



Enhancing moisture transfer and quality attributes of tomato slices through synergistic cold plasma and Osmodehydration pretreatments during infrared-assisted pulsed vacuum drying

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ABSTRACT

The present study examines the impacts of combined cold plasma treated water (PW) and osmodehydration (OD) pretreatment (PO), and operation parameters like PW duration and voltage of treatment on the dehydration, functional and sensory characteristics of sliced tomato fruits subjected to simultaneous infrared-assisted pulsed vacuum drying (IR-PVD). From the results, PO pretreatment modified the surface structures by the formation of microchannels and cavities through impingements from the reactive species (RS), and was improved due to increased treatment duration and voltage, and resulted in accelerating the transfer of moisture from the slices to the surroundings during the dehydration process. Consequently, PO pretreatment achieved an enhancement in the moisture diffusivity by up to 64.83%, shortened the total drying time by up to 40%, and presented substantial improvements in the physicochemical properties including vitamin C, lycopene, colour, total soluble solids, phenolic and flavonoid contents, and overall human acceptability. However, significant decreases in rehydration and hardness properties were shown compared with control, and higher rehydration by up to 21.66% at higher treatment duration and voltage when compared with OD pretreatment. Overall, PO pretreatment incited an effective moisture removal and retention of vital physicochemical and bioactive constituents in the slices due to the activities of plasma injected RS. This study provides an empirical basis for the application of PO during IR-PVD of fruits and vegetables and demonstrated as a suitable energy-saving alternative for improving the conventional OD of foods in the industry.

1. Introduction

Tomato fruit (*Solanum lycopersicum* L.) is popularly ingested throughout the world owing to its enormous supply of important biochemical compounds for improved nutrition and dietary requirements that help in lowering the dangers of contemporary health issues in humans, including malignant tumor and heart diseases (da Costa et al., 2023). Globally, China is recognized as a leading producer of tomato fruits and exporter of tomato products such as lycopene, vitamin C and betacarotene dietary supplements (Obajemihi et al., 2020). Nevertheless, tomato consists of soft tissues that carry a large

amount of moisture making it susceptible to rapid mechanical injury, contamination, deterioration and degradation of essential nutrients during postharvest management, processing and storage. Commercially processed tomatoes are available in different forms including canned, ketchup, puree, juice, paste, sauce and dried (da Costa et al., 2023). However, a small fraction of 0.20% of the total production volume of 180 mT of tomato fruits produced in 2019 was processed by the food industry, and a huge loss was recorded (da Costa et al., 2023).

Certainly, one great challenge encountered by the food industry is manufacturing products that are stable during storage whilst maintaining their highly perishable bioactive and nutritional components.

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Therefore, consistent exertions were made by applying several methods to reduce food wastage and ensure year-round availability.

Drying or dehydration has been deployed for preserving food since earliest times by the removal of moisture as minimized water activity is useful for improved stability of dried products and impedes enzymatic and biochemical activities (Lin et al., 2021, Lin and Sun, 2022; Bassey et al., 2022, Lin et al., 2022; Obajemihi et al., 2023). Interestingly, dehydration of food items has transitioned from the application of conventional (e.g. hot air drying (HAD)) to novel techniques (e.g. infrared drying (IRD)) due to some limitations associated with the conventional methods such as prolonged time, higher energy demand and substandard final product qualities (Su et al., 2019; Su et al., 2020; Lin et al., 2020; Tabibian et al., 2020). Infrared energy is notable for its rapid and consistent heating of food substances with minimal energy requirement and has been combined with numerous conventional drying methods like hot air, spouted, freeze, fluidized and vacuum drying (Jiang et al., 2022; Obajemihi et al., 2022).

In particular, infrared-assisted pulsed vacuum drying (IR-PVD) is suitable for processing heat and oxygen-sensitive agricultural products for improved retention of the bioactives (e.g., lycopene) (Liu et al., 2022). The IR-PVD mechanism is explained by the concurrent heating of food molecules by infrared radiant energy and faster diffusion of moisture to the food surface under reduced pressure resulting in a lowered boiling point of water molecules (Liu et al., 2022). The absence of air in the vacuum chamber ensured the reduction of degradative enzymatic and biological reactions such as oxidation and browning, thus enhancing the overall food quality with reduced energy requirements (Liu et al., 2022). Nonetheless, IR-PVD of food is faced with some bottlenecks, such as increased temperature resulting in collapsing the cell structure and decreasing phytochemicals in blueberries and increasing redness due to non-enzymatic browning reactions in chili peppers revealed the impact of processing conditions such as heating temperature and vacuum pressure during IR-PVD (Xie et al. 2017; Liu et al. 2022). Nevertheless, the optimization of IR-PVD systems for establishing optimum conditions for processing fruits and vegetables has been limited (Saengrayap et al., 2015).

Pretreatments using non-thermal approaches such as cold plasma (CP), osmotic dehydration, ultrasonication, edible film coating and pulsed electric fields have taken center stage during the processing of food products. These techniques have been applied to heat-sensitive products prior to final dehydration processes for preserving the nutritional and aesthetic benefits whilst saving time and minimizing energy requirements compared with some deleterious thermal approaches such as blanching. CP comprises a wholly or partially ionized gas of various particles such as ions, atoms, ultraviolet photons, electrons and free radicals, which are generated by different devices including dielectric barrier discharge (DBD), corona discharge, radiofrequency and gliding arc discharges. Our earlier studies, Esua et al. (2022d); Wang et al. (2023); Wu et al. (2023); Zhu et al. (2023); Zhu et al., (2022) and Ali et al. (2022) have demonstrated that CP can be applied tortuously by exposing H₂O or buffer solution to plasma flame, and the liquid becomes functionalized or activated by the release and formation of reactive species like triatomic oxygen (O₃), diatomic oxygen (O₂), oxygen atom (O), nitric oxide (NO), nitrite (NO₂) and nitrate (NO₃) for triggering biochemical reactions in food products.

CP has been applied in decontaminating and inactivating food enzymes and recently gained traction for the pre-drying treatment of food with promising results for improving drying kinetics and increased bioactives, nutritional and sensory properties of food (Gu et al., 2021; Ali et al., 2022; Khudyakov et al., 2022). However, findings have indicated the need to control the amount of reactive spec(RS) and oxidation-reduction potentials (ORP) generated to minimize the oxidative impact of the species on fresh produce. High doses of RS of oxygen and Nitrogen (RONS) such as hydroxyl radicals, superoxide and hydrogen peroxide have presented an increased colour change in Dongkui bayberry grapes and could be controlled by increased level of

anthocyanin with elevated high oxygen environment (Malahlela et al., 2024). Some key factors such as treatment voltage, duration, frequency and gas pressure have been noted for either increasing or decreasing the amount of RS produced which could affect the level of physicochemical changes in treated food substances (Esua et al., 2021a; Loureiro et al., 2021).

Plasma osmotic solution is a pretreatment technique applied to food materials by combining the beneficial effects of cold plasma and osmotic dehydration to improve the conventional OD. Thus, increasing the number of pores on the food surface and accelerating the removal of moisture during drying. Previously different attempts have been made to improve the OD by combining with ohmic heat (Kutlu, 2022), vacuum (Aloiga et al., 2022), ultrasound (Osae et al., 2019), microwave (Wray and Ramaswamy, 2013), pulsed electric field (Tylewicz et al., 2020) and recently, CP in our previous study (Obajemihi et al., 2023), on food products. The exploitation of PO has shown the potential for improving drying performance, surface structure, bioactive compounds, lightness and the overall colour properties of tomato fruit slices in comparison with conventional OD during HAD (Obajemihi et al., 2023).

Subrahmanyam et al. (2024) studied the effects of CP pretreatment during refractance window drying of apple slices, and increased microchannels on the sample surface led to higher drying performance and rehydration capacity, with improved colour, but reduced polyphenol oxidase and hardness properties compared with control. Yanclo et al. (2024) investigated the impact of low-pressure cold plasma pretreatment prior to HAD of mango slices, and showed a reduction in drying time by 20%, improved colour, phenolics and flavonoids contents, but lowered antioxidant properties when compared with control samples. Ashtiani et al. (2023) conducted a three-stage processing of mushrooms by applying CP pretreatment prior to osmotic dehydration (OD) before the final HAD of samples, and obtained a reduction in drying time by 36.7%, and significantly improved the vitamin C, antioxidant activity and total phenolic compounds compared with control samples. The combined CP and OD pretreatments led to higher retention of the physicochemical and textural attributes of samples when compared with individual CP or OD. Therefore, the combination of CP with OD revealed the potential for reducing some challenges peculiar to OD such as prolonged drying period, poor rehydration capacity and increased colour change (Obajemihi et al., 2023). Recently, Du et al. (2022) conducted a systematic review of the improvement of food drying performance by CP pretreatment, which revealed that investigations were conducted by the direct exposure of food samples to plasma jet prior to HAD, and resulted in an enhancement in drying rates and quality attributes with a reduction in energy consumed.

Although few studies have highlighted the potentials of CP as an emerging novel pretreatment strategy for improving drying rate and retention of bioactive compounds in fruits and vegetables, studies have been limited to the application of CP alone and often by direct exposure to the plasma flame prior to HAD. Investigations based on indirect CP application using the combined plasma-treated water (PW) and OD (PO) for pretreating food materials prior to novel drying methods like IR-PVD were not available in the literature. Therefore, the current study was aimed at evaluating the potential of PO pretreatment for shortening the drying time and increasing the retention of vital bioactives and physicochemical characteristics of tomato fruit slices subjected to combined infrared and pulsed vacuum drying. Besides, the impacts of CP treatment conditions (e.g. voltage and time) on the effectiveness of PO for increasing drying and quality characteristics of IR-PVD tomato products were investigated and foremost.

