



Evaluation of Low-Pressure Cold Plasma Effect on Phytonutrients, Drying and Microstructural Characteristics, and Changes in Microbial Load of Fresh and Hot-Air-Dried 'Heidi' Mango

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Abstract

Alternative pre-treatment strategies before drying offer the prospect to minimize drying time, replacing the use of chemicals, and preserving quality of dried fresh products. This study explored the application of low-pressure atmospheric cold plasma (CP) for 5- and 10 min (CP5 and CP10) as pre-treatments prior to processing and hot air drying (60 °C) of 'Heidi' mango, while non-treated samples served as control. Changes in tissue microstructure and physicochemical properties, bioactive compounds, and microbial load were evaluated, and seven thin layer drying models were applied. Scanned electron microscope images showed that CP pre-treatments altered the tissue microstructure of dried mango slices compared to control. 'Heidi' mango slices with the initial moisture content of $80 \pm 0.2\%$ on a wet basis was reduced by 81% and 76% in dried CP5 and CP10 samples, respectively. Drying time was reduced by 20% for CP pre-treated samples in comparison to control samples, and the drying behavior of 'Heidi' mango slices was best described by the Logarithmic model (R^2 , 0.9999 and $RMSE$, 0.0122). Colour attributes were best retained by sodium metabisulphite (SMB) pre-treated samples, followed by CP5 pre-treated, which performed better than CP10 and control ($p \leq 0.05$). Highest total flavanols (15.0 ± 0.4 mg CE 100 g^{-1}) and higher total phenolics (1528.2 ± 23.6 mg GA 100 g^{-1}) were found in CP5 pre-treated samples compared to the control ($p \leq 0.05$). Lowest antioxidant activities were found in CP10 pre-treated samples compared to the control ($p \leq 0.05$). CP-pretreatment and drying resulted in ≥ 2 Log reduction in microbial load on mango slices. These results demonstrate to the role players in mango value addition chain, the potential of low-pressure CP pretreatment in enhancing/maintaining the bioactive compounds, reducing drying time and microbial load.

Keywords *Mangifera indica* L. · Scanning electron microscopy · Antioxidant capacity · Total phenolics · Aerobic mesophilic bacteria

Introduction

The second largest tropical fruit cultivated globally is mango (*Mangifera indica* L.). It is one of the most important fruits consumed worldwide (Chatha et al., 2020). The fruit contains β -carotene, antioxidants, polyphenols, various flavor compounds, dietary fiber, micronutrients, and minerals (Fam et al., 2020). Global mangoes, mangosteens, and guavas production is projected to eclipse over 84 million tons by 2032, increasing annually at the rate of about 3.3% over the next decade (OECD-FAO, 2023). The global mango market share for fresh mango is estimated to be worth close to US\$ 1.8 billion by the year 2029 (Puspitasari et al., 2021). However, fresh mangoes are highly perishable, and characterized with a short-term storability under ambient conditions due to their high moisture, sensitivity

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to physiological disorders, and ethylene production. This could result in natural ripening and senescence processes (Fatima et al., 2023; Thakur & Mangaraj, 2021), which could lead to serve financial and postharvest losses. Thus, drying as an agro-processing technique, offers the prospect of reducing the moisture content in fresh produce to a threshold that could be effective in preventing the development of microorganisms and extending the storage life (Ashtiani et al., 2023; Roberts & Bastarrachea, 2023). Drying helps to reduce the total shipping weights and storage cost of fresh fruit, thereby minimizing packaging requirements, storage space, and transportation (Bao et al., 2021).

Dried mango is uniquely positioned as a commodity with the potential to reduce malnutrition in the developing and developed countries. Dried mango is a rich source of vitamin A, essential micro/macronutrients, polyphenols (quercetin and carotenoids), which are efficient antioxidants, and anti-inflammatory compounds, enhancing the immune system, and reducing blood sugar levels (Singh et al., 2022). Also, the value addition process makes dried mango a potential for income-generation. Currently the leading exporters of dried mangoes to the European market are Burkina Faso, South Africa, and Ghana (CBI, 2023). In 2021, it was estimated that the European market imported dried mangoes within the range of 6000–7000 tons, and this is projected to have a stable 5–6% annual volume increase (CBI, 2023). There is a growing market for dried mangoes, due to the increase in population, increasing demand for healthier snacks alternatives, and consumer preference for new products rich in exotic flavors and naturally preserved (Mujuka et al., 2021). Therefore, it is important to optimize pre-treatment methods, improve the drying technique and study the drying kinetics for all mango varieties.

Convective hot air (oven) drying without pre-treatment of the fruit is a time-consuming process, and extensively long drying duration could result in the thermal degradation of nutrient and physical properties with cost implication on energy consumption (Ashtiani et al., 2023; Yanclo et al., 2022). The use of pre-treatments prior to drying fresh produce has been shown to reduce the detrimental effects of the drying process such as nutrient degradation, enzymatic activity and, maintaining overall quality of the dried products (Pandiselvam et al., 2022). However, extensive literature on the use of chemicals and physical has been shown to have minimal impact on reducing the drying time of food product (Bao et al., 2021), and it could also degrade essential nutrients and bioactive compounds (Pandiselvam et al., 2023a, b). Hence, it is crucial to investigate other pre-treatment steps that can improve drying rate, preserve quality attributes, and reduce the dependence on sulphur-based pre-treatment solutions prior to drying.

Cold plasma (CP) consists of ionized gases, including differently charged (positive or negative) or neutral electrons,

ions, reactive species, and free radicals. The ionized process gas dissociates due to increase in the frequency of gas collisions, and the increase in kinetic energy of the electrons leading to the formation of active plasma products such as electrons, ions, radical species, elemental gas, and nanoparticles (Farooq et al., 2023; Pathare et al., 2023). Cold plasma is a non-thermal food processing technology that could be applied as a hurdle technique (Paixão et al., 2019; Chen et al., 2020; Rashvand et al., 2023). Recent studies for various fruits have demonstrated the prospects of using CP as pretreatment prior to drying to maintain desired quality traits and enhance drying properties (Ashtiani et al., 2023). Ashtiani et al. (2023) demonstrated that the drying rate of mushroom was improved when pre-treated for 30, 50, 70, and 90 s with dielectric barrier discharge (DBD) plasma operated at 29 kV and 6 kHz. Similarly, Li et al. (2023) showed that pre-treatment with CP improved the effective diffusion rate and drying rate, enhanced the permeability of cell membrane, and modified pectin composition in the cell wall of vacuum freeze-dried haskap berries. Ashtiani et al. (2020) demonstrated that the use of CP improved the drying characteristics, total phenolics (3.1–30.5%), vitamin C (17.9–168.7%), and antioxidant properties (7.3–62.3%) of grapes fruit dried at 60 °C. Ashtiani et al. (2023) reported that CP pre-treatment prior to osmotic dehydration reduced the drying time for mushrooms and energy consumption by about 37%. It could be established that CP pre-treatment possesses the potential to influence drying processes, reduce the drying time considerably and use less energy to maintain quality of dried fruit compared to non-treated control samples.

Mango fruit surface is loaded with a broad range of microorganisms, which could be retained on the downstream product (Machado-Moreira et al., 2019). Taïbi et al. (2022) reported that a total of 304 fungal and 562 bacterial genera were detected on the surface of cv. Cogshall mango fruit; however, it was indicated that drying reduced the richness of microbial diversity and limited the growth of cultivable microbes during storage. After drying the members of the *Saccharomyces* genera became the most dominant fungal taxa, while *Enterococcus* and *Ralstonia* were the most prevalent bacterial genera (Taïbi et al., 2022). In a study conducted by Wu et al. (2022) DBD plasma treatments for 9 min were found to be effective against the pathogenic fungi *Colletotrichum asianum*, the causative agent of anthracnose, one of the most consequential pre- and post-harvest diseases of mango. The application of CP technology for decontamination of *Escherichia coli* in food was recently published by Niveditha et al. (2021).

Comprehensive reviews on the influences of CP treatments on the physical, biochemical, functional, bioactive, textural, and sensory properties of food and on food processing (Farooq et al., 2023; Sruthi et al., 2022). Highlighted the potential of cold plasma as an emerging non-conventional

food processing technique. However, there is no report in literature on the effects of low-pressure atmospheric cold plasma as a pretreatment alternative to sodium metabisulphite (SMB) before hot-air drying (60 °C) of fresh-cut mango slices and the impact on essential bioactive compounds and microbial load. Thus, the set objectives for this study were to (i) apply mathematical models describing the drying properties of the dried slices of mango, (ii) investigate the impact of low-pressure cold plasma on changes in the mango tissue slices using scanning electron microscopy (SEM), and (iii) evaluate the combined impact of CP treatment and drying on the physical, biochemical, and phytonutrients attributes of dried slices of ‘Heidi’ mango.

Materials and Methods

Plant Materials

Fresh mango fruits (*Mangifera indica* L. cv. Heidi) were harvested at maturity stage 4 (with pulp coloration at $\approx 85\%$; titratable acidity (TA), $0.08 \pm 0.003\%$ citric acid; total soluble solids (TSS), 14.6 ± 0.18 °Brix; and pH, 3.4 ± 0.26 ($n = 10$)) from the Tamarak Mango Estate situated adjacent to the Clanwilliam Dam at the foot of the Cederberg mountains ($-32^{\circ}24'85.03''S$, $18^{\circ}94'07.71''E$), Western Cape, South Africa. Bulk mango harvest was transported to the Agro-Processing Pilot Plant, ARC Infruitec-Nietvoorbij, Stellenbosch, South Africa. Mango fruits were sorted and only those without blemishes were used. All fruit samples were rinsed with clean tap water and allowed to air-dry for 3 h. Thereafter, the bulk was grouped into three treatment batches.

