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Impact of electrolyzed water as pre-treatments on drying properties and total colour difference of fresh-cut 'Tommy Atkins' mangoes

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ABSTRACT

Mango fruits are a rich source of nutrients, however, due to their perishability and seasonality, minimal processing and drying offer the potential ensure a shelf stable and safe product. The use of sodium metabisulphite (SMB) as pre-treatment in the dried fruit industry has been widely adopted, but sulphite residue remains a health public concern. Therefore, this study investigated the effects of alkaline and acidic electrolyzed water (AIEW and AEW, mg/mL) as alternative pre-treatments to SMB (1% w/w) for 'Tommy Atkins' mango slices prior to hot air drying at 60 °C. Fresh-cut and untreated samples were used as a control. During the drying process the weight of the slices were monitored every 60 min for 10 h, which was used to calculate moisture ratio (MR), drying rate (DR), and the experimental data of the samples were subjected to eight thin layer models. Colour parameters (L^*, a^*, and b^*) were measured, and use to determine colour intensity (C^*), hue angle ($h°$), and total colour difference (TCD) before and after drying. Based on measured weight, continuous decline in *MR* was recorded for all dried mango slices over the drying time irrespective on treatment. Out of the eight applied thin layer models Henderson & Pabis and Logarithmic were the best appropriate models describing and predicting the drying behavior of 'Tommy Atkins' mangoes ($R^2 = 0.94$, $RMSE \geq 0.0006$). Samples treated with AEW treated samples had lowest L^*, $h°$, and TCD values ($p < 0.05$). No significant different were found in $h°$ values amongst all pre-treated and dried samples ($p > 0.05$), but these samples were significantly different from dried untreated (control) and fresh samples ($p < 0.05$). Pre-treatments maintained the visual quality of dried 'Tommy Atkins' mango slices; SMB > AIEW > AEW > untreated (control). This study provided science-based evidence for the application of acidic and alkaline electrolyzed water as an alternative pre-treatment to sodium metabisulphite for the drying of 'Tommy Atkins' mango.

1. Introduction

Mango (*Mangifera indica* L.) fruit belongs to the Anarcadiaceae family. It grows in tropical and subtropical climates, but it is native

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to southern Asia. The cultivar 'Tommy Atkins' is considered as one of the most desired, due to its preferred colour, great productivity with acceptance in the market worldwide, and satisfactory postharvest storage potential [1]. It is rich in antioxidants, carotenoids such as provitamin A, β-carotene, and lutein, as well as other health promoting benefits [2]. Considering that mango value increases during off-season and the produce have a limited storage life, drying offers the opportunity to solve the challenge of post-harvest losses of the fresh fruit and maintain essential nutritional benefits. This adds value and fetch higher prices than the fresh samples, therewith improving the livelihood of smallholder farmers.

Drying as a preservation technique is suitable to extend the storage life of minimally processed fresh produce, by removing its free available moisture content, which minimizes impact of natural senescence and spoilage microorganisms [3]. Drying involves the simultaneous heat and mass transfer, during this process water is transferred from the core of the food material to the air-food surface interface via diffusion, and from the air-food interface into the surrounding atmosphere by convection [4–7]. Furthermore, moisture content is removed to certain limit in the food product, which prohibits microbial growth [8]. Moreover, drying controls the product quality, influences the moisture content and alters some physical (viscosity, hardness and colour), biological (enzymatic and microbial activity), and chemical (aroma, flavor, and palatability) properties of the product [9,10].

Bright colour fleshed fruit (like mango) rapidly darkens after cutting and prolonged exposure to air. This rapid darkening could include maillard reaction, caramelization, and the oxidation of ascorbic acid [11]. Hence, the use of pre-treatments that prevent the browning/darkening of fruit tissue is recommended. Sulphite dipping or sulphuring and salt solutions have been applied as chemical pre-treatments on fresh-cut fruit samples before drying [12,13]. Drying temperature is one of the fundamental factors that affects the physical, chemical, and drying properties of the product [14]. Kinetics of drying describe the behavior (macroscopic and microscopic mechanisms of heat and mass transfer) during the process of drying [14,15]. Moreover, understanding drying kinetics via the use of mathematical models enables the optimization of the fruit drying process to establish the most suitable drying conditions [15].