2. Materials and methods

2.1. Reagents

Methanol (CH₃OH), Catechin hydrate (C₁₅H₁₄O₆), AlCl₃, n-hexane (C₆H₁₄), potassium persulfate (K₂S₂O₈), Sodium carbonate (Na₂CO₃),

NaNO_2 , metaphosphoric acid (HPO_3), $\text{C}_{18}\text{H}_{12}\text{N}_5\text{O}_6$ and L-ascorbic acid ($\text{C}_6\text{H}_8\text{O}_6$) were acquired from the Aladdin Biochemical Tech. Company (China). Gallic acid ($\text{C}_7\text{H}_6\text{O}_5$), NaOH and 2, 6-dichlorophenolindophenol ($\text{C}_{12}\text{H}_7\text{Cl}_2\text{NO}_2$) were obtained from the Macklin Biochemical Company (Shanghai, China), and Folin-Ciocalteu reagent was purchased from Sangon Biotech. Company, China.

2.2. Plasma treated water production and measurement

A cold plasma instrument known as silent electrical or dielectric barrier discharge (DBD) (model no: CTP-2000K) produced in China by Suman Electronic Company Ltd. was used in this research for generating PW, full description of the device could be seen in a prior research by Pan et al. (2020). The generation of PW was actualized by introducing a dielectric material between a couple of electrodes placed analogous to one another in such a way that the dielectric material functioned as a barrier to shield one of the electrodes for preventing an arc discharge and to ensure a steady and even flow of plasma species generated into the surface of the treated liquid. The discharge frequency was maintained at 1 kHz and a 5 mm distance was introduced between the water meniscus and the high volts electrode. DW contained in a 25 mL Petri dish of 60 mm width amid the two conductors visible to plasma flumes at varied treatment durations of 2, 6 and 10 min, and 50 and 70 V, presented in Fig. 1. For each sample, the process was done 6 times to achieve a PW volume of 150 mL. The plasma osmotic solution (PO) was prepared by slight modification of the procedures of Obajemihi et al. (2020), which was carried out by dissolving 89 g of sucrose in 150 mL of PW at ambient condition of 28.9 °C, and twirled in a vortex mixer manufactured by the Aohua Instrument Co., Ltd., Changzhou, China (Model no: 78-1) for a duration of 10 min to obtain uniformity, and an electronic refractometer produced by Atago Co., Ltd., Tokyo, Japan (Model no: PAL-1 A) was used in obtaining the degree of concentration of 37 °Bx. The solution prepared were tagged as PO2V5, PO2V7, PO6V5, PO6V7, PO10V5 and PO10V7, following their variation in cold plasma treatment time and voltage of 2 min at 50 V, 2 min at 70 V, 6 min at 50 V, 6 min at 70 V, 10 min at 50 V and 10 min at 70 V, respectively, achieved from a preliminary test for determining suitable treatment parameter for tomato slices. The preparation of the osmotic dehydration solution (OD) followed similar procedure by dissolving 89 g of sucrose in 150 mL of DW at an ambient condition of 28.9 °C to obtain an osmotic concentration of 37 °Bx. The concentration was selected from previous investigation by Obajemihi and Asipa (2020) for pretreatment of tomato slices prior to drying.

The physicochemical properties of the PO solution were evaluated by

following the procedures of Obajemihi et al. (2023). An O_3 meter by Chuangyue Environmental Protection Technology Company (DOZ30, China) was used for the estimation of O_3 , while the hydrogen peroxide level was obtained using the H_2O_2 assay kit (Beyotime Biotechnology Company, China). The electrical conductivity (EC) was measured with an EC meter by Leici-Chuangyi Instruments and Meter Company (DDS-11A, China). A multi-parameter meter by Inesa Instrument Company (PHS-3C, China) was employed for measuring the oxidation-reduction potential (ORP) and pH.

2.3. Preparation and pretreatment of samples

Tomato fruits (millennium variety) that were fresh, uniformly sized and mature were acquired from a store in University Town, Guangzhou, China. Samples were cleaned, sorted and temporarily stored (4 °C) in a refrigerating unit produced in Hefei, China by Midea Refrigeration Company (Model no: BCD-525WKPZM (E)) before use. The slicing of fruits was done to form a spherical shape of 5 mm thickness by discarding the seeds to reduce enzymatic reactions when undergoing the drying process. The moisture of the samples was estimated by placing 5.0 g of the fruit slices in the oven fabricated in Shanghai, China by the Bluepard Instruments Co. Ltd. (Model no: DHG-9140A) and dehydrating at 105 °C for 1 day without stoppage (AOAC, 2000).

The pretreatment of samples was conducted in the DW, PO and OD disjointedly by immersing sliced samples (100 g) in the solutions (1:1.5 w/v) for 40 min at ambient condition (28.9 °C), and thereafter withdrawing and trickling for 10 min on wire nets, and finally excess water was mildly wiped with absorbent paper. The fruit samples in PO were designated as POS and further labelled depending on their treatment conditions as PO2V5S, PO2V7S, PO6V5S, PO6V7S, PO10V5S and PO10V7S, while those immersed in DW and osmotic solution were designated as DWS (control) and ODS, respectively.

2.4. Drying experiment

The drying procedure was conducted using an infrared-aided pulsed vacuum system designed for the research and fabricated in Suzhou, China by the Gaopeng Automation Equipment Co. Ltd. (Model no: GP1500-3) presented in Fig. 2. The device comprises three drying chambers provisioned with different radiators and wavelengths; the sample trays could be rotated at 360° at different speeds between 1 and 100 rpm. The power rating of each lamp was 0.3 kW, and the chambers were connected to a pulsed vacuum system with a pressure level (0–50 kPa) and 1450 rpm speed. The device was run empty on idle mode

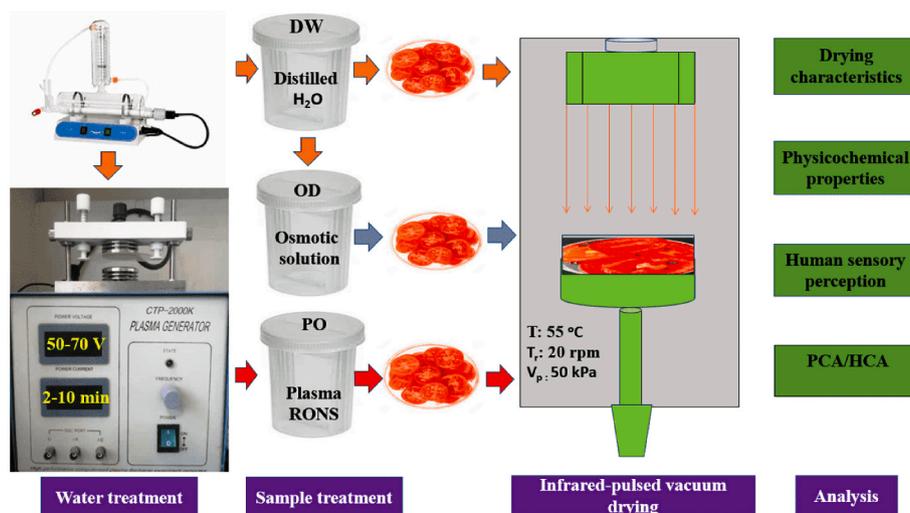


Fig. 1. The graphical illustration of the experimental arrangement.

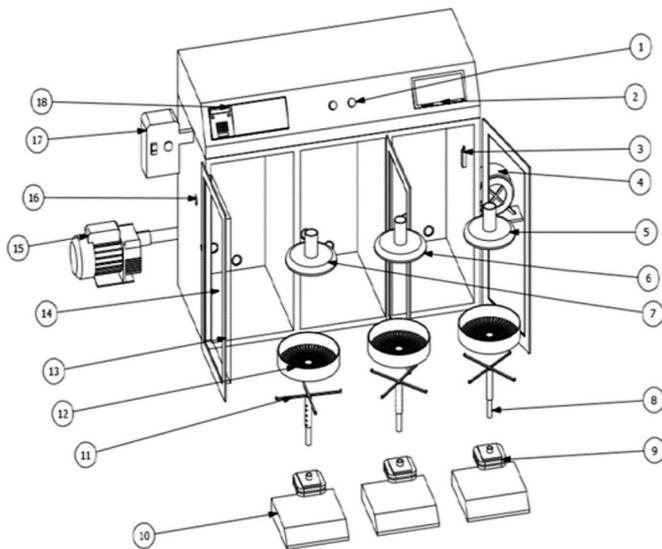


Fig. 2. The automatic infrared-assisted pulsed vacuum drying device. 1. Power display, 2. Data display, 3. Temperature and relative humidity sensors, 4. Fan, 5. NIR lamp, 6. MIR lamp, 7. FIR lamp, 8. Tray shaft, 9. Rotor, 10. Rotor platform, 11. Tray guard, 12. Sample plate, 13. Metal frame, 14. Glass door, 15. Pressure pump, 16. Humidity release orifice, 17. Electric control, 18. System control.

for about 10 min and allowed to attain the chosen functional temperature at 55 °C, subsequently, tomato samples (100.0 g) were placed on the tray and positioned in the drying system. The drying parameter of 55 °C was chosen based on the previous experiment by Obajemih et al. (2020). The drying commenced with a vacuum pressure (50 kPa) sustained for each 60 s and trailed by a stopping time of 15 s through the drying course. The steady drop in weight was continually monitored and logged at gaps with a digital scale produced in Germany by G&G GmbH (Model no: JJ1000) with a precision (± 0.01 g) and the drying process was put to an end as soon as the samples revealed no further loss in mass. Afterwards, the stabilisation of the dried samples was conducted at ambient conditions, samples were packed in polyethylene packages and stored in a desiccator prior to physicochemical examination in the laboratory.

2.5. Drying properties

Drying parameters such as the moisture ratio and diffusivity (D_{eff}) were utilized for determining the drying characteristics of sliced tomato fruits by the application of the subsequent equations (Loureiro et al., 2021):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

where MR , M_0 , M_t , and M_e represent the moisture ratio, initial MC (% db), MC (% db) at any given time t , and equilibrium MC (% db), respectively, as shown in Equation (1).

Fick's second law of diffusion was used in calculating D_{eff} by assuming that there was persistent moisture diffusivity and insignificant shrinkages according to Equation (2) (Obajemih et al., 2021; Khudya-kov et al., 2022):

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \quad (2)$$

where t is the drying time, n is the term number for the Fourier, D_{eff} (m^2/s) is the moisture diffusivity and L is a characteristic geometry parameter which was half of the thickness of the slices (m).