Pre-treatments, Minimal Processing, and Hot Air-Drying

A low-pressure atmospheric cold plasma (ACP) unit (Diener, Zepto Model 2, Germany) was used in this study to treat whole fresh ‘Heidi’ mango fruit prior to minimal processing and drying. The selection of a low-pressure ACP unit for this study was due to the following benefits; (a) its capacity to generate homogenous reactive species and particles, (b) the discharged reactive species and active particles have even coverage over a large surface area, and (c) most importantly the applied low-pressure (vacuum system) ensures that the reaction of the process gas and discharged active particles are maintained at the ambient temperature.

In contrast, the atmospheric plasma jet unit; (a) does not generate homogeneous and cannot cover a large surface like a whole mango fruit evenly, (b) under atmospheric pressure and depending on the treatment duration as well as the distance from source the plasma jets or flames discharged could

increase the surface temperature of sensitive fresh produce, and (c) for food processing applications, the atmospheric plasma jet is not sustainable due to the high cost of carrier/process gas required (Harikrishna et al., 2023; Pathare et al., 2023; Yudhistira et al., 2023).

The low-pressure ACP unit was equipped with a vacuum chamber made of borosilicate glass (ϕ 105 mm, and 200 mm long). Fresh mango samples were placed inside the vacuum chamber and the experiments were carried out at 90 kV and the pressure was 1.4 mbar for 5 and 10 min. Immediately after low-pressure ACP treatments, no change was observed in the fruit surface or core temperature using thermosensor (TFX410 Ebro, Xylem Analytics, Germany). The second batch of fruit samples were sliced and immersed for 2 min in 1% sodium metabisulphite solution (standard industry practice). The third group remained untreated whole fruit samples, minimally processed and dried (control).

Mango fruits were peeled and sliced using sharp stainless-steel knife and the thickness of each slice was approximately 8 mm. Mango slices prepared from the pre-treated and control fruit were uniformly single layer spread on the stainless-steel tray with grid and dried using a tunnel dehydrator (designed in-house). The capacity of the dryer is 50 kg, and ≈ 1 kg of mango slices was kept in the chamber for each treatment. Drying was conducted at 60 °C air temperature (standard industry practice condition) with the air-flow rate and relative humidity (RH) maintained at 49.50 Hz and 35%, respectively. The dryer was set idle for 2 h before placing the samples inside, to ensure that the desired temperature was stable. The drying experiments were conducted from a moisture content of $80.0 \pm 0.2\%$ to $10.2 \pm 1.8\%$ on a wet basis (Supplementary (Fig. S1)).

Drying Kinetics

Sliced mango samples were monitored on an hourly basis until the final weight remained constant after repeated measurement using a Precision Top-loader weighing balance with ± 0.01 g accuracy (Labotec, Cape Town, South Africa). For each batch sample, drying was replicated six times ($n = 6$) and mean value calculated thereafter. Moisture content can be calculated using equation (Eq. (1)):

$$\text{Moisture content (Mc)} = \frac{M(t) - M_s}{M(t)} \quad (1)$$

In this equation, $M(t)$ is the mass of wet mango slice at initial instant t , M_s the mass of mango slice after drying. The final MC of mango slices was maintained at below 13 (w.b.).

To describe the change in the ratio of moisture in each sample, Eq. (2) was applied:

$$\text{Moisture Ratio (MR)} = \frac{M_t - M_e}{M_i - M_e} \quad (2)$$

where, M_t represents Mc measured given time t (dry basis d.b⁻¹), M_e describes Mc equilibrium, and M_i stands for the samples' original Mc (dry basis). To apply Eq. (2), an assumption was made that $M_e = 0$.

Based on empirical data obtained for moisture loss, drying rate (DR) was estimated by applying Eq. (3):

$$\text{Drying rate} = \frac{M_i - M_t}{t_2 - t_1} \quad (3)$$

DR which is the moisture loss per unit time, M_i expresses initial Mc (g water gdb⁻¹), and M_t describes Mc at a specific time (g water gdb⁻¹). Empirical data were fitted using the thin-layer drying models summarized in Table 1. In this study, drying was achieved by circulating hot air through a mass of mango slices, and the air moves imparting the heat to the samples, it absorbs the humidity of the outmost layer. Hence, the moisture in the outer layers of the slices evaporates much faster and more easily than that of the internal layer. Thin-layer models are widely used to describe the convection drying kinetics of biological materials such as fruits and vegetables, seeds, and grains (Bryś et al., 2021). Parameter constants were determined by non-linear regression analysis for each model type. Considering the correlation coefficient (R^2 , i.e., highest) and the root mean square error ($RMSE$, i.e., lowest) values the best performing model that describes the characteristics of drying the samples was selected. The R^2 and $RMSE$ are described in Eqs. (4) and (5), respectively:

$$R^2 = \frac{\sum_{i=1}^N (MR_i - MR_{prd,i}) \cdot \sum_{i=1}^N (MR_i - MR_{emp,i})}{\sqrt{[\sum_{i=1}^N (MR_i - MR_{prd,i})^2] \cdot [\sum_{i=1}^N (MR_i - MR_{emp,i})^2]}} \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{prd,i} - MR_{emp,i})^2} \quad (5)$$

$MR_{emp,i}$ represents empirically determined MR , $MR_{prd,i}$ represents the i th predicted MR value, N represents the

number of observations, and z , the number of drying constants (Yancló et al., 2023).

Microstructural Changes

The microstructural changes of mango slices treated with low-pressure CP and control were examined using the approach described by Bao et al. (2021). ZEISS Gemini scanning electron microscope (SEM) 300 (Carl Zeiss Microscopy GmbH, Oberkochen, Germany), was used for this imaging. Fresh and dried mango slices from pre-treated and control were allowed to set overnight at 4 °C. Fruit tissues were soaked for 15 min in 2.5% glutaraldehyde containing 0.1 M phosphate buffer with pH of 7, to preserve the morphology. After fixation, samples were gradually dehydrated at a regular interval of 15 min using a graded series of ethanol (from 30 to 100%). The dehydrated tissues were dried further using 100% hexamethyldisilazane for 15 min (this step was repeated twice). Finally, the dried tissues were fixed on glass slides with double-sided carbon tape and coated with ≈10 nm thick, thin layer of gold, using Gold Sputter Coater EM ACE200 (Promolab (Pty.) Ltd., Johannesburg, South Africa). The coated samples were labelled with reference codes to avoid prejudices during imaging. All samples were imaged with SEM and viewed at a magnification ranging from ≈5X to ≈600X using a voltage of 3 kV, 100 IProbe.

Physical and Biochemical Attributes

Biochemical Attributes

Baseline measurement of pH, total soluble solids (TSS), and titratable acidity (TA) for fresh 'Heidi' mango fruit were taken using mango juice, before minimally processing for pre-treatment, and drying as described by Nsumpi et al. (2020). After the drying experiment, the dried mango slices were cooled, packed in glass containers (hermetically sealed), and stored in a dark cupboard for 48 h. Thereafter, using a 300 W, 2-speed with pulse blender (Model RSH – 080475, China) dried samples were crushed into powder.

Table 1 Thin-layer moisture ratio equations applied during the drying of 'Heidi' mangoes

| Models | Formula | Number | References |
|---------------------|--|--------|----------------------------------|
| Henderson and Pabis | $MR = a \exp(-kt)$ | (7) | Abbaspour-Gilandeh et al. (2020) |
| Midilli Kucuk | $MR = a \exp(-kt^n) + bt$ | (8) | Yancló et al. (2023) |
| Verma et al. | $MR = a \exp(-kt) + (1 - a) \exp(-gt)$ | (9) | Yancló et al. (2023) |
| Weibull | $MR = \exp(-(\frac{t}{a})^n)$ | (10) | Ashtiani et al. (2018) |
| Logarithmic | $MR = a \exp(-kt) + c$ | (11) | Manikantan et al. (2022) |
| Wang and Singh | $MR = 1 + at + bt^2$ | (12) | Manikantan et al. (2022) |
| Aghbashlo et al. | $MR = \exp(-\frac{k_1 t}{1+k_2 t})$ | (13) | Yancló et al. (2023) |

MR is the moisture ratio, k , k_1 , k_2 , a , b , c , n , and g are model drying constants, t is the drying time

To measure the TSS, TA and pH, ground samples (6 g) for each treatment were added to distilled water (60 mL) and mixed thoroughly until completely dissolved. The pH was determined using a Model 00924 basic 20 + pH meter (Crison Instruments, SA, Barcelona, Spain). Digital handheld refractometer (Atago N1, Tokyo, Japan) was used to measure TSS of the mixture and reported in °Brix. Furthermore, using a CRISON automated titrator (Crison Instruments, SA, Barcelona, Spain), the mixture TA was determined by titrating against NaOH (0.33 N) reaching the endpoint of pH 8.2. Results were communicated as percentage (%) citric acid (CA).

Colour Parameters

The colour measurements of 6 mango slices were taken on opposite sides prior to drying (baseline, fresh-cuts) and after drying, using a calibrated Minolta Chroma Meter CR-400 (Minolta Corp., Osaka, Japan). Results were recorded according to the colour space CIELAB colour coordinates with L^* describing the lightness (black to white), a^* as the redness (green to red), and b^* as the yellowness (blue to yellow) (Ashtiani et al., 2018). Chroma (C^*) which is expressed as colour intensity, hue angle (h°) that determines the position of the vector, and the total colour difference were calculated using Eqs. (6), (7) and (8):

$$C^* = (a^{*2} + b^{*2})^{1/2} \quad (6)$$

$$h^\circ = \arctan(b^*/a^*) \quad (7)$$

$$TCD(\Delta E) = \sqrt{(L_i^* - L^*)^2 + (a_i^* - a^*)^2 + (b_i^* - b^*)^2} \quad (8)$$

where, TCD (ΔE) implies total colour difference, L_i^* , a_i^* and b_i^* represent measured original values of the fresh cut mango fruit, while L^* , a^* and b^* represent the values of mango slices after drying.