Study by Adepoju et al. focused on effects of pre-treatments (ascorbic acid dip at 31% (w/v), honey dip at 20% (v/v) and steam blanching at a temperature of 120 °C) and three drying methods (solar, sun and oven) on quality attributes of dried mangoes [16]. The authors showed that none of the pre-treatments influenced the drying rate, but the honey pre-treatment combined with sun drying retained highest vitamin C and β-carotene. Similarly, Nyangena investigated the impact of different pre-treatments (citric acid, lemon juice and blanching) on the physical quality attributes of dried 'Apple' and 'Ngowe' mango chips [17]. Authors demonstrated that the samples pre-treated with 1% citric acid and 0.5 v/v lemon acid best retained colour parameters and rehydration characteristics. Furthermore, thin layer drying models have been successfully applied to describe the kinetics properties and the influence of different thermal air-drying methods on quality of mango slices [18]. However, based on the available literature, there are no studies on the comparative investigation of acidic electrolyzed water (AEW) and alkaline electrolyzed water (AlEW) as pre-treatments as well as alternative to sodium metabisulphite (SMB) for minimally processed 'Tommy Atkins' mango.

Therefore, the hypothesis for this study was that the use electrolyzed water as pre-treatment would improve drying rate and better retain dried the colour 'Tommy Atkins' mango fruit compared to SMB (the standard industry practice) and untreated control. To test this hypothesis, two research objectives were set; (i) to evaluate the drying kinetics of pre-treated (with EW and SMB) fresh cut 'Tommy Atkins' mangoes by applying thin layer drying models, and (ii) to investigate the effects of the pre-treatments (EW and SMB) and hot air drying on the colour retention of dried 'Tommy Atkins' mango slices.

2. Materials and methods

2.1. Plant material

Freshly harvested, fully ripe 'Tommy Atkins' mangoes were obtained for processing at maturity stage 5 (with ≈95% pulp colouration, total soluble solids (TSS, ±15.45 °Brix), titratable acidity (TA, ±0.53 mg/100 g), and pH = ± 5.1 ($n = 10$)) from a fresh fruit retail market in Stellenbosch, Western Cape, South Africa. The fruit were transported to the Agricultural Research Council (ARC) Infruitec-Nietvoorbij, Agro-Processing Pilot Plant, Stellenbosch, South Africa. Damaged or decayed mango fruit were discarded, and good quality samples were cleaned with tap water to remove dust and other organic matters. Samples were allowed to air dry for 2–3 h and wiped with clean tissue paper. Thereafter, mangoes were minimally processed with a sharp sterile stainless-steel knife and sliced into pieces approximately 8 mm thick.

2.2. Pre-treatments and drying

Electrolyzed water was generated in-house as described by Nyamende et al. [19] and Belay et al. [20]. Fresh-cut mango slices were divided into four batches based on the total dipping pre-treatment steps before drying and corresponding to the following treatments: (a) slices were dipped for 10 min, in acidic electrolyzed water (AEW, using KCl) solution (200 mg/mL); (b) slices were dipped for 10 min, in alkaline electrolyzed water (AlEW, using NaCl) solution (200 mg/mL); (c) slices were dipped, in 1% SMB (10 g/kg) solution for 2 min (to mimic stand industry practice); and (d) non-treated samples as control. All samples were drained well after pretreatment and placed on trays for drying (Fig. 1).