Eq. (2) was further simplified to a finite or limited diffusion equation for extended drying periods as revealed in Equation (3):

$$\ln(MR) = \frac{8}{\pi^2} \exp\left\{-\frac{\pi^2 D_{eff} t}{4L^2}\right\} \quad (3)$$

By plotting $\ln MR$ against t from Equation (3), produced a straight line with a slope, K and was applied for measuring the D_{eff} as presented in the following Equation (4):

$$K = \frac{\pi^2 D_{eff}}{4L^2} \quad (4)$$

2.6. Quality properties determination

2.6.1. Rehydration characteristics

The evaluation of the rehydration ratio (R_r) was carried out in compliance with Obajemih et al. (2023) with some slight modifications. 1 g of dried tomato fruit slices was dipped in 10 mL of DW for a duration of 0.5, 1, 2, 3 and 4 h at 30 °C, the slices were removed and trickled on wire nets for 60 s after rehydration, and used an absorbent paper to remove traces of water, and measured on an electronic balance. The procedure was continued by re-immersing the fruit slices into the rehydration water until no more alteration in mass, and R_r was expressed using the following Equation (6):

$$R_r = \frac{W_2}{W_1} \quad (6)$$

where W_1 and W_2 are the original weight and weight after rehydration of the samples, correspondingly.

2.6.2. Total soluble solids

The analysis of the total soluble solids was conducted by the dipping 1 g of dried tomato sample in 10 mL of distilled water for a duration of 30 min, and then homogenizing with a crushing mill produced in China by the Digital Ultra Turrax, IKA Co. Ltd. (Model no: T18), and rotated at 3500 rpm for 10 min with a centrifuge machine manufactured in China by Anhui Jiaven Equipment Co. Ltd. (Model no: JW-3024HR) to obtain the filtrate. The extract was released on an optical prism of the refractometer and readings were recorded, while for the fresh tomato fruit samples juice was extracted and dropped on the prism for readings.

2.6.3. Lycopene content

The lycopene content of the samples was analyzed following the procedures of Obajemih et al. (2023). In brief, 4 g of dried tomato sample was dipped in a volume of 8 mL of hexane (C_6H_{14}) for a period of 30 min, and spun for uniformity by a centrifuge produced in China by Anhui Jiaven Equipment Industry Co. Ltd. (Model no: JW-3024HR) at 3500 rpm for 10 min. Subsequently, the top layer was taken and absorbance was obtained at 503 nm wavelength with the aid of a UV-spectrophotometer manufactured in Japan by Shimadzu Co. Ltd. (Model no: UV-1800). The modified Beer-Lambert equation was applied for estimating the lycopene (mg/kg) as shown in Equation (7):

$$c = \frac{V}{W} \times \frac{A_{503}}{\epsilon \times l} \times M = \frac{V}{W} \times A_{503} \times 3.1215 \quad (7)$$

where c denotes lycopene value (mg/kg), V is hexane volume (mL), W is sample mass (g), A_{503} is absorbance at 503 nm wavelength, M denotes lycopene molecular weight (536.9 g/mol), path length (1 cm) is l , and ϵ is the coefficient of molar extinction of lycopene in C_6H_{14} (1.72×10^5 L/mol cm).

2.6.4. Vitamin C content

The evaluation of vitamin C was conducted in line with the technique of Obajemih et al. (2023) with minor amendments. Succinctly, 3 g of tomato fruit sample was dipped in 10 mL of 3% HPO_3 solution, and the

mixture was vortexed for 10 min to achieve homogeneity and centrifuged at 4 °C and 5000 rpm for another 10 min. Thereafter, the resulting extract was sifted by a filter paper with average speed (No.102) produced in Hangzhou, China by the Truecan Trading Co. Ltd. and 1 mL filtrate was added to 9 mL of 0.05 mM of $C_{12}H_7C_{12}NO_2$ solution, and absorbance was achieved at 515 nm wavelength from a UV-spectrophotometer and the vitamin C (mg/100 g) was measured from the standardisation curve of the L-ascorbic acid ($C_6H_8O_6$).

2.6.5. Total flavonoid and phenolic contents

The total flavonoid content (TFC) and total phenolic content (TPC) were analyzed according to Tabibian et al. (2020) with slight adjustments. For the TFC, 0.5 mL of sample extract was diluted with 2 mL of DW, and the mixture was reacted with 0.15 mL (5%, w/v) $NaNO_2$ solution for 6 min. Afterwards, 0.15 mL (10%, w/v) $AlCl_3$ solution and 2 mL (4%, w/v) NaOH solution were introduced and carefully shaken for homogeneity, and the resulting mixture was topped to rise to a 5 mL mark on the test tube using distilled water and left alone for 15 min. Later, the mixture absorbance was obtained from the UV-spectrophotometer at a wavelength of 510 nm, and TFC values (mg catechin equivalent/100 g) were calculated from the standard curve.

For the assessment of the TPC, a sample extract of 500 μ L was introduced to 2.5 mL of diluted Folin-Ciocalteu reagent in a ratio of 1:10 in a glass tube. The procedure was continued by the addition of 2 mL of 20% (w/v) Na_2CO_3 , followed by rotation for 10 min in a centrifuge, and reaction for 30 min at 28 °C ambient temperature. The optical density of the mixture was analyzed at 760 nm from a UV-spectrophotometer with a blank of 80% methanol. TPC value was measured in mg gallic acid acid equivalent/100 g and realised from the standard curve.

2.6.6. Texture analysis

The textural properties were evaluated by a texture analyzer manufactured in the UK by Stable Micro Systems Co. Ltd. (Model no: TA-XT PlusC). The textural parameters were analyzed at a prompting force of 0.05 N and 1 mm/s speed from a P/50 cylindrical probe and utilized two speeds of 2 and 5 mm/s for the pre-test and post-test from two sequential strain cycles of 50%. Accordingly, the data measured were interpreted by the force (N) - time (min) profile of Proprietary Exponent Connect Software (Version 7.0.6.0.) produced in the UK, and useful for deriving various TPA parameters (Esua et al., 2022a).

2.6.7. Colour determination

Various colour indices such as the lightness (L^*), redness (a^*) and yellowness (b^*) indices of the dried fruit samples were evaluated with a digital colorimeter produced in Osaka Japan by the Konica Minolta Incorporated (Model no: CR-400), built on the chromaticity coordinates of the 3D colour space of the CIE $L^* a^* b^*$ and the chroma (C), hue (H) and colour difference (ΔE) were calculated from the data obtained as presented in Equations (8)–(10):

$$H = \tan^{-1} \frac{b^*}{a^*} \quad (8)$$

$$C = \sqrt{a^{*2} + b^{*2}} \quad (9)$$

$$\Delta E = \sqrt{(L_o^* - L^*)^2 + (a_o^* - a^*)^2 + (b_o^* - b^*)^2} \quad (10)$$

where L_o^* = initial lightness samples in fresh state, a_o^* = original redness of fresh fruit samples, and b_o^* = original yellowness of samples in the fresh state.

2.6.8. Sensory evaluation

The sensory properties assessment was conducted by 20 semi-trained panelists who were postgraduate students of the laboratory in which this experiment was conducted. The dehydrated fruit slices were evaluated

for colour, flavour, appearance, texture and total product acceptability (OA) by employing the nine (9) point hedonic scale process rated between one (1) to nine (9), and one represents “dislike extremely” and nine represents “like extremely”.

2.6.9. Scanning electron microscopy

The microscopy evaluation of fruit slices with size (2 x 2 x 1.5 mm) fixed to the pedestal was done using the scanning electron microscopy (SEM) device produced in Germany by Zeiss Merlin Field Emission (Model no: EVO18). Prior to the evaluation, as a way of improving conductivity, the samples were plated with a layer of gold films, followed by micrographs capturing at different intensifications by applying appropriate distance, voltage and pressure of 11.20 mm, 5.0 kV and 100.0 kPa, correspondingly.

2.7. Statistical analysis

All data from the experiment were inputted on the Microsoft Excel spreadsheet in triplicates and were copied to the data interface of the Statistix analytical software (Version 9) made in the USA by the Analytical Software Company. The data were run for one-way analysis of variance and the least significant difference (LSD) test at $p \leq 0.05$ by the means post hoc. Thereafter, the outcomes were presented as mean \pm SD, and the data visualization aspect of this work was conducted by the application of OriginPro 2022 software produced in Northampton, USA by the Origin Lab Corporation.

3. Results and discussion

3.1. Physicochemical attributes of plasma and osmotic solution

The analysis of the optical emission spectra conducted by Pan et al. (2020) showed that the sufficient introduction of oxygen and nitrogen to treated liquid initiated the reactions that transformed into RONS at the gas-liquid boundary. The physicochemical properties of PO employed for the pretreatment of tomato fruit slices are presented in Fig. 3. For this research, distilled water was utilized at 25.80 °C and an initial pH of 5.48, and the temperature was substantially raised to 43 °C after treatment, then sucrose was added, and the pH recorded significant decreases to 3.37, 2.92, 2.96, 2.39, 2.32 and 1.98, for PO2V5, PO2V7, PO6V5, PO6V7, PO10V5 and PO10V7, respectively, while OD solution without cold plasma treatment indicated a pH of 4.90. The results revealed that CP treatment and OD have significant impacts on lowering the pH of liquids.

Moreover, as indicated in Fig. 3, an increase in the treatment duration and voltage for the PO solution led to higher ORP value which falls between 407 and 538 mV compared with DW (405 mV), also the EC values for the PO solutions ranged from 0.05 to 1.24 mS/cm and was significantly increased at higher treatment conditions when compared with distilled water (0.28 mS/cm). But OD solution showed a reduced value of 187 mV for ORP and 0.03 mS/cm for EC compared with distilled water. For H_2O_2 and O_3 , PO revealed increased concentrations between 0.48 and 1.99 μ M and 0.12–0.67 mg/L, respectively, in comparison with 0.00 μ M and 0.05 mg/L, achieved for distilled water. The increase in treatment duration and voltage revealed a rise in the production of reactive species in PO, due to increasing discharge of current, and was manifested in the enhancements of O_3 , ORP, EC and H_2O_2 generated.