Determination of Bioactive Compounds

Mango Juice Extract Preparation

Dried mango powder (10 mg) was added to distilled water (DW, 2000 μ L) and mixed thoroughly. The mixture was vortexed for about 30 s to homogenize and was further centrifuged at $2951 \times g$ for 5 min (Hermle Z206A, Wehingen, Germany). After centrifuging, the buoyant suspension obtained was used to quantify phenolics, flavonoids and antioxidant capacity.

Phenolic Content

To quantify the phenolic content in mango extracts the Folin-Ciocalteu's (FoC) approach was used (Phan et al., 2018). The mango extract (200 μ L) was mixed with DW (1800 μ L), and of this new mixture, 50 μ L was pipetted into a clear plate well from each sample. Approximately, 0.5 mL FoC mixture was added to each well, thereafter the mixture was slightly shaken for 15 s to ensure homogenous mix. Subsequently, 7.5% Na_2CO_3 (1 mL) and DW (1 mL) was added. The plate wells were placed in a dark room at 20 °C for 2 h before the absorbance reading at 750 nm with a microplate spectrophotometer (Fluostar Omega, BMG Labtech, Offenburg, Germany). Furthermore, TPC was extrapolated using concentrations varying from 180 to 220 of gallic acid standard curve (Equation: $0.0093X + 0.0529$; $R^2 = 0.9995$). Values were reported as mg gallic acid equivalents (GAE) L^{-1} of juice.

Flavonol and Flavanol Content

Based on the methodology described by Nyamende et al. (2022), total flavonol content (TFC) was quantified. Mango supernatant (5 mL) was homogenized for 30 s using the overhead stirrer (E-OHS20-D, Eins-Sci, United Scientific, South Africa) and was extracted by placing it on the tube rotator for 15 min. Thereafter, samples were centrifuged at $2951 \times g$ for 3 min and the supernatant transferred to a 15 mL screw cap tube and was protected from light. Quercetin was used for the standard and 12.5 μ L of sample was placed in a clear well plate. A volume of 12.5 μ L 0.1% Hydrochloric acid (HCl) was pipetted into each well then 2% HCl (225 μ L) was added. After incubating the mixture for 30 min, readings were taken. Total flavonol was extrapolated using concentrations varying from 27 to 33 mg L^{-1} (Equation: $0.0024X + 0.0089$; $R^2 = 0.9933$) and the values reported in mg quercetin equivalent (QE) g^{-1} .

A modified method described by Nyamende et al. (2022) was used to quantify the flavanol content (TFAC). The supernatant obtained prior was sonicated, then centrifuged for 5 min at 2951 g. Afterwards, supernatant was extracted and 25 μ L added to 1 mL of p-DMACA (0.1% in 1 M HCl in MeOH) to initiate the reaction for 10 min. Thereafter, absorbance readings were taken at 640 nm and compared to a known blank. Calibration curve with catechin used as the standard. Total flavanol was reported using concentrations varying from 5.94 to 4.86 mg L^{-1} (Equation: $0.0372X + 0.0036$; $R^2 = 0.9996$). Values obtained were reported as mg catechin equivalents (CE) g^{-1} .

Antioxidant Capacity Contents

Trolox equivalent antioxidant capacity (TEAC) assay was described by Nyamende et al. (2022). Value of 25 μL of supernatant and Trolox standard was used per well and for the control wells. Approximately 1 mL of ABTS was mixed with 20 mL EtOH. Furthermore, 300 μL of ABTS was mixed to each well and incubated at room temperature for 30 min afterwards absorbance was measured. TEAC was reported using concentrations varying from 190 to 210 μM Trolox (Equation: $0.0043X + 0.0065$; $R^2 = 0.9983$). Results were presented as μM Trolox mg^{-1} .

Antioxidant power based on the reduction of Ferric (FRAP) assay was achieved by preparing the reagent using acetate buffer (30 mL), ferric 2,4,6-tripyridyl-s-triazine (TPTZ) solution (3 mL), ferric chloride (FeCl_3) solution (3 mL) and 6.6 mL of DW. Ascorbic acid was used as standard and a volume of 10 μL was added as standard into each tube and poured in the allocated wells in the microplate as well as in the control well. A quantity of FRAP reagent (300 μL) was added into each well and followed by 30-min incubation at 37 °C. FRAP results were reported in μM Vitamin C mg^{-1} , using concentrations varying from 360 to 440 μM (Equation: $0.0072X + 0.001$; $R^2 = 0.9998$).

Freshly prepared 0.1 mM DPPH solution mixed with 95% ethanol (180 μL) was added to 20 μL of mango juice extract and incubated in the dark for 30 min. Thereafter, 275 μL of DPPH reagent was dispensed into all wells of the microplate and Trolox standard (25 μL) was dispensed in the standard well, as well as in the control well. The mixture was kept for 30 min at 37 °C, and afterwards the absorbance readings were taken at 593 nm. For the reaction mixture of the microplate absorbance readings were taken at 734 nm. The results were calculated using concentrations varying from 190 to 210 μM (Equation: $0.0125X + 0.2312$; $R^2 = 0.9829$) and reported in μM Trolox mg^{-1} .

Microbial Analysis

To establish the efficacy of the low-pressure cold plasma treatment against total aerobic mesophilic bacteria (TAMB), and yeast and mold (Y&M). Using the total plate count approach, the microbial load on fresh whole fruit (WF) immediately after treatment was compared to the untreated (control) samples. To remove the surface microbes on the whole fruit and dried mango slices, samples were placed in sterile saline solution and gently shaken for 60 min. Afterwards, 1.0 mL from each diluent was added into 9.0 mL of sterile physiological saline solution to prepare a three-fold serial dilution (Nyamende et al., 2022). Thereafter, 1.0 mL from each of the dilutions was transferred into the Petri dish and mixed with potato dextrose agar (PDA) and plate count agar (PCA) for Y&M and TAMB, respectively.

The poured plates were incubated at 37 °C for 48 h and 25 °C for 3–5 days for the PCA (TAMB) and PDA (Y&M), respectively. After the respective incubation period, the colonies were counted (25 to 250) and data transformed to Log colony forming units (CFU). The results were presented as Log CFU cm^{-2} . The experiment was done in triplicate per dilution ($n = 9$).

Statistical Analysis

A full factorial experimental design was implemented in this study. Data were subjected to One-way analysis of variance taken into consideration main effects/factor (pre-treatment). General Linear Models Procedure of SAS vr. 9.4 software (SAS Institute Inc, Cary, USA) was used for data analyses. Besides the microbial analysis ($n = 9$), all other measurements were replicated six times. Results were presented as mean ($n = 6$) \pm standard error. Differences in mean values were tested using Fisher least significant difference (LSD) test at $p < 0.05$.

Results and Discussion

Drying Characteristics

Moisture Ratio

Figure 1 represents the difference in moisture ratio (MR) of mango slices treated with cold plasma for 5 and 10 min, pre-treated sodium metabisulphite and untreated (control) with drying time. 'Heidi' mango slices with the initial moisture content of $80\% \pm 0.20$ on a wet basis (w.b.) was reduced by 81% and 76% in dried CP5 and CP10 pretreated samples, respectively. It can be observed that the MR decreased as the drying time progressed for all the samples, however, the CP pre-treated mango samples resulted in faster changes in MR . Fresh 'Heidi' mango samples cold plasma pre-treated for 5- and 10-min achieved the average minimum drying time of 9 h and consequently dried faster than the untreated control and sodium metabisulphite treated samples (10 h). The faster rate of MR decline observed for CP pre-treated samples could indicate an accelerated ease of the transfer of heat from the surface of the fruit into the inner fruit tissue, thus leading to an increase in the vapor pressure. The fast decrease in the MR observed in CP pre-treated samples could be explained by the impact of low pressure, charged and non-charged particles (including electrons and ions) and reactive species discharged by the CP. According to Wang et al. (2017) CP treatment could cause etching on the surface of the fruit creating micro-holes and tissue disruption during pre-treatment, thus facilitating the moisture migration process.