An in-house dehydrator tunnel was used for the drying experiments at the ARC Infruitec-Nietvoorbij, Agro-Processing Pilot Plant laboratory. The dehydrator was fitted with temperature and airflow velocity regulators. The drying tunnel contained carriers for trays with mango fruit samples. All the samples (treated and non-treated) were arranged in a single layer. Drying experiment was carried out at air temperature (60 °C) for 10 h according to previous method described by Zhang et al. and McLoughlin et al. with slight modification using an in-house design dehydrator with the air flow of 49.50 Hz, and relative humidity (RH) of 35% [21,22]. During drying,

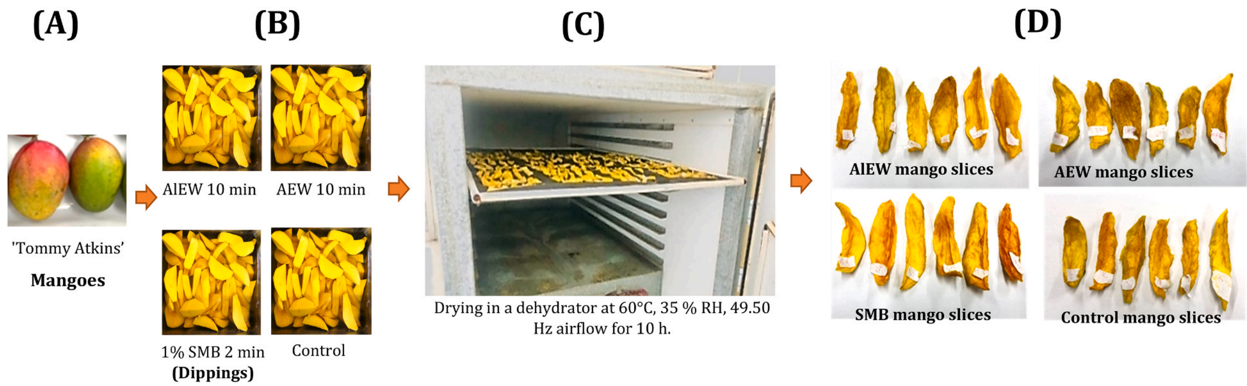

Fig. 1. Annotation illustrating the drying process followed for whole fresh 'Tommy Atkins' mango (A), fresh cut samples pre-treated by dipping in alkaline electrolyzed water (AlEW), acidic electrolyzed water (AEW), sodium metabisulphite (SMB) and untreated (control) (B), drying oven set at 60 °C for 10 h (C), and the final dried slices (D).

the weights of mango slices were measured at intervals of 60 min for 10 h using a laboratory scale (Labotech Precision Toploader, China). Drying experiments were performed in triplicate and repeated six times for each treatment batch ($n = 18$) and the average data was calculated. After drying, the samples were cooled to room temperature for 15 min and packed in airtight glass containers for colour assessment purposes [23]. Samples were kept in clear zip-lock polyethylene bags stored under dark and cool conditions (15 °C ± 0.85, under 50–65% RH) for 18 months [24]. Afterwards, samples treated (10 g) with SMB were crushed for sulphur dioxide analysis using a modified Monier Williams method, based on acidimetric determination approach. Sulphur dioxide undergoes oxidation to sulphuric acid using phosphoric acid (60%) and water steam received in a hydrogen peroxide solution (6%) and then, quantified titrimetrically with sodium hydroxide (0.05 N) using methyl red (0.1%) as indicator in alcohol until a yellow colour is reached [25,26].

2.3. Mathematical modeling of drying kinetics

Weight of mango slices was recorded for ten separate occasions at an hourly interval. Moisture content can be calculated by using the different masses obtained after weighing from the following equation (1) [27]:

$$Moisture\ content\ (M) = \frac{M(w) - M(d)}{M(w)} \tag{1}$$

where M (w) is the mass of fruit on a tray at instant t, M (d) the corresponding dry mass, and M, mango slice's moisture content in dry basis (db) (kg_{water}/kg_{dm} d.b).