The results affirmed the efficiency of the indirect application of the DBD cold plasma device for activating DW from the bombardment of the RONS. The interactions among reactive species such as the NO_3^- , NO_2^- , and H_2O_2 could be responsible for lowered pH (5.48–1.98) in treated solutions due to rapid acidification by the creation of acidic species such as the ionic ONOO⁻ and ONOOH which have powerful abilities for oxidation and hydroxylation processes (Esua et al., 2021b, Esua et al., 2022d). Previous studies have signified the influence of the differences in treatment duration and voltages on the rate of generation of reactive

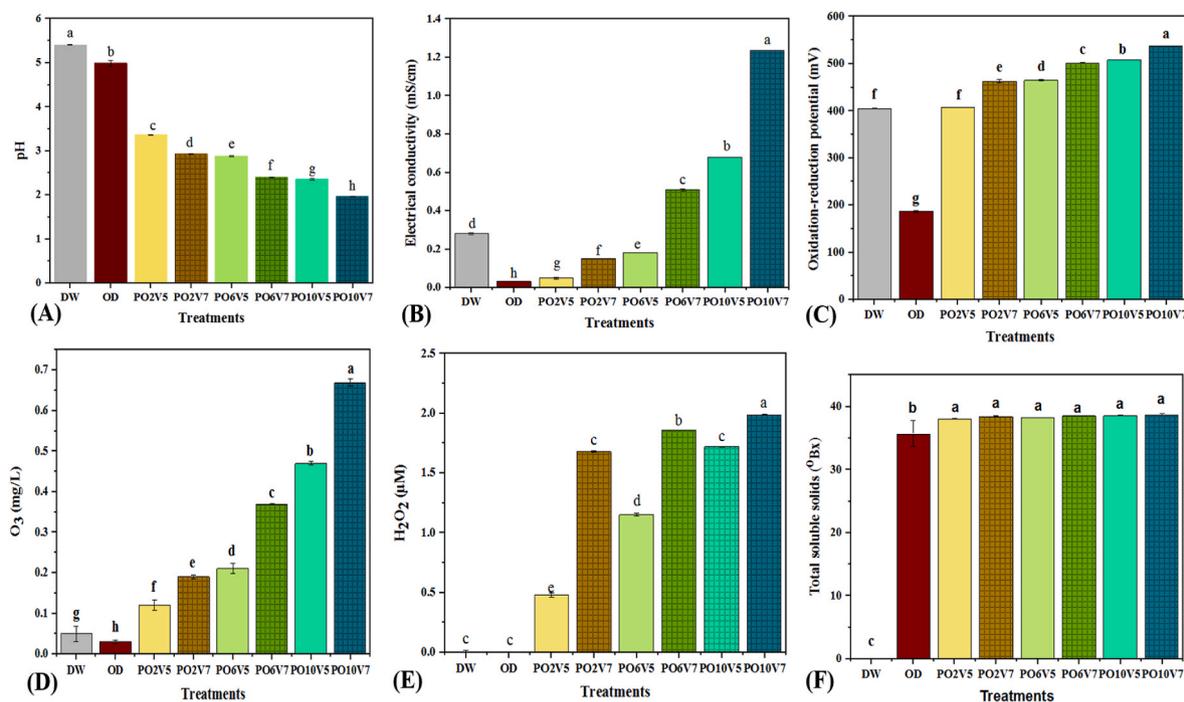


Fig. 3. Physical-chemical properties of the plasma osmotic and osmotic solution at different treatment conditions.

species in treated solutions (Esua et al., 2022b). The reactive interactions impact the type of electron activity and ions produced, and the concentration of the oxidation agents that could be short-term (O_2^- and OH^-) and continuing half-life species (H_2O_2 and O_3) which perform principal roles in the etching and modification of food structures (Zhang et al., 2022; Esua et al., 2022c; Ali et al., 2021b).

The action of PO on tomato slices could be attributed to loosening the rigid cell walls by the impingement of the reactive species (NO_3^- , NO_2^- , O_3 , OH^\bullet , H_2O_2) and osmotic stress capable of breaking the intracellular bonds, and manifested in the modification of food microstructures and

shrinkage effects. This process creates more pores and intracellular sites for higher moisture transfer from sample to the environment during drying.

3.2. Influences of PO pretreatment on dehydration properties during infrared-assisted pulsed vacuum drying

The influences of PO pretreatment on combined infrared and pulsed vacuum drying of tomato slices are revealed in Fig. 4A, and results proposed a typical drying curve of MR versus drying time revealing an

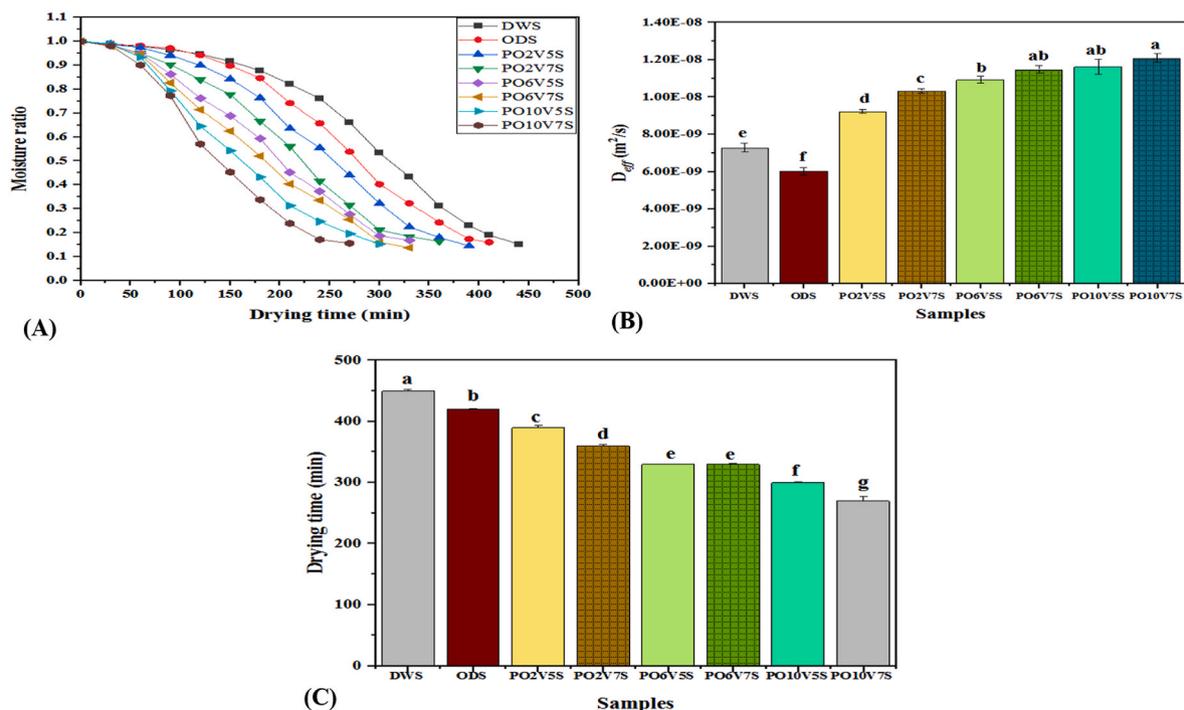


Fig. 4. IR-PVD behaviour of tomato slices: (A) moisture ratio, (B) D_{eff} , and (C) drying time, at different pretreatment conditions.

initial point of heating which the tomato fruit slices was adjusted by the removal of surface free moisture for the sample to undergo a falling rate period, the process was faster for the PO pretreated samples as compared with the control (DW) samples. The swift change noticed in the pretreated samples was evidenced by the action of PO on the tomato fruit slices. Similar to other processed biological products such as jujube, wolfberry and red dragon, the moisture ratio (MR) of all tomato slices gradually dropped with increasing drying time during the drying procedure until reaching the equilibrium moisture content (EMC) (Bao et al., 2022; Khudyakov et al., 2022). Additionally, the impacts of the variation in PO treatment conditions on the fruit slices were manifested by the increased loss of moisture for the POS with increasing treatment duration and voltages, when compared with lower loss of moisture for ODS and DWS. The duration for drying the samples was significantly different ($p \leq 0.05$), wherein PO10V7S exhibited the shortest time of 270 min compared with a prolonged 450 min for DWS (Fig. 4A and C). These observations could be correlated with an intensity in the production of RONS (e.g. O_3 , H_2O_2 and EC) in PO resulting from an increase in treatment duration and voltages, responsible for strong acidification of the liquid and increased infiltration of the reactive species into the surface of the tomato slices and lessening the rigidity of the cell walls and modification of the food structure for improved moisture transfer during drying (Bao et al., 2022; Obajemihi et al., 2024).

For the effective moisture diffusivity, tomato slices showed data between $6.01 \times 10^{-9} - 1.21 \times 10^{-8} \text{ m}^2/\text{s}$ (Fig. 4B), and functional within a range of $10^{-12} - 10^{-7} \text{ m}^2/\text{s}$ acceptable for biological materials (Loureiro et al., 2021). The results fell between $9.23 \times 10^{-9} - 1.21 \times 10^{-8} \text{ m}^2/\text{s}$ for POS and controlled by the treatment duration and voltage, whereas DWS and ODS demonstrated a reduction of 7.28×10^{-9} and $6.01 \times 10^{-9} \text{ m}^2/\text{s}$, respectively. The enhanced water conveyance from the tomato slices internal to the exterior for POS could be due to the severing of the Carbon-Hydrogen (C-H) and Carbon-Carbon (C-C) bonds in the pectin of the cell walls by the actions of the reactive species in PO, which increases with rising treatment duration and voltage and consequently modified the surface structures of the samples and increasing

the cell wall porosity (Bao et al., 2022). Similarly, studies have reported cleavage of the waxy cuticles of chili pepper and jujube by the action of RONS for speeding moisture flow during HAD (Zhang et al., 2019). Likewise, Loureiro et al. (2021) reported that varied frequencies during CP treatment of tucuma slices influenced D_{eff} during HAD, although the D_{eff} was heightened at lower frequencies due to an increased energy bombardment and voltage.

