed to the breakdown of phenolic compounds into soluble phenolics and the formation of Maillard reaction products, both of which possess antioxidant properties [54]. However, the current data is significant as an initial endeavour to evaluate appropriate drying techniques with pretreatment, taking into account the presence or absence of total phenolic content (TPC) in the samples under investigation. Hence, it is recommended that additional investigation be conducted to elucidate the underlying mechanism behind the fluctuations in total phenolic content (TPC) by employing modern techniques such as high-performance liquid chromatography (HPLC) for individual phenolic compound profiling in dehydrated carrot.

Antioxidant activity was determined in terms of IC_{50} value which means the concentration of the respective sample that induce 50 % inhibition of DPPH free radicals [55]. Mbondo [56] reported that an increase in IC_{50} value correspond to a decrease in the antioxidant activity content and vice versa. In our study, D4 had high antioxidant activity because of higher temperature and shorter drying time. Another study, conducted by Ref. [43], found that increasing the processing temperatures resulted in reduced drying durations and greater levels of antioxidant activity. In addition, the production and buildup of Maillard-derived melanoidins with varying levels of antioxidant activity can further boost antioxidant capabilities at elevated temperatures [55]. The DPPH scavenging activity exhibited a stronger connection with total phenolic content (TPC) and a weaker correlation with total flavonoid content (TFC). Prior studies have also suggested that the antioxidant properties of carrot slices may be attributed to the presence of various total phenolic compounds (TPC) and total flavonoid compounds (TFC) [57,58]. Furthermore, it was noted that the box dryer and dehydrated samples pretreatment with 1 % KMS displayed higher levels of antioxidant activity in comparison to the other dried samples. The chemical changes that impact the phenolic and flavonoid composition of dried products can be ascribed to alterations that occur during the drying process at temperatures ranging from 40 to 80 °C. These modifications have a substantial effect on the improvement of antioxidant activity [59]. The rise in antioxidant activity in dried fruits and vegetables may be due to the presence of partially oxidized polyphenols, which have been shown to have higher antioxidant activity than non-oxidized polyphenols [60]. Furthermore, research has demonstrated that the Maillard reaction products, which are generated through the application of heat or prolonged storage, exhibit strong antioxidant properties. These chemicals have been proposed to contribute to the augmentation of antioxidant

capacity during the drying process [60].

In terms of pretreatment effect, C5 (KMS 1 %) treated sample followed by C4 (citric acid 5 %) treated sample retain the higher quantity of nutritional qualities. This might be due to their capability of shortening drying time and retain color by inactivating enzymatic reaction. Putsakum [61] also reported similar result in nutmeg that KMS or citric acid immersion would inactivate the enzyme and retain the quality of the produce. The acidic nature of citric acid (C4) caused a decrease in pH in the slices. Comparable findings were observed with dehydrated mango that underwent treatment with lemon juice [62]. The decrease in pH may suggest that the product has a longer shelf-life due to its resistance to microbial contamination [63]. Li [40] reported that vitamin in sulphury fruits were preserved which might be due to the presence of sulphur dioxide in KMS. The higher ascorbic acid content was also reported from dried aonla shred treated with KMS [64,65]. C5 helped in the inactivation of enzymes and prevented oxidation of total phenol that helps to improve the antioxidant properties of the dried sample [43]. C5 also had the highest retention of ascorbic acid, total phenol, total flavonoid and total carotenoid compounds and C6 treated sample had the lowest retention of bioactive ascorbic acid, total carotenoid, total flavonoid and phenolic compounds, which are also the antioxidant properties. All the pretreated sample showed considerable increase in TSS. This may be due to the loss of weight by water evaporation during drying and also may be due to the conversion of carbohydrates to sugar, organic acid and other soluble material by metabolic process. C5 also showed the highest total sugar content, which might be attributed because of the protective effects of sulfites towards hydrolysis and inversion of non-reducing to reducing sugar.

The color of dehydrated foods is a crucial quality factor that significantly influences consumer acceptance. The fresh items underwent a sequence of procedures during the drying process, resulting in color degradation due to enzymatic and non-enzymatic browning. Fruits and vegetables that have high levels of polyphenols, polyphenol oxidase (PPO), and peroxidase (POD) are susceptible to enzymatic browning. Non-enzymatic browning, on the other hand, involves the oxidation of phenols, changes in temperature, the Maillard reaction, caramelization, and maderization [66]. Hence, it is desirable to carry out pretreatments prior to drying in order to safeguard the items against browning and maintain their color. Potassium metabisulfite (KMS) is commonly used as a pretreatment to prevent browning. It effectively slows down both enzymatic and non-enzymatic reactions, hence preserving the color of the goods [66]. The results of the current investigation indicate that pretreatment had a substantial impact on the color of dried carrot products. The superior color was achieved when subjected to C5 (KMS 1 %) pretreatment, as indicated by the peroxidase (POD) and polyphenol oxidase (PPO) enzyme inactivation test (Fig. 4 A, B; Supplementary Table 1). The PPO activity was significantly reduced in the C5 (KMS 1 %) treated sample, indicating the deactivation of PPO enzyme, which contributes to better color retention. These results are consistent with the observations in bottle gourd [55]. They hypothesized that this occurrence may be attributed to reduced enzymatic and non-enzymatic browning in the pretreated sample as compared to the untreated sample. Enzymatic browning is triggered by the action of polyphenol oxidase (PPO), which facilitates the conversion of phenolic compounds into quinones. These quinones then lead to the formation of melanins, resulting in the production of various brown colors. Meanwhile, the PPO activity was observed 100 % in fresh sample owing to its presence in the tissues of higher plants. Additionally, it is synthesized a proproteins and contains putative plastid transit peptides at the N-terminal in the plant cells which target the enzyme into chloroplast and thylakoid lumen. However, this PPO is highly susceptible while exposed to oxygen that forming a relatively insoluble pigment of enzymatic browning through oxidation [67]. Hence, the deactivation of the PPO activity is essential in order to regulate the browning process that occurs as a result of the combination of physical and chemical methods. In this study, we utilized physical drying procedures and chemical pretreatments to enhance the quality of dehydrated carrots, specifically focusing on improving their look and color retention. According to Orphanides [68], sulphur dioxide found in KMS acts as a disinfectant, preventing the oxidation and discoloration of carrots when exposed to sunshine, hence preserving their color. Potassium metabisulfite ($K_2S_2O_5$) is commonly employed as a water-soluble sulphide salt in the food sector. Its primary purpose is to minimize browning and maintain the quality of dehydrated items during the drying process [66]. Upon the application of KMS to the sample, the examined material absorbs SO_2 and undergoes conversion into sulfite ions. It aids in the inactivation of PPO by facilitating a reaction between sulfite ions and quinones, hence inhibiting PPO activity and depleting oxygen levels. Additionally, it functions as an antioxidant by inhibiting the degradation of ascorbic acid and safeguarding carotenoids from oxidative damage during the drying process. In addition, it offers the benefits of preserving color, accelerating the pace of drying, improving drying efficiency, and enhancing the rehydration ratio by altering the permeability of cell membranes in dehydrated products [66].