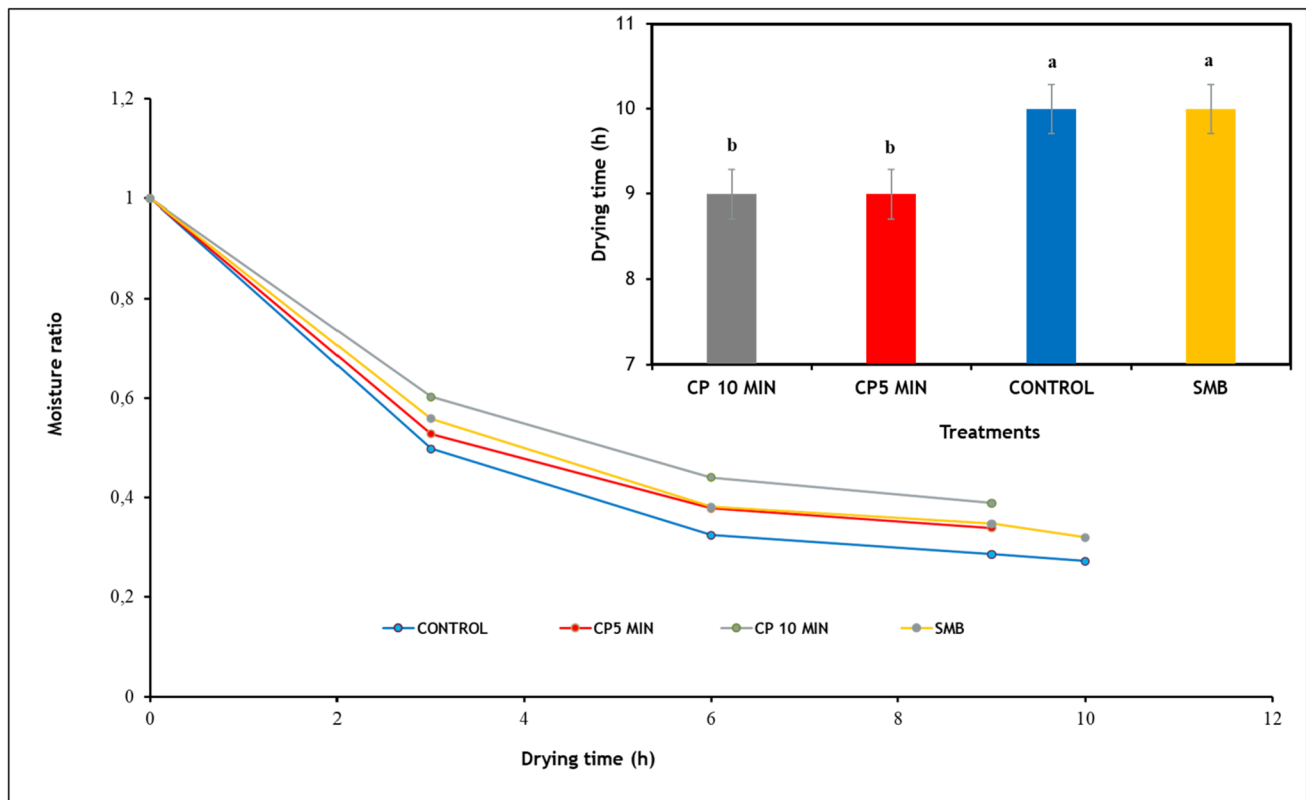


Fig. 1 Effects of cold plasma for 5 min, 10 min, sodium metabisulphite and untreated control dehydrated at 60 °C on the relationship between moisture ratio of 'Heidi' mangoes. Error bars represent stand-

ard deviation (SD) of mean ($n=6$) values of treatments, and different lower-case letter indicate significant difference in means ($p < 0.05$)

This confirms that pre-treatment of fresh cuts could reduce resistance mass/moisture flow and increase drying rate.

Furthermore, the observed effectiveness of CP on *MR* in this study was consistent with other reports in literature. For instance, the drying of—'Junzao' jujube at 60 °C (Bao et al., 2021), mushrooms at 50 °C (Ashtiani et al., 2023), and freeze-drying of haskap berries at -80 °C (Li et al., 2023) were enhanced by the application of CP. Similarly, the decline in *MR* was also demonstrated in work done by Tabibian et al. (2020). It was shown that the dehydration time for saffron declined by $\approx 54\%$ after 60 s exposure to cold plasma with power supply of 1 kW AC (50 Hz) and 8 kV amplitude and drying at 60 °C. Huang et al. (2019) observed more than 20% reduction in drying time using atmospheric-pressure air plasma at 25 kHz and 500 W before hot-air oven (70 °C) drying of 'Sugraone' grapes. Ashtiani et al. (2023) demonstrated that mushroom drying time at 50 °C was reduced by 4.7%, 10.2%, 19.0% and 26.0% for samples treated with CP for 30 s, 50 s, 70 s, and 90 s, respectively.

Furthermore, no significant differences were found between mango slices treated with SMB and the untreated control. In contrast, Kayran and Doymaz (2021) showed

that SMB pre-treated 'Cataloglu' apricots had shorter drying time compared to non-treated control, within the range of 11.4 to 19.6% when dried at 50, 60, 70, and 80 °C. The variations observed between these studies could be attributed to the concentration of SMB solution used and the dipping duration as well as the differences in the fruit-type and -tissue structure. For instance, in this study 1% sodium metabisulphite solution with dipping duration of 2 min was applied on the sliced mangoes, however, Kayran and Doymaz (2021) applied 8% SMB solution with dipping duration of 10 min. Overall, cold plasma pre-treatment was most efficient compared to SMB-treated and untreated 'Heidi' mango slices dried at 60 °C. This finding demonstrates that cold plasma could be an effective pre-treatment in the drying protocol for fresh cut mangoes.

Drying Rate

Changes in the drying rates of untreated (control), CP- and SMB-treated 'Heidi' mango slices summarized in the Supplementary (Fig. S2). Drying time for CP pre-treated samples was reduced by 20% as compared to sodium metabisulphite treated and control samples. The drying rate of 'Heidi' mango

decreased as the moisture ratio decreased in all samples. At the start of drying, the drying rate was slow followed by a progressive acceleration as the drying time increased. According to Ashtiani et al. (2018), the drying process is caused by a freedom of moisture migration from the surface of the fresh mango slices (via evaporation), which further enhanced the migration of water molecules from internal/inner tissues of samples to continue drying. This phenomenon was explained as diffusion-efficiency. Moreover, Huang et al. (2019) demonstrated that the falling rate commences once the water that is freely available is removed from a sample. In agreement with this work, after the first falling rate; decline in DR was observed as the non-saturated surface area to moisture increases and the DR decreased gradually at the final stage due to the slow movement of moisture from inward to outward surface (Manikantan et al., 2022).

Furthermore, as drying progressed, the falling rate period continued to the second stage with further decline observed in DR from 3 to 9 h in CP-treated samples and from 3 to 10 h in samples SMB-treated and control samples. Furthermore, the successive decline in the falling rate period could be attributed to the movement of water from the tissue core to the surface layer before evaporation. The drying during this period suggests that internal mass transfer was completed through a dominant physical mechanism of diffusion. The internal mass transfer governing the moisture movement via diffusion, started from initial moisture content to the point of moisture content equilibrium (Ashtiani et al., 2023; Zhang et al., 2019). Therefore, the process of internal diffusion is accountable for moisture loss during drying. This study showed that decline in the DR was enhanced in samples pre-treated with cold plasma compared to the other samples while the drying time increased.

Modelling the Drying Process

To describe the drying process, the best fit of the seven models applied was the Logarithmic model with R^2 value within the range of >0.999 and 1.1 and $RMSE$ value ≤ 0.0432 as presented in Supplementary (Table S1 and S2). Based on their drying curves obtained, the Logarithmic model provided the most adequate description for the thin-layer drying behavior for untreated, CP- and SMB-treated dried 'Heidi' mango slices (Fig. S3A–D). This was followed by Henderson & Pabis and Midilli-Kucuk models across all the dried samples. However, the existing relationship between R^2 and $RMSE$, wherein the suitability of a model is based on higher the R^2 and lowest $RMSE$ values – Logarithmic model conformed to this as the best fitting models in this study to describe hot air-drying process of 'Heidi' mango slices.

Furthermore, taken into consideration the mass transfer constant (k) derived. The drying constant k value, which

describes various transport rates of moisture removal and the effective water diffusion rate of the samples (Li et al., 2023). Based on results in Tables S1 and S2, for the Logarithmic model, k values in CP5-treated samples increased compared to the untreated samples, suggesting an enhanced drying rate. This observation is consistent with studies conducted by Li et al. (2023) and Shishir et al. (2020). However, CP10-treated samples had lower k values compared to CP5-treated and control samples but had a highest empirical constant c . This could suggest irregular changes in the tissue samples at a microstructural level that influenced porosity or tissue thickness and convective drying.

Microstructural Properties

The cross-section of tissue cavitation of untreated (control) and CP pre-treated 'Heidi' mango slices differed as shown in Fig. 2. The cross-section of untreated sample (control) had very limited open intracellular spaces and the few cavities opened are close to the surface of mesocarp (as marked in red) compared to the 5- and 10-min CP-treated samples. This observation supports the suggestion that the core tissue of the untreated mango slices would take longer time to dry due to the compactness compared to CP treated samples (Fig. 2A). Furthermore, the micrographs of the surface of the untreated dried mango slices showed a smooth and almost consistent surface layer. However, for the CP-treated samples, many rough stretches and irregularly etched micro-holes could be seen on the tissue surface and 10 min (Fig. 2B). Similar observations we reported by Ashtiani et al. (2023) that pre-treatment with CP modified cellular structures and created inconsistent micropores on the mushroom surface.