3.3. Influence of plasma and osmotic pretreatment on the microscopy image

The scanning electron micrographs of dehydrated fruit slices at different magnifications were presented in Fig. 5, and revealed the highest reduction of the inherent cellular composition of tomato fruit with minimal existence of tiny pores and fissures for DWS, thus, suggesting the damaging influence of heat on the food material during the simultaneous IR-PVD, whereas on the other hand, some levels of shrinkages were found on the ODS signifying the impact of osmotic stress on the samples, and for POS the impact of the reactive species on the tomato tissues resulted in huge disruption of the intrinsic cellular structures and showed improvements in the formation of microchannels and cracks responsible for effective moisture transportation from the internal to the surface layers. Moreover, the impacts of the treatment conditions showed higher disruptions of the surface structures for POS, with PO10V5S and PO10V7S presenting higher levels of disruption of the microcellular structures resulting from a rise in treatment duration and voltages, which were strongly responsible for increased RONS impingement activities on tomato slices. This process could increase the efficiency of the drying process and lower the degradation-rate-volatility of essential biomolecules as would be discussed in detail subsequently. From previous investigations, cold plasma pretreated mushroom, tomato, jujube, rosehip and golden berry slices prior to HAD have indicated an alteration of the surface structures due to the etching activities of RONS, resulting in higher formations of microchannels and increased drying characteristics and physicochemical qualities (Bao et al., 2022;

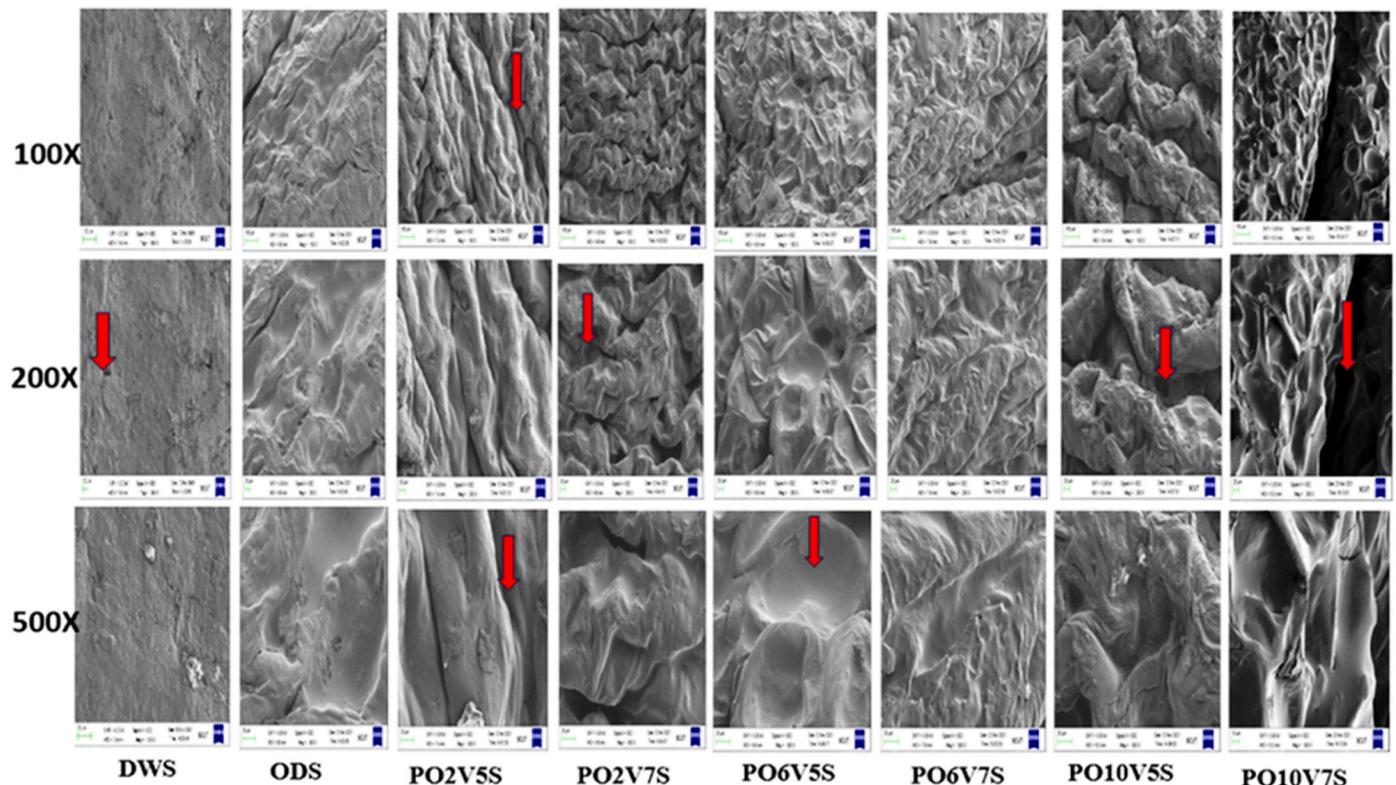


Fig. 5. Scanning electron microscope of IR-PVD tomato slices at different pretreatment settings.

Goztepe et al., 2022).

Overall, PO pretreatment resulted in the bombardment of the tomato slices with reactive species which impinges the fruit's surface and weakens the cell wall structures by diminishing the non-covalent bonds including van der Waals forces, hydrogen (H) and hydrophobic bonds existing among the cell walls, polymers such as pectin, cellulose and hemicelluloses, which minimize the strength of the cells turgor pressure, creates micro-perforations and shrinkages. Notably, increasing the treatment duration and voltages was found to result in higher production of RONS for achieving more efficient outcomes for mass flux.

3.4. Influence of plasma and osmotic pretreatment on the physical and chemical characteristics

3.4.1. Rehydration property

The R_r of pretreated IR-PVD tomato fruit slices were compared with the control at different holding times (30–240 min) as shown in Table 1, and results revealed that R_r increased with the rehydration holding period, and variation in R_r became negligible after reaching their peaks at 240 min and further attempts resulted in tissue disintegration into the surrounding water instead of water uptake. The rehydration peaks obtained for each sample were controlled depending on their pretreatment conditions and were significantly different ($p \leq 0.05$), PO2V5S, PO2V7S, PO6V5S, PO6V7S, PO10V5S and PO10V7S recorded R_r of 2.12–3.36, 2.37–2.96, 2.14–2.89, 2.30–3.20, 2.51–3.25, and 2.50–3.37, respectively, while, DWS and ODS showed 3.13–6.16 and 1.93–2.77, respectively. From the data, DWS demonstrated higher R_r compared with the POS and ODS, which might be elucidated by the concurrent counterflow of mass transport phenomenon causing disintegration of trapped solutes in POS and ODS into the water as the uptake of moisture progressed, resulting in a decrease in sample's weight following rehydration and lowering the R_r (Sahoo et al., 2015; Obajemihi et al., 2023). However, samples immersed in PO (POS) presented higher rehydration capacities at different holding times revealing the positive advantage of cold plasma pretreatment compared with ODS, and similar to the trend achieved for drying characteristics of samples. The lower R_r achieved for ODS might be linked to the gradual accretion of mechanical stress during a prolonged drying period and has yielded a weakening of the hydrophilic properties. The optimum rehydration value of 3.37 was achieved at 240 min for PO10V7S signifying the strong impact of treatment voltage and time during processing of the fruit slices.

The rehydration mechanism could be established by the action of RONS present in PO produced large openings and micro-channels for the speedy removal of moistures during dehydration, and was reversely replaced during rehydration and increasing the R_r . Loureiro et al. (2021) observed that cold plasma-induced micro-channels resulted in the improvement of moisture absorption by tucuma slices during rehydration. The microstructure of treated samples could explain most of its rehydration occurrences and suggest the potential for higher R_r with a rise in treatment voltages and time. Loureiro et al. (2021) observed increasing R_r for CP pretreated samples with decreasing frequency which was synonymous to higher voltage. Similarly, Ashtiani et al. (2023) and Obajemihi et al. (2023) reported higher R_r for mushroom and tomato slices pretreated with the combined CP and OD (PO) compared with the OD suggesting the improvement of the conventional OD of food products by the application of CP technology.

3.4.2. Total soluble solids

The TSS of the studied samples during IR-PVD are shown in Fig. 6A, and generally, the dried samples presented higher TSS contents resulting from their higher levels of dry matter compared with the fresh samples. Data revealed substantial increases in TSS which were 90.95% for ODS and ranging from 87.84 to 91.70% for POS in comparison with the fresh fruit slices. The rise in the TSS value due to dehydration may be associated with the change to reducing sugars from non-reducing carbohydrates during dehydration (Zzaman et al., 2021; Obajemihi et al., 2023).

ODS presented an increase in TSS (4.98%), and POS revealed a higher increase in TSS at some certain pretreatment conditions for PO2V5S (7.35%) and PO10V5S (14%) compared with DWS. The impacts of the treatment conditions revealed that increasing the treatment voltage from 50 to 70 V showed a negative effect on the TSS value and caused a significant decrease for PO6V7S (4.93 °Bx) compared with PO6V5S (6.37 °Bx). Generally, POS with treatment condition of 50V achieved higher TSS compared to DWS and ODS which signifies the capability of the combined PO for improving soluble solids retention in tomato slices during IR-PVD. However, few studies have reported reductions in the TSS contents for CP pretreated orange juice in comparison with the fresh (Xu et al., 2017), and Obajemihi et al. (2023) reported a reduction in TSS for hot-air dried tomato slices with plasma-treated water (PW) pretreatment. The pretreatment liquid type (PO) and CP operating conditions, coupled with the IR-PVD method might explain the increase in TSS retention of the current study.