Meanwhile, ascorbic acid (C3), citric acid (C4) and potassium tartrate (C6) were used as the pretreatment with the assumption of improving the quality attributes of the dehydrated carrot. However, all of these had slighter accelerated drying process compared to the KMS (C5) through effecting on the cellular membrane, flexibility of moisture movement and inhabiting enzymatic browning. Besides, some pigments such as chlorophylls and carotenoids are reported as sensitive to ascorbic acid and citric acid those cause the color changes from green to brown [69] those were consistent with the present findings regarding the color changes pattern compared to the KMS (C5) treated samples (Fig. 4 A, B).

The drying processes had an impact on the color of the product. The D4 drying processes yield a favorable color for the final dried products due to their efficient utilization of sun light. The interior surface is coated in black to effectively absorb the solar light it receives. Due to the insulation of the box, the inside temperature increases, resulting in the ventilation of hot air through the small holes at the end. This process effectively reduces both the drying time and browning. This observation is consistent with the results of [55], which demonstrated that the overall color change index value of bottle gourd dried by solar drying was of higher quality compared to open sun drying.

All the studied physiochemical attributes were found correlated with each other that allowed to perform PCA to choose the best drying technique and the pretreatment. The PCA thus confirmed significant differences in the nutritional composition of dehydrated carrots depending on the dryer types and pretreatments variations. At the same time, it also indicated some distinguishing features of

the dryers and pretreatments with better nutrition attributes and antioxidant, owing to which it is possible to divide them than other studied treatments.

5. Conclusion

Solar drying methods are considered sustainable and economically efficient due to their utilization of abundant and renewable solar energy, which is readily accessible even in remote locations. Hence, this study presented alternative solar drying techniques to enhance the typical solar drying process for dehydrating carrots and evaluating their nutritional composition in comparison to the fresh sample. Results showed that the color and nutritional quality attributes were better retained in the KMS 1 % (C5) pretreated carrot products dried using the box solar dryer (D4) than that drying using the traditional open sun drying method. Moreover, the highest color retention was also confirmed in the C5 pretreated carrot samples dried in the D4 through PPO and POD enzyme test. Correspondingly, the total phenolic contents, flavonoids and antioxidant activity was found the highest in the D4 (box solar dryer) dried carrots pretreated with C5 (KMS 1 %) than that of the other pretreatments and drying methods. Subsequently, the PCA results demonstrated that the D4 drier with C5 pretreatment played a crucial role in maintaining the dried carrot products' excellent color, nutrient composition, and bioactive components. Therefore, the box solar dryer (D4) is recommended as a very promising technology with potassium metabisulfite (KMS 1 %) (C5) pretreatment against the traditional sun drying methods (D1). If successfully deployed, this technique could serve to address the seasonal glut and associated postharvest losses of perishable horticultural commodities through effective drying and value-addition. Considering sustainable economic demand, this finding could open a new potential way to enhance the shelf life of carrot with food values that would be effective for producing the functional food products by the food processing industries.

However, future efforts should be carried out to ascertain the economic profitability of the newly proposed box solar dryer (D4) in compare with the traditional and mechanical drying techniques for boosting the utilization of the D4 among the resource-limited farming communities in Bangladesh including diversified products.

Ethical statement

The present study utilized carrot (*Daucus carota* var. sativus) as the plant material. The carrot seeds were obtained from the department of Horticulture at Bangabandhu Sheikh Mujibur Rahman Agricultural University in Gazipur-1706, Bangladesh. The carrot seeds are being cultivated and stored in the Horticulture department for utilization in research endeavors. The study was done within the same department's research field, adhering to regular cultivation protocols and complying with the necessary guidelines and regulations regarding scientific ethics and plant management.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Jiasmin Akter: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Jahidul Hassan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M. Mizanur Rahman:** Writing – review & editing, Supervision, Investigation. **Md Sanaullah Biswas:** Writing – review & editing, Methodology, Investigation. **Haider Iqbal Khan:** Writing – review & editing, Investigation, Data curation. **Md Mijanur Rahman Rajib:** Writing – review & editing, Visualization, Validation, Data curation. **Mohammed Razu Ahmed:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Md Noor-E-Azam Khan:** Writing – review & editing, Visualization, Investigation. **Md Faisal Ahamed Hasan:** Writing – review & editing, Visualization, Investigation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e24165.

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