The changes noted in micrographs (Fig. 2A), suggest the combined effects of low-pressure cold plasma as pre-treatment and drying on samples treated and highlight the prospect of enhanced disruption of fruit tissue and enhance drying process. Pandiselvam et al. (2023a, b) demonstrated in their review the benefit of pretreatment (ultrasonic) as it leads to cavitation, creation of microchannel and a sponge effect on food matrix. These effects are consistent with our observation and could have contributed directly to mass transfer as seen with CP5 and CP10 pre-treated samples (Fig. 1) and the ruptured of tissues and structural changes caused by low-pressure and cold plasma. According to Bao et al. (2021), the occurrence of these micro-holes with irregular shapes on fruit tissue was associated with the impact of exposure to cold plasma. Reactive species generated during cold plasma treatment could diffuse from the fruit surface into the tissues creating cavitations via etching and ion bombardment of charged particles on the cell structure of the fruit. Furthermore, the cellular deformation, shrinkages

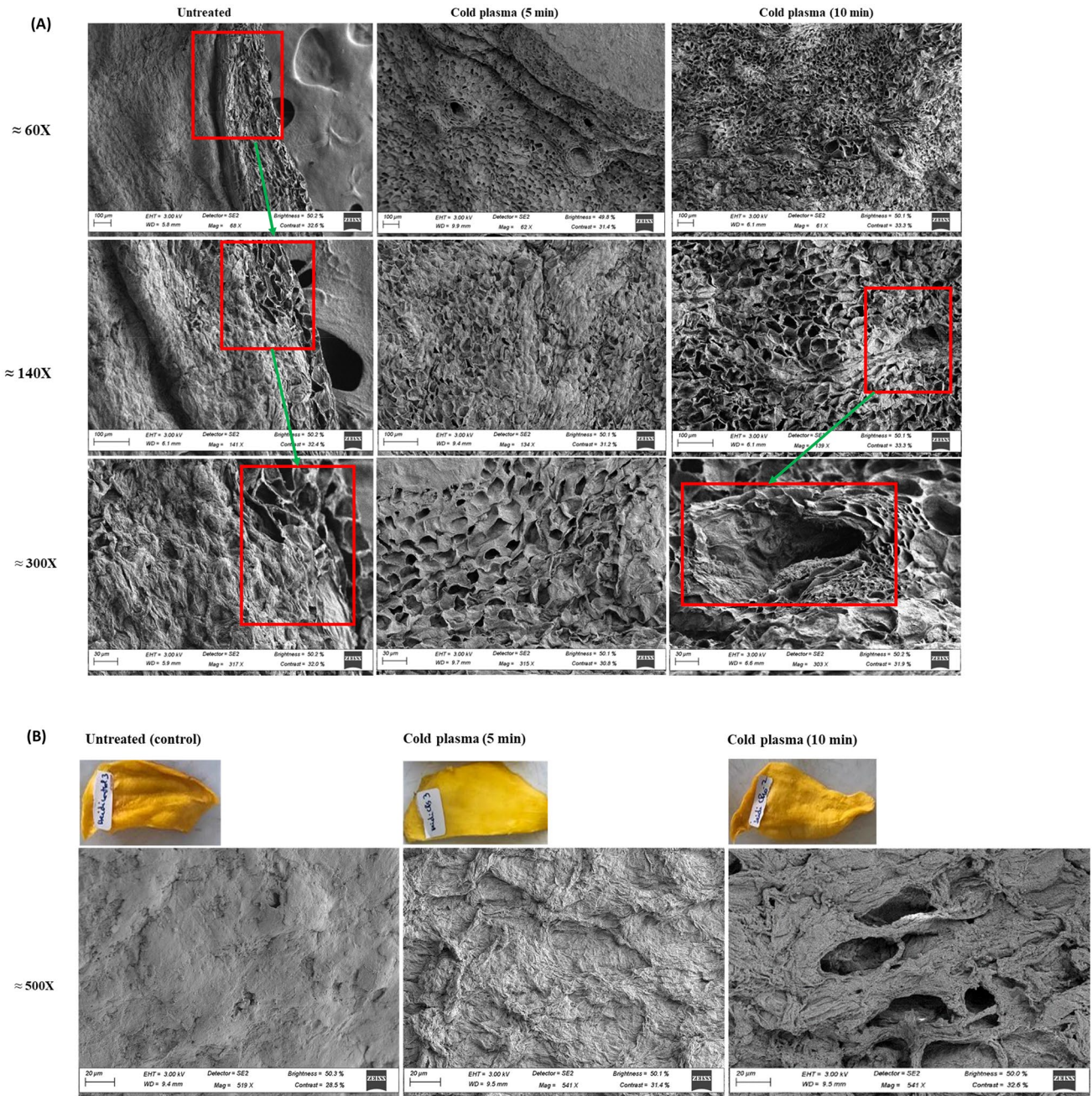


Fig. 2 A Scanning electron microscope micrographs representing the microstructural changes occurring on cross section of fresh 'Heidi' mangoes slices pre-treated with cold plasma for 5 and 10 min. *The red marked region shows compactness of the tissue core with minor

cavitation on the upper layer. **B** Micrograph of the surface of the dried 'Heidi' mangoes untreated control and pre-treated with cold plasma for 5 min and 10 min dehydrated at 60°

and altered microstructure of mango slices could be further enhanced by vacuum low-pressure. This phenomenon could also explain the reduction of surface resistance against moisture evaporation or mass transfer, and the decrease in drying time and rate observed in treated samples compared to the untreated.

All these changes in fruit tissue of the CP-treated samples could facilitate moisture transfer (via diffusion and evaporation) from the core accelerating the drying process as previously observed in our moisture analysis. Similarly, Zhang et al. (2019) observed that CP pre-treatment efficiently aided removal of moisture and enhanced drying of chili pepper.

The authors attributed this improvement to the etched pores on the surface of the pre-treated samples during hot air drying at 70 °C. Bao et al. (2021) observed similar results after pre-treating 'Junzao' jujube fruit with cold plasma treatment for 15 s prior to drying at varying air temperatures (50, 60 and 70 °C). These authors observed that the microstructure of non-treated slices was compacted, with restricted intracellular spaces and minute cavities compared to CP-treated ones, which showed a deformation in the cell with shrinkages. Authors concluded that CP prior drying changed the microstructure of treated samples (Ashtiani et al., 2023; Bao et al., 2021; Zhang et al., 2019). These findings support this work that, the use of low-pressure cold plasma — (i) was responsible for the surface topography modification, (ii) created the intracellular spaces on the fruit tissue microstructure, and (iii) facilitated moisture transfer during drying.

Biochemical Attributes

Total soluble solids content (TSS) of untreated and treated 'Heidi' mango is reported in Table 2. Compared to the fresh-cut baseline (measured before drying), TSS values were significantly higher in all the dried samples, and highest in CP10 ($p \leq 0.05$). The increase in TSS could be attributed to the effect of drying (i.e., removal of moisture) that resulted in the development crusted surface layer, which prevents the movement of soluble solids from the fruit core and thereby concentrating the soluble solids. Similarly, Bao et al. (2021) observed a significant increase in the TSS value of jujube slices (cv. Junzao) 30 or 60 s cold plasma pre-treated for samples dried at 70 °C. The authors attributed the observed phenomenon to the formation of a thick layer on the surface of the fruit slices. Sruthi et al. (2022) reported in their extensive review that a considerable rise in the TSS values in plasma-treated could be linked to the conversion of starch into sugars.

A similar trend as the TSS was observed in the titratable acidity (TA) of 'Heidi' mango between the fresh-cut and dried samples. However, the TA concentration was significantly

lower in the fresh samples (0.08 ± 0.003) in comparison to the dried ones ($p < 0.005$). In addition, TA was not significantly difference for all the pre-treated samples compared to the untreated control samples. The decline in TA in the fresh cut samples during postharvest storage could be explained through the occurrence of acid metabolism during fruit ripening, converting starch and acid to sugar (Brizzolara et al., 2020). The increase TA in the dried mango slices could be attributed to non-enzymatic reactions during the drying process that could lead to the formation of different organic acids (Dufera et al., 2022), as well as the removal of moisture (Sruthi et al., 2022). The findings from this work also agree with the results presented in Yao et al. (2020).

Furthermore, pH value of fresh 'Heidi' mango was significantly lower ($p < 0.05$) compared to all pre-treated and control dried samples (Table 2). After the drying process was ended, SMB pre-treated samples maintained the highest pH (4.39 ± 0.0) compared to other treatments ($p < 0.05$). This was followed by samples pre-treated with CP for 10 min (4.22 ± 0.02), CP5 (4.16 ± 0.01) and the control (4.09 ± 0.01) samples. Other studies have reported insignificant change in pH of CP-treated samples (Rana et al., 2020; Ziuzina et al., 2020). The increase observed in pH values from fresh cut to the dried product could be associated with the initial change in the metabolic process due to CP treat to the process of drying resulting in the loss of loss of moisture. This finding demonstrated that the combined effects of cold plasma and drying could influence greatly the biochemical components of mango.

Change in Colour

Compared to the fresh-cut samples, L^* value (75.77 ± 1.41) declined significantly ($p < 0.05$) for all the CP-treated dried mango slices (Table 3). At the end of drying SMB treated samples maintained higher L^* value in comparison to CP-treated samples ($p < 0.05$). Similarly, when compared to fresh produce, a decline in the lightness was reported for dried CP-treated mushrooms by Ashtiani et al. (2023). Dereje and Abera (2020) demonstrated that dried 'Keitt' mangoes slices decreased in lightness compared to the fresh slices. Furthermore, these results agree with the decline observed in the lightness of the dried mango slices by Nyangena et al. (2019) and Mexican plum (Muñoz-López et al., 2018). The authors further explained that decrease in L^* values because of evaporation through loss of water during drying process, tissue surface deformation of dried slices and formation of brown pigments. Decline in lightness could be associated with the extended hours of drying and the oxidative action of oxygen (Yancló et al., 2023). Melgar-Lalanne et al. (2017) suggest that the drastic colour change after drying could be due to non-enzymatic browning reactions that lead to darkened samples.