3.4.3. Bioactive compounds

The influence of PO on the lycopene content of tomato samples during dehydration is shown in Fig. 6B, data suggested that the lycopene contents of dried tomato slices were higher (up to 96.66%) due to increased dry matter present in the finished samples compared with the fresh state. The lycopene values of the dried fruit slices ranged between 11.24 and 54.92 mg/100 g and exhibited higher values in comparison with 15.99 mg/100 g obtained for fresh slices. This corroborates the reports given by Goztepe et al. (2022) and da Costa et al. (2023) on increased lycopene contents of dried rosehips and tomato fruits. The POS at certain treatment conditions presented an enhancement in the lycopene values compared with DWS and ODS. Higher lycopene values of 46.62, 54.91 and 42.37 mg/100 g were obtained for PO2V5S, PO6V5S and PO6V7S, respectively compared with 28.88 and 23.30 mg/100 g attained for DWS and ODS, respectively. However, adverse impacts on the lycopene were noticed in some PO pretreated samples (PO2V7S, PO10V5S and PO10V7S) due to a higher treatment time (10 min) or voltage (70V). Therefore, appropriate CP conditioning of the PO would show a significant enhancement of lycopene retention during the dehydration of tomato slices.

Carotenoids are essential bioactive compounds found in fruits and vegetables with significant health effects for lowering risks of cardiovascular and cancer diseases. The increases in lycopene contents noticed for PO pretreated samples might be attributed to higher bioavailability of the lycopene compounds due to the breaking of the cellular boundaries by the infiltrating activities of the RONS and aiding the diffusion of extracting liquids for effective removal of the biochemicals (Obajemihi et al., 2023). On the other hand, the increased bombardment of the sample slices by the reactive species (NO, NO₂, ONOO⁻ and ONOOH⁻) during pretreatment could have led to rapid oxidation, nitrosation and nitration of the biomolecules noticed at increased treatment duration and voltage (Esua et al., 2020; Esua et al., 2021c; Dharini et al., 2023). Furthermore, the multi-dimensional processing conditions of tomato samples responsible for the larger formation of cavities from intense alterations in cellular structures at increased treatment duration and voltage, combined with the radiation intensity of the infrared emitter and vacuum enlargement of food products, might cause further lycopene loss during IR-PVD. Generally, the carotenoids are thermolabile biomolecules and could undergo isomerization chain reactions (cis and trans) when exposed to bright and hot sources, and despite limited investigation on the influence of CP processing settings on lycopene, CP treatments have shown significant enhancements in β-carotene contents for tucuma slices (Loureiro et al., 2021).

As represented in Fig. 6C, the vitamin C content for the IR-PVD tomato slices ranged from 4.48 to 33.93 mg/100 g in comparison to a measured value of 14.98 mg/100 g found for the fresh slices. POS revealed substantial vitamin C enhancements ranging from 83.70 to 86.78% retentions, whereas, ODS presented 81.80%, compared with DWS (4.48 mg/100 g). Data suggested that an increasing the CP

Table 1
Some physicochemical attributes of tomato slices.

Parameters	Fresh	DWS	ODS	PO2V5S	PO2V7S	PO6V5S	PO6V7S	PO10V5S	PO10V7S
Rehydration ratio									
30 min	–	3.13 ± 0.02 ^a	1.93 ± 0.05 ^f	2.12 ± 0.01 ^e	2.37 ± 0.02 ^{bc}	2.14 ± 0.04 ^{de}	2.30 ± 0.00 ^{cd}	2.51 ± 0.12 ^b	2.50 ± 0.16 ^b
60 min	–	4.04 ± 0.05 ^a	2.23 ± 0.01 ^d	2.23 ± 0.02 ^d	2.59 ± 0.08 ^e	2.62 ± 0.00 ^c	3.13 ± 0.12 ^b	2.69 ± 0.01 ^c	2.66 ± 0.16 ^e
120 min	–	5.10 ± 0.08 ^a	2.56 ± 0.03 ^e	3.10 ± 0.16 ^c	2.61 ± 0.01 ^{de}	2.70 ± 0.03 ^{de}	3.31 ± 0.02 ^b	2.77 ± 0.01 ^d	2.81 ± 0.08 ^d
180 min	–	5.90 ± 0.08 ^a	2.67 ± 0.01 ^e	3.15 ± 0.01 ^b	2.71 ± 0.16 ^{de}	2.71 ± 0.16 ^{de}	3.35 ± 0.08 ^b	2.88 ± 0.00 ^{cd}	2.94 ± 0.01 ^c
240 min	–	6.16 ± 0.06 ^a	2.77 ± 0.16 ^d	3.36 ± 0.08 ^c	2.96 ± 0.16 ^d	2.89 ± 0.16 ^d	3.37 ± 0.08 ^b	3.25 ± 0.08 ^c	3.20 ± 0.16 ^c
Colour properties									
L	37.99 ± 0.02 ^a	35.58 ± 1.47 ^a	31.17 ± 1.37 ^b	30.59 ± 3.99 ^b	37.33 ± 2.34 ^a	35.73 ± 2.05 ^a	37.60 ± 1.04 ^a	38.79 ± 2.62 ^a	29.66 ± 3.24 ^b
A	20.91 ± 0.06 ^d	26.25 ± 2.46 ^c	35.24 ± 0.63 ^{ab}	34.83 ± 2.19 ^{abc}	36.17 ± 0.79 ^a	35.58 ± 0.26 ^a	32.35 ± 2.79 ^b	35.67 ± 1.77 ^a	34.14 ± 1.77 ^{ab}
B	12.98 ± 0.06 ^c	30.24 ± 3.62 ^a	29.96 ± 0.25 ^b	30.07 ± 2.12 ^b	35.23 ± 1.02 ^a	33.77 ± 1.29 ^a	36.48 ± 1.40 ^a	34.74 ± 1.32 ^a	28.34 ± 1.74 ^b
Chroma	24.00 ± 0.27 ^d	40.00 ± 4.35 ^c	46.25 ± 0.65 ^{bc}	46.02 ± 2.91 ^{bc}	50.50 ± 1.06 ^a	49.06 ± 0.83 ^{ab}	48.77 ± 2.85 ^{ab}	49.80 ± 2.31 ^{ab}	44.37 ± 2.28 ^c
Hue	0.56 ± 0.24 ^e	0.85 ± 0.012 ^a	0.70 ± 0.004 ^d	0.71 ± 0.01 ^d	0.77 ± 0.01 ^c	0.75 ± 0.02 ^c	0.86 ± 0.02 ^b	0.77 ± 0.01 ^c	0.69 ± 0.02 ^d
ΔE	–	18.36 ± 4.89 ^c	23.54 ± 1.40 ^{bc}	23.81 ± 1.57 ^{bc}	27.08 ± 1.16 ^a	25.65 ± 0.50 ^{ab}	26.19 ± 1.75 ^{ab}	26.51 ± 2.93 ^{ab}	22.20 ± 1.49 ^c
V									
Visual									
Pictorial inspection									
									
Textural analysis									
Firmness (N)	4555.22 ± 41.81 ^a	1380.40 ± 42 ^b	2923.80 ± 40.50 ^b	775.52 ± 45.50 ^d	766.67 ± 33.14 ^d	309.07 ± 22.01 ^e	702.62 ± 22.03 ^{de}	1028.50 ± 73.00 ^{cd}	301.49 ± 13.00 ^e
Springiness	0.15 ± 0.06 ^b	0.08 ± 0.05 ^b	0.15 ± 0.01 ^{bc}	0.17 ± 0.02 ^a	0.18 ± 0.04 ^a	0.16 ± 0.01 ^b	0.16 ± 0.02 ^{ab}	0.15 ± 0.03 ^b	0.11 ± 0.03 ^d
Chewiness	56.58 ± 1.04 ^a	12.17 ± 0.80 ^{bc}	56.83 ± 6.20 ^b	23.75 ± 1.17 ^d	20.45 ± 0.60 ^d	7.22 ± 0.10 ^f	15.97 ± 0.43 ^e	51.09 ± 6.31 ^c	3.13 ± 0.02 ^g
Cohesiveness	0.08 ± 0.007 ^c	0.08 ± 0.004 ^e	0.14 ± 0.001 ^c	0.17 ± 0.007 ^a	0.16 ± 0.002 ^{ab}	0.15 ± 0.002 ^{bc}	0.14 ± 0.003 ^c	0.12 ± 0.006 ^d	0.09 ± 0.000 ^e
Gumminess	388.81 ± 4.71 ^a	109.52 ± 13.32 ^b	367.21 ± 6.51 ^b	135.29 ± 4.22 ^d	112.98 ± 1.86 ^{de}	45.09 ± 3.13 ^f	102.32 ± 8.51 ^e	339.90 ± 4.11 ^c	27.60 ± 2.07 ^f
Consumer preference									
Colour	–	3.91	7.50	8.17	7.75	7.83	7.50	8.17	7.83
Aroma	–	5.58	5.58	5.75	5.75	6.33	5.91	6.91	6.75
Texture	–	5.67	6.50	6.75	6.75	6.25	6.25	6.83	6.25
Appearance	–	3.66	7.33	7.75	7.67	7.41	7.50	7.91	7.50
Overall acceptance	–	4.33	6.33	6.83	7.16	7.00	7.08	7.58	6.75

Data denotes the mean ± SD error of triplicates. Values with different letters (a-g) in the row are significantly different ($p \leq 0.05$) according to Tukey's test. DWS: distilled water treated sample; ODS: samples dipped in osmotic solution; PO2V5S: samples dipped in PO with 2 min, 50 V treatment conditions; PO2V7S: samples dipped in PO with 2 min, 70 V treatment conditions; PO6V5S: samples dipped in PO with 6 min, 50 V treatment conditions; PO6V7S: samples dipped in PO with 6 min, 70 V treatment conditions; PO10V5S: samples dipped in PO with 10 min, 50 V treatment conditions; and PO10V7S: samples dipped in PO with 10 min, 70 V treatment conditions.