Table 2 Effects of pre-treatment and hot air drying on chemical attributes of 'Heidi' mango dehydrated at 60 °C

| Treatments | pH | TA (% citric acid) | TSS (°Brix) |
|------------|-------------------|--------------------|--------------------|
| *Baseline | 3.44 ± 0.26^e | 0.08 ± 0.003^b | 14.57 ± 0.18^c |
| CP10 | 4.22 ± 0.02^b | 2.02 ± 0.02^a | 17.93 ± 0.11^a |
| CP5 | 4.16 ± 0.01^c | 2.06 ± 0.01^a | 17.33 ± 0.28^b |
| SMB | 4.39 ± 0^a | 2.02 ± 0.005^a | 17.73 ± 0.13^a |
| Control | 4.09 ± 0.01^d | 2.06 ± 0.01^a | 17.23 ± 0.17^b |

Mean ($n=6$) \pm S.E. presented. Mean values in the same row followed by different letter (s) indicate significant difference ($p < 0.05$) according to Duncan's multiple range test. *Baseline means measured quality attributes of fresh-cut mango slices before drying

Table 3 Effects of pre-treatment and hot air drying on colour attributes of 'Heidi' mango dehydrated at 60 °C

| Treatments | Lightness (L^*) | Redness (a^*) | Yellowness (b^*) | Chroma (C^*) | Hue angle (h°) | TCD |
|------------|---------------------------|---------------------------|-----------------------------|----------------------------|---------------------------|----------------------------|
| *Baseline | 75.77 ± 1.41 ^a | -2.92 ± 0.86 ^d | 55.33 ± 0.80 ^{bcd} | 55.47 ± 0.79 ^{cd} | 93.06 ± 0.89 ^a | 0 |
| CP10 | 61.46 ± 2.62 ^c | 2.63 ± 0.39 ^b | 52.55 ± 2.17 ^{cd} | 52.63 ± 0.17 ^d | 87.04 ± 0.49 ^b | 10.71 ± 0.14 ^b |
| CP5 | 66.91 ± 1.68 ^b | 2.53 ± 0.28 ^b | 55.96 ± 1.38 ^{bc} | 56.06 ± 1.39 ^{bc} | 87.47 ± 0.40 ^b | 10.39 ± 0.59 ^b |
| SMB | 68.52 ± 2.57 ^b | 3.93 ± 0.45 ^a | 62.61 ± 2.01 ^a | 62.80 ± 1.19 ^a | 86.36 ± 0.24 ^c | 13.09 ± 1.51 ^a |
| Control | 69.14 ± 2.44 ^b | 3.99 ± 0.64 ^a | 57.90 ± 1.02 ^b | 58.07 ± 1.01 ^b | 85.02 ± 0.55 ^d | 11.07 ± 0.71 ^{ab} |

Mean ($n = 12$) ± S.E. presented. Mean values in the same row followed by different letter (s) indicate significant difference ($p < 0.05$) according to Duncan's multiple range test. *Baseline means measured or calculated colour parameters of fresh-cut mango slices before drying

Similarly, higher a^* values were observed in both control and SMB treated samples in comparison to CP-treated samples. The higher a^* values could indicate undesired intensive browning in this fruit compared to the CP-treated samples (Table 3). These findings indicated the occurrence of browning, which may be due to higher values observed in a^* parameter of the dried slices (Yancló et al., 2023). Zielinska et al. (2018) suggested that the higher values observed in a^* sample symbolizes the redness and represents an important indicator of fruit quality. In contrast, no significant change in the b^* value was recorded for pre-treated mango slices indicating that treatments applied did not influence the yellowness of the dried samples in this study. Samples pretreated with CP5, SMB and control had higher b^* value compared to CP10, which exhibited lower values (Table 3). Dereje and Abera (2020) reported that the yellowness of dried mango declined compared to the fresh samples. The b^* also reveals the carotenoid contents present in the fruit and increase in b^* values is attributed to a better retention of carotenoids in dried products, which is accountable for the yellow pigmentation of mangoes. Higher values for b^* are recommended to have yellow dried products such as dried mango slices (Salehi & Kashaninejad, 2018). The possible pathways imparting on yellow colour changed after treatment could be due to combined effects of light and reactive oxygen species, Millard reaction and enzymatic browning catalyzed by polyphenol oxidase (Kashfi et al., 2020; Pandiselvam et al., 2023a, b).

Highest hue angle (h°) values were found in the fresh-cut mango slices before drying, while this was followed by the CP pre-treated, SMB treated and untreated (control) samples (Table 3). However, the lowest C^* value was recorded in the CP10 pre-treated slices, and SMB pre-treated slices retained the highest C^* value ($p < 0.05$). This demonstrated that the SMB- and CP5-treated samples retained the intensity and saturation of the colour. Similar observation was reported by Darvish et al. (2022); it was demonstrated that low-pressure CP significantly increased the C^* compared to control sample for saffron. The total colour difference (ΔE) values recorded for the SMB treated (13.09 ± 1.51) and untreated samples (11.1 ± 0.71) were significantly higher

compared to the samples pre-treated with cold plasma for 10 min (10.71 ± 0.14) and 5 min (10.39 ± 0.59) as shown in Table 3. ΔE reveals the calculation of the combination of the parameters L^* , a^* and b^* . An increase in ΔE shows a greater loss in dried fruit colour (Wang et al., 2019). Li et al. (2018) demonstrated that an increase in ΔE for dried fruit could be attributed to extensive interaction with light and atmospheric oxygen during solar drying. Same observations were made for edamame fruit hot air dried at 70 °C (An et al., 2022). However, the samples pre-treated with SMB had the higher ΔE compared to all the other treatments. Furthermore, these results suggest that a decrease in the CP pre-treatment time duration could lead to a greater difference in colour.

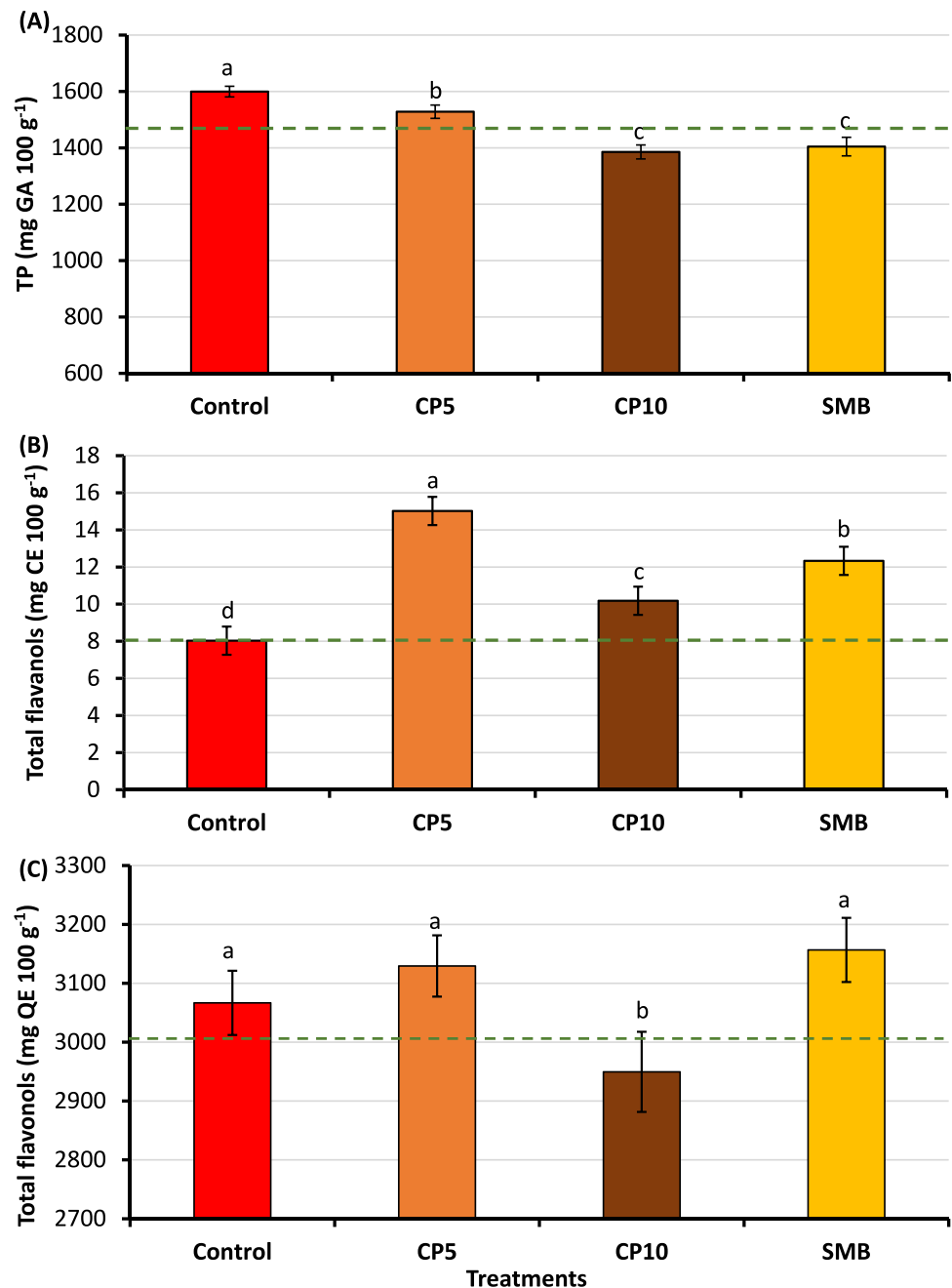
Effects on Bioactive Compounds

Total Polyphenols

The total polyphenols content (TPC) in the fresh sample prior to drying was approximately 1510 ± 1.69 mg GAE L^{-1} and was significantly lower than dried control samples (1599.53 ± 18.80 mg GAE L^{-1}) as shown in Fig. 3A. The TPC accumulation at the end of drying could be attributed to the removal of water content. Furthermore, non-treated dried 'Heidi' mango slices (control samples) retained the highest TPC (1599.53 ± 18.80 mg GAE L^{-1}) followed by CP5 pre-treated samples (1528.16 ± 23.61 mg GAE L^{-1}), and SMB treated samples (1404.46 ± 12.96 mg GAE L^{-1}), while CP10 samples had the lowest TPC (1385.43 ± 12.36 mg GAE L^{-1}) (Fig. 3A). This work showed that the cold plasma treated dried samples showed decline in TPC at the end of drying compared to control. This result corresponds with the report by Ashtiani et al. (2023) and Bao et al. (2021).

According to Pich et al. (2023) phenolic compounds attached to the fresh produce cellular/tissue matrix could be released during the drying process exposing them to thermal degradation. In addition, decline in polyphenol contents was associated drying (via the circulation of hot water and removal of moisture). Bao et al. (2021) suggested that the accumulation of reactive species generated during CP pre-treatment led to cell deformation and

Fig. 3 Effects of cold plasma exposure for 5 min, 10 min, sodium metabisulphite and untreated (control) on changes in: **A** total polyphenol (TP), **B** total flavanols, and **C** total flavanols of ‘Heidi’ mangoes dehydrated at 60 °C. Error bars represent standard deviation (SD) of mean ($n=6$) values of treatments, and different lower-case letter indicate significant difference in means ($p < 0.05$). Continuous dashed line indicates baseline measurement. *Coloured graphs only available online



contraction inducing the decline in polyphenols inside jujube slices. In contrast, Pich et al. (2023), Majumder et al. (2021) and Vidinamo et al. (2022) reported enhances TPC for pink pepper, ginger, and pineapple, respectively. Notably, these authors did not pre-treat with CP, and attributed higher retention of TPC to the development of thicker layer on the surface of dried samples that protects against the degradation of bioactive compounds.

Flavanols and Flavonols

No significant difference in the total flavanols of the fresh mango slices before and after drying (control) was observed ($p > 0.05$). At the end of drying, and in comparison, to control samples, all other CP and SMB-treated samples retained a higher content of total flavanols (Fig. 3B). The CP5-treated samples retained the highest flavanols (15.0 ± 0.38 mg CE

100 g⁻¹, $p < 0.05$), and this suggests that this treatment could effectively inhibit the degradation of total flavanols during the drying process of sliced ‘Heidi’ mangoes. In contrast, for the total flavonol contents SMB (3156.64 ± 54.50 mg QE 100 g⁻¹) and CP5 (3129.64 ± 52.05 mg QE 100 g⁻¹) pre-treated samples retained higher concentration in comparison to the control (3060.72 ± 46.05 mg QE 100 g⁻¹, $p > 0.05$), and CP10 (2900 ± 48.06 mg QE 100 g⁻¹, $p < 0.05$) as shown in Fig. 3C.

Based on available literature, there is no other work that has opined on the role or impact of CP treatment on flavonol and flavanol content of mango fruit. Hence, it is suggested that CP generated reactive species bond with the tissue surface, which led to oxidative breakdown, pores formation, cell wall destruction, that facilitate the release of flavanols and flavonols contents. Lower concentrations under CP10 could suggest further oxidative degradation of the flavonoids due to prolonged exposure to the reactive particles. Similarly, for dried haskap berries, an initial increase in total flavonoids was recorded and followed by decline due CP exposure. The initial increase in the flavonoids was associated with CP-induced alteration of the haskap berries cellular structure, this results in enhanced release of cell content, and over time of drying and exposure of to air led to oxidative degradation (Li et al., 2023).

Antioxidant Capacity

A significant increase in antioxidant capacity was reported in dried samples compared to fresh cut. The antioxidant capacity in fresh cut samples (385 ± 5.06 mg TE 100 g⁻¹) increased significantly in the dried control, CP10- and SMB-treated samples. In contrast, samples under CP5 had the lowest TEAC compared to the fresh cut and dried control samples (Fig. 4A). For fresh cut slice samples, the FRAP activity was 2600 ± 15.46 mg VitCE 100 g⁻¹, and at the end of drying this increased significantly for samples under control and CP5 treatment, while a slight increase was recorded for SMB dipped samples (Fig. 4B). A similar trend as FRAP was observed for DPPH activity. Lowest values of FRAP and DPPH were recorded for CP10 treated samples ($p < 0.05$) compared to control and CP5 values (Fig. 4). The increased antioxidant activity for CP5-treated samples could be explained by the corresponding increase in phenolic content as shown in Fig. 3A.

Similarly, increase in antioxidant activity upon plasma processing was reported by Keshavarzi et al. (2020) and de Castro et al. (2020) on minimally processed produce. The authors attributed the observed increase to low intensity and limited exposure to plasma and noted longer exposure times at higher intensity resulted in the decline in antioxidant activity (de Castro et al., 2020; Keshavarzi et al.,

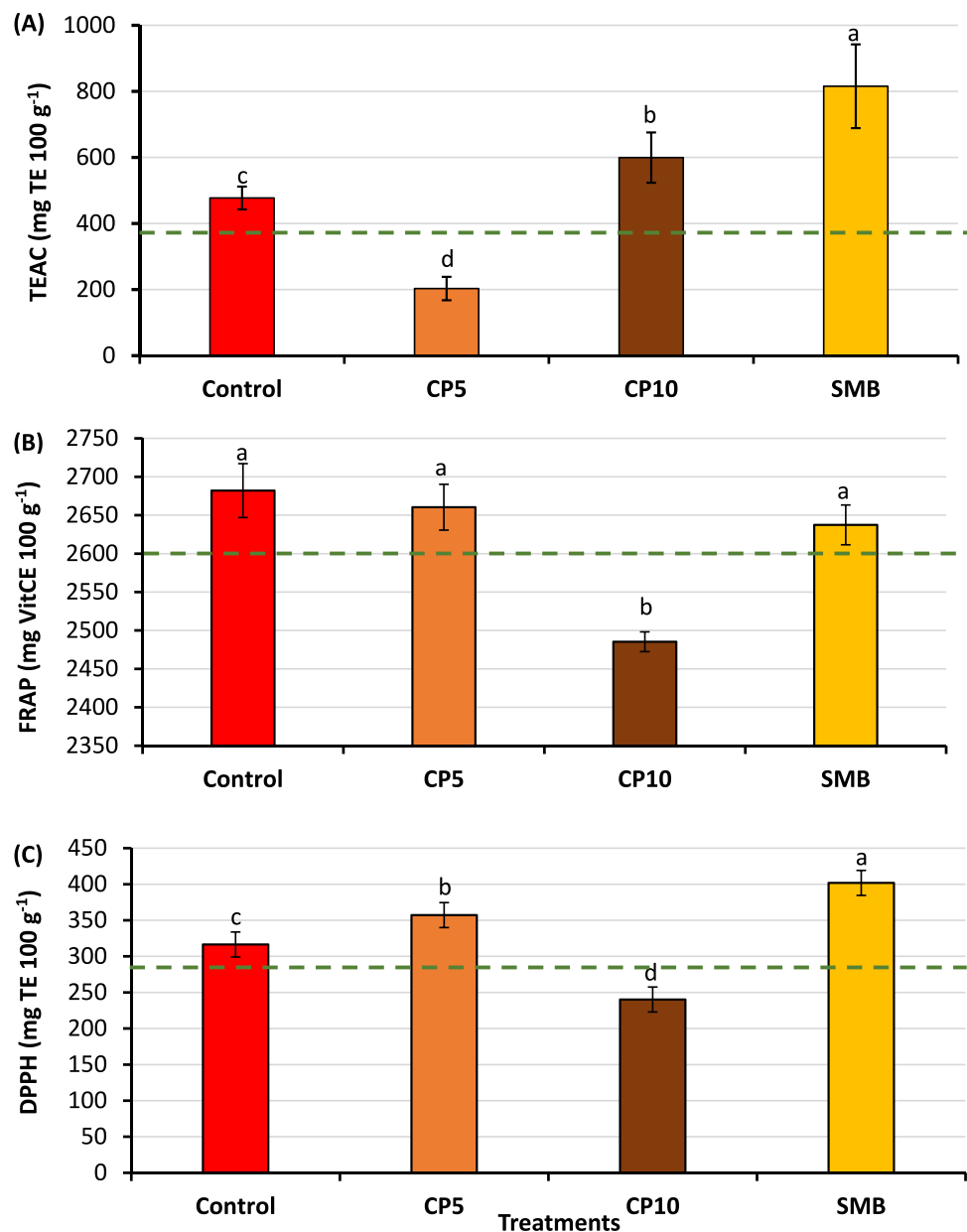
2020). This observed reduction in antioxidant activity after extended exposure times was also reported for CP10 pre-treated samples. The reduction in antioxidant activity could be attributed to (i) the accumulation of reactive oxygen species and hydroxyl radical after longer duration of exposure to CP, which could have increased their reaction powers and reduced free radicals during the drying process; and/or (ii) the impact of etching on the surface tissue after extended CP exposure, which could lead to the exposure of cytoplasmic contents to reactive species and increased rate of antioxidant degradation (Bevilacqua et al., 2018; Sruthi et al., 2022). Chen et al. (2019) reported a decline in DPPH radicals scavenging activities in plasma activated water treated fresh-cut pears with storage time and indicated that reactive oxygen species scavenging capacity degraded over time. However, varying outcomes was reported for antioxidant activity of strawberries by Yang et al. (2023) as a function of plasma treatment types and storage duration. The difference in antioxidant activities between this finding and the current study could also be attributed to the type of produce (e.g., thickness of the fruit mesocarps), the mode of plasma discharge, the effects of treatment voltage and time (Feizollahi et al., 2021; Rajan et al., 2023). Overall, at the end of this work CP5 pre-treatment and drying successfully enhanced the antioxidant activity of the mango slices. This could be of application interest for the extraction of bioactive compounds.

Microbial Load

Microbial load on fresh whole mango fruit surface was effectively reduced by > 0.5 under CP5 and > 1 Log CFU under CP10 for TAMB and Y&M, respectively (Fig. 5). The TAMB count was reduced from initial 3.4 Log CFU cm⁻² to 2.8 and 2.2 Log CFU cm⁻² under CP5 and CP10 treatment, respectively, while Y&M was reduced from 3.7 Log CFU cm⁻² and 3.0 and 2.3 Log CFU cm⁻², respectively. Highest reduction was observed for CP10-treated whole fruit ($p < 0.05$). These results indicated that prolonged exposure to low pressure cold plasma treatment was efficient.