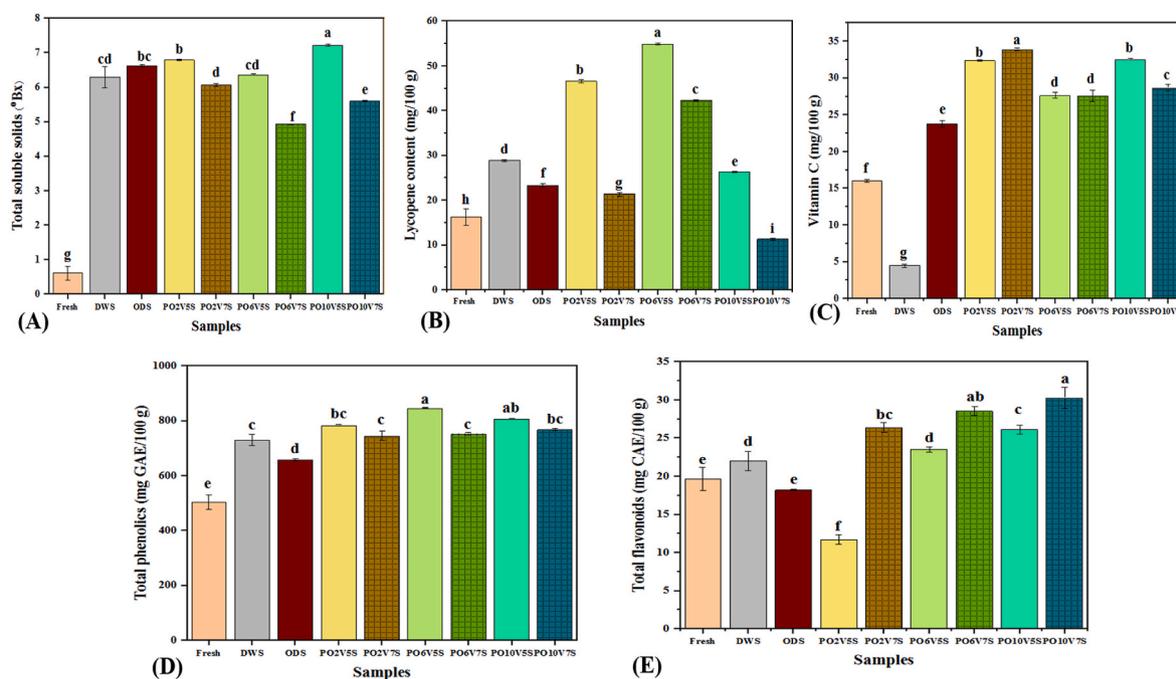


Fig. 6. Quality properties of IR-PVD tomato slices at different pretreatment settings, (A) total soluble solids, (B) lycopene, (C) vitamin C, (E) phenolics, and (F) flavonoids.

treatment duration and voltage indicated momentous alterations in the value of vitamin C retained which appears to slightly decrease at higher conditions and peaked at lower treatment time. The increase in the treatment voltage from 50 to 70 V during a 6-min treatment duration had no noticeable effect on vitamin C, but a reverse was observed for treatment times of 2 and 10 min, respectively. The highest retention of ascorbic acids for PO2V7S indicated the efficacies of handling at lower processing time coupled with a higher voltage during IR-PVD of tomato slices and might influence systems design for PO pretreatment and dehydration of tomato fruit slices for commercial applications in the future, particularly when achieving optimum level of vitamin C becomes essential.

From the results, PO pretreatment demonstrated the improved retention of vitamin C during IR-PVD, and the mechanism responsible for this phenomenon might be associated with activities of the reactive species percolating the food mass and modifying the surface structures by the breakage of pectin bonds in the cell walls for increased moisture transportation and accomplishment of drying within a shorter period thus diminishing the degradation effect of prolonged heating on biological compounds (Ashtiani et al., 2023; Obajemihi et al., 2023). Higher CP treatment voltage increased NO production known for boosting the performance of dehydroascorbate reductase and lowering the oxidation reaction of the vitamin C (Ali et al., 2021a; Zhang et al., 2022).

The TPC and TFC of tomato slices are presented in Fig. 6D and E, and data suggests improvements between 30.50 and 68.00% for dried samples with phenolics values ranging from 745.70 to 547.73 mg GAE/100 g in comparison with the fresh samples, whereas the flavonoids were 11.69–30.29 mg CAE/100 g and improved by 19.64–54.22% in comparison with the fresh samples. As revealed in Fig. 6D, POS presented an enrichment of up to 16.00% for TPC compared with DWS (730.55 mg GAE/100 g), and enhancements of 37.12% were achieved when compared with a DWS (22.09 mg GAE/100 g) for flavonoid content. Khudyakov et al. (2022) reported enhancements in phenolics and flavonoids during infrared drying of apple slices, an occurrence which was attributed to higher concentrations of biochemical constituents resulting from increased dry matter in dried slices compared with fresh slices. Also, the etching of food surfaces by the infrared energy and the

enlargement of surface area by the vacuum pressure could increase the pores and catabolizing the large molecules by altering the original phenolics structure, and transformation from undissolved to dissolved molecules increases phenolics extractability (Boateng and Yang, 2021). In a similar investigation fragmentation of covalent bonds by heating has been attributed to increasing the extractability of flavonoids during the dehydration of ginkgo seeds (Boateng and Yang, 2021).

The outcome of this study is in consonance with increased bioactive components (phenolics and flavonoids) resulting from CP pretreatments by direct and indirect exposures of jujube and *Centella asiatica* leaves prior to convective and combined oven and vacuum drying, respectively, and higher TFC retentions in CP pretreated tomato and apple slices preceding convective drying (Khudyakov et al., 2022; Bao et al., 2022; Tripathy and Srivastav, 2023). For the TPC, the impacts of higher treatment duration were more substantial for POS when held at 50V compared with 70V, as PO2V50S, PO6V50S and PO10V50S presented significant alterations in their phenolic contents of 784.65, 847.73, and 807.93 mg GAE/100 g, respectively, and in agreement with enhancements of up to 52% achieved by increased CP treatment time during convective dehydration of grape samples, which ascribed to the increased cavities resulted from the impingement of reactive species and responsible for lowering total drying time (Ashtiani et al., 2020).

Conversely, data for TFC indicated significant changes in treatment time and voltage, and showed an increment with increasing treatment conditions, as a result, samples immersed in PO with 70V performed efficiently in TFC retention compared with 50V, thus, an optimum TFC retention of 30.30 mg CAE/100 g was recorded for PO10V7S, and an increase of 37.66 and 66.48% was observed when compared with DWS and ODS, respectively. In agreement studies have shown the beneficial impacts of CP on retaining TFC during infrared drying of apple fruits, however, reductions in CP treatment time have indicated improvement in TFC for grape samples processed with hot-air drying (Khudyakov et al., 2022; Bao et al., 2022).

3.4.4. Sensory properties

The textural profile analysis (TPA) is a multi-parameter test and includes mechanical characteristics which were categorized into primary (e.g. hardness (firmness), cohesiveness, and springiness) and secondary

(e.g. chewiness and gumminess) properties (Petikirige et al., 2022). From the TPA data shown in Table 1, POS indicated significant decreases in firmness, gumminess and chewiness, and some improvements in springiness and cohesiveness, with figures between 301.49 and 775.52 N, 3.01–23.75 and 27.60–339.90, and 0.11–0.17 and 0.08–0.17, respectively, when compared with 4555 N, 56.58 and 388.81, and 0.15 and 0.08 for fresh samples, respectively. For the POS, hardness value was significantly lowered by up to 78.47% and 89.68% when compared with DWS (1380 N) and ODS (2923.8 N), respectively, while substantial increases in gumminess up to 67.63% were noticed for POS compared with DWS (109.52). For the POS, the increased gumminess, and relative values for the springiness, cohesiveness and chewiness of tomato slices noticed were in accordance with the findings of Obajemihi et al. (2023) during HAD of CP pretreated samples. However, the reduced hardness property of the dried samples obtained for POS contrasted with the earlier study on tomato slices and might be attributed to change in the drying methods as the impingements of ROS coupled with infrared radiation might have reduced the hardness property in the present study as compared to during HAD with casehardening effects on the fruit's surface, and also, Loureiro et al. (2021) despite CP pretreatment of tucuma slices still observed increased hardness during HAD. Moreover, the impacts of CP pretreatment conditions indicated increases in the hardness and springiness of tomato slices at a higher voltage (70V) particularly for those handled at lower treatment durations (2 and 6 min), while the cohesiveness property was lowered for increased treatment durations. Improvements in the textural profile of PO pretreated samples were attributed to structural modifications of food samples due to CP-induced microchannel creation and revealed the potential of CP technology as a viable pretreatment alternative for fruit and vegetables (Loureiro et al., 2021).

The colour is a key property for selecting food products by consumers who are conscious of quality and safety implications and indicated the degree of enzymatic browning in processed foods (Khudyakov et al., 2022), and presentation of data achieved from the colorimeter and visual analysis of processed tomato fruit slices are done in Table 1. The lightness (L^*), yellowness (b^*) and redness (a^*) indices for POS ranged from 29.80 to 38.80, 28.30–36.40, and 32.30–36.10 while values for the fresh and DWS were 38.50 and 36.70, 12.90 and 30.20, and 20.90 and 26.20, correspondingly. Additionally, For POS the chroma, hue, and ΔE ranged from 44.30 to 50.50, 0.69–0.86, and 22.20–27.08, compared with fresh slices and DWS values of 24.00 and 40.00, 0.56 and 0.85, and 0.00 and 18.30, respectively. The impact of the PO pretreatment revealed increases in the chroma, hue, and ΔE for POS to be up to 26.06% and 9.19%, 1.16% and 18.60%, and 42.64% and 9.86% in comparison with DWS and ODS, respectively. Also, the CP processing parameters revealed significant changes ($p \leq 0.05$) for hue, chroma and ΔE at different times and voltages as shown in Table 1, while the visual images indicated changes in the colour attributes and appearance with respect to treatments, and could be seen that PO pretreatment revealed improved brightness and redness attributes and appeared more similar to the fresh samples at the highest treatment condition for PO10V7S, compared with DWS and ODS.

Previous studies have revealed increased colour properties of dried fruit slices including apples, pineapple and tomatoes subjected to HAD, sequential infrared-freeze and convective drying, while, contradictory evidence was reported during tucuma and mango slices dehydration by hot-air (Antal and Kerekes, 2016; Zzaman et al., 2021; Loureiro et al., 2021; Obajemihi et al., 2020, 2023). Furthermore, the outcome of this study revealed the impact of PO pretreatment at different treatment times and voltages for the enhancement of sensory parameters of tomato fruit slices processed by simultaneous IR-PVD, however, reduced lightness of colour was reported for CP pretreatment of tucuma and saffron during HAD (Tabibian et al., 2020; Loureiro et al., 2021). The main cause of colour degradation in processed fruit and vegetables, especially by drying could be attributed to pigment obliteration due to the effects of heat and oxidation, shorter processing time for POS during combined

infrared and pulsed vacuum dehydration lessens the occurrence of enzymatic browning of the samples (Khudyakov et al., 2022).

The sensory properties of dried tomato fruit slices were analyzed based on the mean scores of the intensity as shown in Table 1, and data revealed that all verified sensory properties were substantially affected due to pretreatment in comparison with DWS. The panelist choice for colour, aroma, texture and appearance of POS falls between 7.50 and 8.17, 5.75–6.91, 6.25–6.83, and 7.41–7.58, in comparison with DWS figures of 3.90, 5.60, 5.70, and 3.70, respectively. The overall or general acceptability (OA) falls between 6.75 and 7.58 for POS compared with 4.33 and 6.33 for DWS and ODS, respectively. Principally, POS was chosen over DWS and ODS for colour, aroma, texture and appearance (aesthetic) for most stages of treatment duration and voltage, especially for higher conditions. For the OA, POS was favorite over DWS and ODS at all levels of treatment duration and voltage. Overall, the panelists choice for all tested properties of POS becomes higher with increasing treatment duration but presents minor irregularities, hence the higher the treatment duration, the more preferable the dried tomato fruit slices. Sensory properties are key features of food products influencing the purchasing intents, and evaluation of quality by humans. The outcomes revealed that PO pretreatment preceding IR-PVD affects the aroma, texture, colour and appearance of tomato fruit slices and agrees with the results from the colorimeter and texture meter analysis discussed earlier, and signified the potential of PO pretreatment for increasing the selection of processed fruits and vegetables for commercializing dried products.

3.5. Multivariate component analysis

The data from the present investigation was further analyzed using general factor or principal component (PC) and hierarchical clustering (HC) analyses for identifying, selecting and scrutinizing the relations among different treatments and tested quality parameters of tomato fruit slices as illustrated in Fig. 7. The biplot shown in Fig. 7A represents the plot diagram for locating the treatments, loading directions and evaluated parameters in a lone presentation, and exhibited the maximum level of similitudes among samples in the same section, and also differentiated quality attributes into groups matching samples. PC1 and PC2 provided an explanation for 38.12 and 20.62% variances, correspondingly, and as a sum justified 58.74% of the whole disparity. PO2V7S, PO6V5S and PO6V7S were positioned in the positive (+) axis of PC1 and negative (–) axis of PC2 and associated with chroma, lightness (L^*), yellowness (b^*), vitamin C, lycopene, colour change (ΔE) and OA, and PO2V5S and PO10V5S were situated in the (+) axes of PC1 and PC2 and matched with most TPA parameters (gumminess, chewiness, cohesiveness and springiness), redness (a^*) and TSS. PO10V7S and DWS indicated correlations with hue and TFC in the (–) axes of PC1 and PC2, while ODS correlated with hardness and rehydration in the (–) axis of PC1 and (+) axis of PC2. The chart revealed a clear segregation of DWS and ODS from the POS within the data sets and confirmed the effectiveness of the PO pretreatment on tomato slices during simultaneous IR-PVD.

Moreover, the HC dendrogram was engaged using the Euclidean distances and bands, with colour groups suggesting values of the conforming variables for additional scrutiny and insights (Fig. 7B). Eight distinct clusters were discovered and correspond with DWS, ODS, and the six POS, thus, suggesting separate distinctions in quality characteristics of tomato fruit slices subjected to diverse treatments. Tetrad (4) major clusters were found for quality indices, the first cluster comprising L^* , b^* , hue, TFC and rehydration, with DWS, PO10V5S and PO10V7S showing a higher level of significance. a^* , vitamin C, chroma, colour change (ΔE), OA, springiness and cohesiveness were situated in the second cluster with PO10V5S, PO6V5S, PO6V7S, PO2V5S and PO2V7S giving more significant values, while TPC, lycopene and TSS were located in the third group with PO10V5S and PO6V5S indicating increased significance levels. ODS and PO10V5S demonstrated

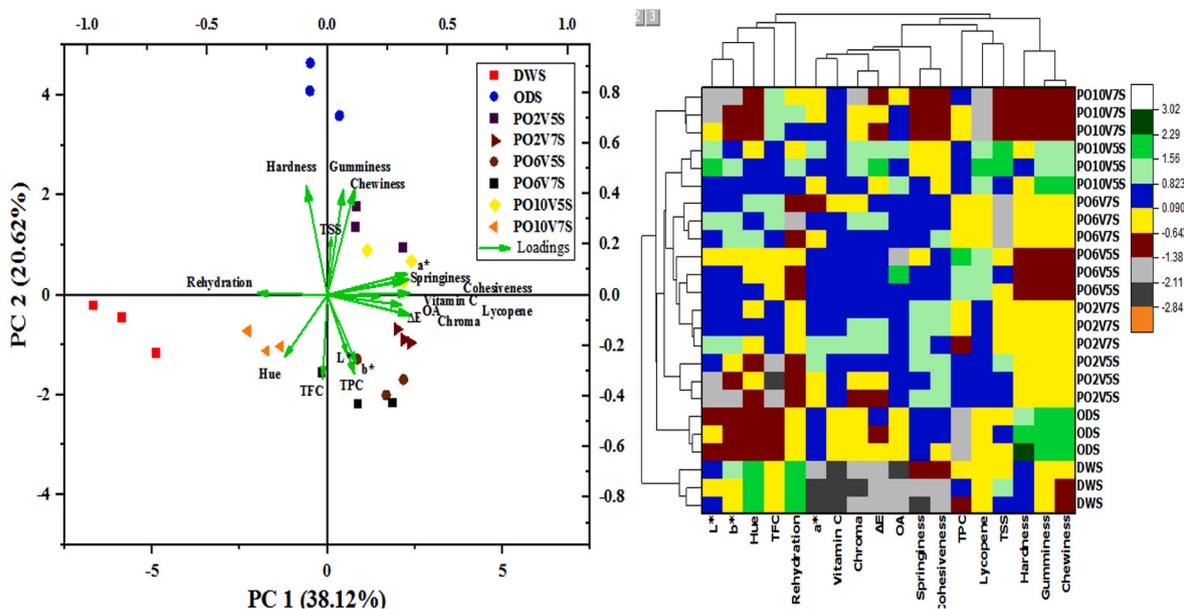


Fig. 7. Principal component and hierarchical cluster analysis of physicochemical properties of dried tomato slices, with different pretreatments (A) bi-plot, and (B) heatmap plot.

increased significance for hardness, gumminess and chewiness, located in the quarter (4th) cluster. In summary, the HC clusters for sample pretreatment conditions and tested quality indices showed some connections with the quadrants (squares) of the PC biplot and additionally confirmed the impacts of pretreatment conditions on the quality characteristics of tomato fruit slices during IR-PVD.

4. Conclusions and recommendations

The present investigation discovered that PO pretreatment of tomato fruit slices preceding IR-PVD led to the formation of cavities and microchannels, and increased the porosity in the microstructure with substantial cracks and shrinkages when compared with DW and OD pretreatments. The significant modifications of the microstructure were attributed to the activities of the reactive species which were heightened at higher treatment conditions and produced strong acidifications, etching and impingement capabilities, thus aiding efficient moisture removal, momentous lowering of the dehydration time and improvements in the retention of sensory attributes and bioactive compounds. Specifically, POS has shown up to 38.89 and 33.73% reductions in the drying process time, and substantial improvements in rehydration, TSS, bioactives, and sensory (colour and visual appearance) properties, but some decreases in texture (e.g. hardness) were noticed compared with the slower rate of moisture removal and degradation of essential nutritional and sensory components associated with DWS and ODS, respectively. The consumer's acceptance of the POS has been rated high and increased with treatment duration and voltage, and PO10V5S presented the highest degree of acceptability and became a popular choice. Overall, data suggested that PO pretreatment as a function of treatment duration and voltage could effectively control the drying properties and quality attributes of tomato fruit slices during IR-PVD, and becomes crucial for retaining optimum functional and sensory properties of dried fruit products for meeting consumers' nutritional and aesthetic needs. The outcomes of this study could be used for improving the conventional OD technique by combining with PW (PO) and bridging some knowledge gaps in the literature towards extending research in this direction for increasing drying efficacy and enrichment of the functional and nutritional characteristics of novel foods and supplied vital ideas for developing innovative eco-friendly pretreatment strategies for the food industry.

Furthermore, it is recommended that future research should be focused on optimization of various input parameters involved in the production of PO liquids for enhancing the quality attributes of fruits and vegetables whilst minimizing energy consumption and processing time, as this would provide optimal processing conditions for some specific agricultural products and lower cost. In addition, further research should be devoted to simulation and optimization of infrared-assisted drying conditions by the application of mechanistic models for understanding the underlining physicochemical transformations occurring in processed food materials during drying operations, as this would increase operational speed, reduce experimental trials, increase overall energy efficiency and product quality attributes.

CRediT authorship contribution statement

Obafemi Ibitayo Obajemihi: Conceptualization, Investigation, Formal analysis, Writing – original draft. **Jun-Hu Cheng:** Supervision, Funding acquisition, Resources. **Da-Wen Sun:** Writing – review & editing, Supervision, Resources, Funding acquisition.

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.

Data availability

No data was used for the research described in the article.

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