Studies based on other plasma discharge methods have confirmed the antimicrobial efficacy of CP. For instance, Rana et al. (2020) treated ‘Duch’ strawberries for 15 min with Di-electric barrier discharge (DBD) at 60 kV, 260 V, and 50 Hz and observed ≈ 2 Log reduction of Y&M. Longer exposure for up to 10 min to plasma jet, with 10 kHz frequency and 18 kV led to a decrease in *S. aureus* (Kumar et al., 2018). The efficiency of CP treatment in reducing microbial load in mango fruit is dependent on various factors such as treatment time, voltage, power, frequency (Liao et al., 2018), type of gas used (Xu et al., 2017), relative

Fig. 4 Effects of cold plasma exposure for 5 min, 10 min, sodium metabisulphite and untreated (control) and drying on changes in: **A** Trolox Equivalent Antioxidant Capacity (TEAC), **B** Ferric Reducing Antioxidant Power (FRAP), and **C** 1,1-Diphenyl-2-picrylhydrazyl (DPPH) of ‘Heidi’ mangoes dehydrated at 60 °C. Error bars represent standard deviation (SD) of mean ($n=6$) values of treatments, and different lower-case letters indicate significant difference in means ($p<0.05$). Continuous dashed line indicates baseline measurement. *Coloured graphs only available online



humidity, temperature, and flow rate (Yadav et al., 2019), material thickness and spacing (Pathare et al., 2023).

Furthermore, significant reduction in both AMB and Y&M counts (> 2 Log CFU, $p < 0.05$) were recorded at the end of the drying process. Pre-treatment played a role in final count CP10 treated samples maintained the lowest microbial load followed by SMB ($p < 0.05$), but no difference was found between dried mango slices treated with CP5 and the control ($p > 0.05$). Further decline in microbial counts on the samples after drying was associated with the impact of drying heat and removal of free available moisture (Dereje & Abera, 2020). The final AMB and Y&M counts on the dried mango slices were below the

allowable limit for yeast and molds, set by the International Commission for microbiological specifications for foods, and the South African Foodstuffs, Cosmetics and Disinfectants (FCDA) legislation (Act 54 of 1979). These results demonstrated that the combination of low-pressure CP pre-treatment and drying at 60 °C further reduced the microbial load on dried mango slices.

The potential for low-pressure cold plasma pre-treatment in improving the drying process, reducing microbial load, and preserving quality attributes of ‘Heidi’ mango was demonstrated in this work. However, besides these highlighted benefits of implementing, low-pressure cold plasma technology could have some drawbacks and/or limitations,

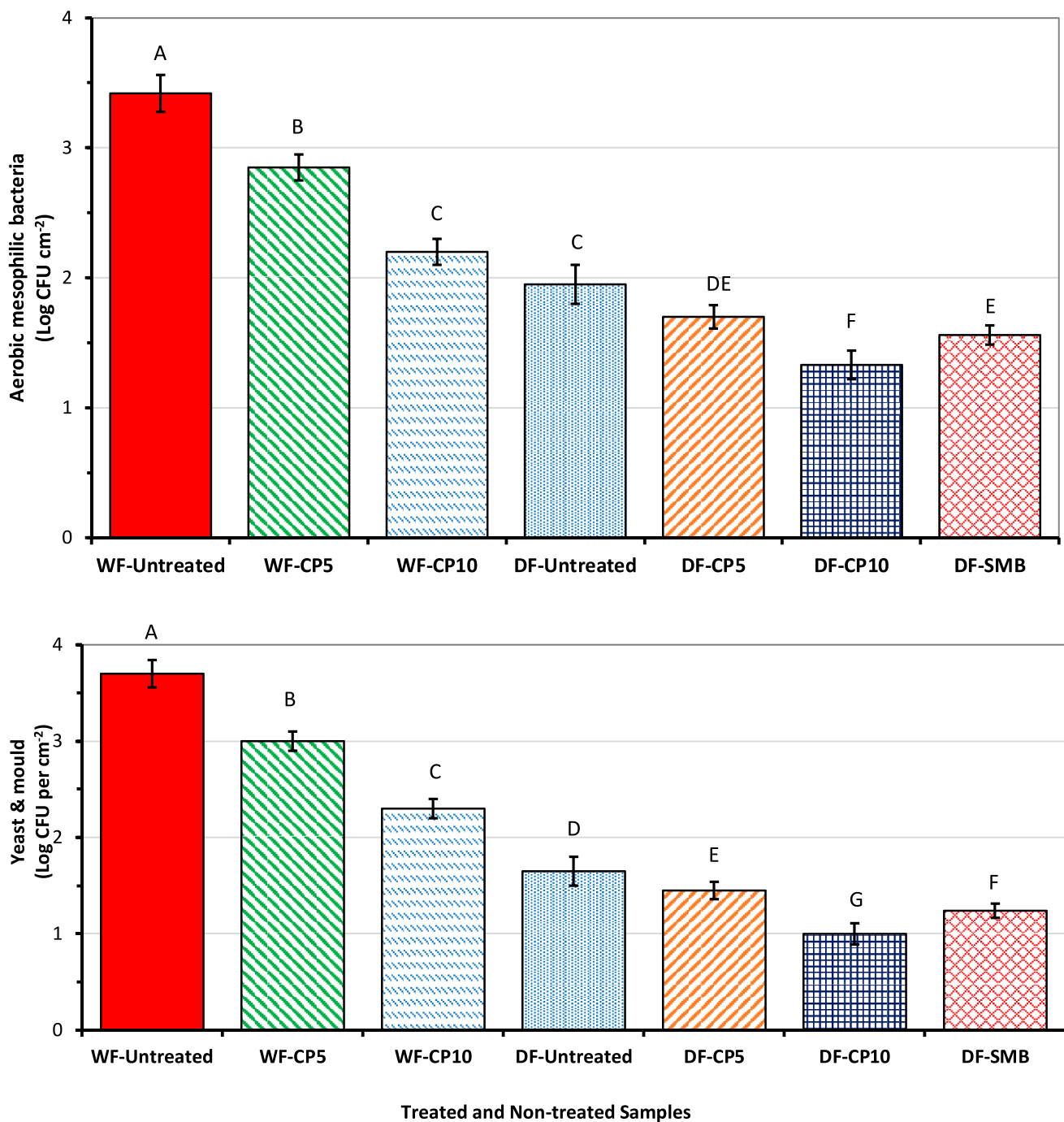


Fig. 5 Total aerobic mesophilic bacteria (AMB) (A), and yeast and mould (B) count on the surface of cold plasma treated and untreated fresh whole fruit (WF) and dried fruit (DF) 'Heidi' mangoes. Error

bars represent standard deviation (SD) of mean ($n=9$) values of treatments, and different upper-case letters indicate significant difference in means ($p < 0.05$). *Coloured graphs only available online

implicating scaling up from the laboratory units. This includes (i) the relative high cost of vacuum chambers, complicated operation, and maintenance procedures; (ii) the complexities of ensuring even plasma generation and

treatment are a large scale (Coutinho et al., 2018; Zhang et al., 2022); and (iii) the compatibility of low-pressure cold plasma unit with commercial packhouse procedure is also drawback.

Conclusion

This study demonstrated the relevance of low-pressure cold plasma as a pre-treatment step to drying of mango fruit. Outcome showed that CP treatment had significant impact on moisture ratio, drying properties, tissue micro-structure and quality of dried ‘Heidi’ mango slices. Low-pressure CP pre-treatment enhanced the drying rate of mango slice at 60 °C compared to SMB treated and control samples. Overall, the drying kinetics of ‘Heidi’ mango slices were best described Logarithmic models (R^2 , 0.9999 and $RMSE$, 0.0122). Low-pressure cold plasma as pretreatment effectively disrupted the tissue structure of the sliced mango and generated larger intracellular cavities. However, exposure ‘Heidi’ mango to the CP10 resulted in significantly lower total phenolic and flavonoid contents, but this treatment duration enhanced the microbial inactivation on the samples. This outcome re-emphasizes the need to maintain a balance between microbial efficacy and retention of bioactive compounds in minimally processed produce.

Based on the percentage reduction in drying time with the use of low-pressure cold plasma as pretreatment (20%), this could reduce the energy consumption for conventional hot air oven drying on an industrial scale. However, future work that takes into consideration the effective volume/mass of drying unit, energy consumption per unit volume/mass for the drying unit, and energy consumption for the low-pressure cold plasma unit is required. Furthermore, the potential of integrating spectroscopic methods such as the use of UV absorption or optical emission or electron paramagnetic resonance spectroscopy to quantify cold plasma discharged reactive species should be investigated. This would be beneficial to characterize the role of reactive species generated by the carrier or process gas and elucidate the reaction with the microbial population and food matrix. In addition, the characterization of the dynamics of specific bacterial and fungal communities (via the use of metabarcoding and new generation sequencing) on the fresh whole to dried mango fruit and the impact on textural properties would ensure better understanding of the impact of the value addition processes. Overall low-pressure cold plasma pre-treatment can be explored for development of a process to enhance the drying process for agrifood systems applications.

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Author Contribution Loriane A. Yanclo: Conceptualization, data curation, formal analysis, writing-original draft. Gunnar O. Sigge:

Conceptualization, supervision, visualization, writing-review and editing. Zinash A. Belay: Conceptualization, Supervision, methodology, validation, writing-review and editing. Ayodeji B. Oyenih: Methodology, Resources, validation. Oluwafemi J. Caleb: Conceptualization, validation, project administration, supervision, and writing-reviewing and editing.

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Data Availability Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Conflict of Interest The authors declare no competing interests.

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