Dimensionless moisture ratio was determined using equation (2):

$$Moisture\ Ratio = \frac{X - Xeq}{X_{0-Xeq}} \tag{2}$$

X is the average moisture content of the product, X_0 the initial moisture content, X_{eq} the equilibrium moisture content [28,29], and the X_{eq} was assumed as zero [30]. Hence, the X_{eq} was considered negligible and equation (2) becomes the following equation (3) [28]:

$$Moisture\ Ratio = \frac{X}{X_0} \tag{3}$$

Consequently, the development of equation (3) becomes the following equation (4):

$$Moisture\ Ratio = \frac{M(t)}{M_i} \tag{4}$$

where $M_{(t)}$ and M_i represent weight (kg) of fruit at instant time (t) and initial instant, respectively.

Equation (4) was used to determinate the moisture ratio during this experiment. The experiment was stopped after 10 h of drying, and the moisture content used for drawing kinetics were the mean values of moisture content of six replications.

Based on the experimental moisture loss data the drying rate was calculated using equation (5):

$$Drying\ rate = \frac{M_O - Mt}{t2 - t1} \tag{5}$$

where Mo refers to initial moisture content (kg water kg d/b), M_t accounts for moisture content at a given time in dry weight basis (kg water kg d/b), and t is the sampling time interval.

To describe the drying behavior of horticultural commodities several mathematical models have been applied. Eight types of thin layer drying models that describe drying curves were fitted using non-linear regression analysis to find the most suitable model [31]. Semi-theoretical drying models are best applicable between theory and application. These include the Henderson and Pabis, Lewis, Page, and Logarithmic and Midilli Kucuk models, which were represented by equations (6)–(10), respectively [32]. These models resulted from the simplification of general series solution of Fick's second law and are only effective when temperature, relative humidity, air velocity and moisture within the drying conditions for which the models are established [33]. Henderson and Pabis thin layer model was developed and applied to describe the internal resistance to moisture transfer [33]. On the other hand, Lewis model describes the variation of moisture content during the falling rate period as a function of the instantaneous difference between the moisture content and the predictable moisture content equilibrium using drying air for permeable hygroscopic produces. During this process, the product to dry is thin, the air velocity is high, while both temperature and RH are constant [34]. The Page model was designed as a modification of Lewis model for precision. This was obtained with the addition of a dimensionless empirical constant (***n***) [35]. The Logarithmic model was proposed by Chandra and Singh, which has similarities to the Henderson and Pabis model with an empirical term addition and was originally applied to dried laurel leaves [36,37]. Similarly, Midilli Kucuk model was designed to modify the Henderson and Pabis model by adding extra empirical terms [38], as listed below:

$$\text{Henderson and Pabis}: MR = \text{a} \exp - kt \tag{6}$$

$$\text{Lewis}: MR = \exp(-\text{kt}) \tag{7}$$

$$\text{Page}: MR = \exp -kt^n \tag{8}$$

$$\text{Logarithmic}: MR = a \exp(-kt) + c \tag{9}$$

$$\text{Midilli Kucuk}: MR = a \exp(-kt^n) + bt \tag{10}$$

Furthermore, the empirical models such as Wang and Singh, Aghbashlo et al. and Verma et al. presented in equations 11–13 are used to describe correlation between average moisture content and drying time through regression analysis [32]. Both semi-theoretical and empirical models are considered as external resistance to moisture transfer between product and air [39]. The following models were applied to the experimental data:

$$\text{Aghbashlo et al.}: MR = \exp\left(-\frac{k_1 t}{1 + k_2 t}\right) \tag{11}$$

$$\text{Verma et al.}: MR = a \exp(-kt) + (1 - a)\exp(-gt) \tag{12}$$

$$\text{Wang and Singh}: MR = 1 + at + bt^2 \tag{13}$$

MR = moisture ratio, k, k_1, k_2, a, b, c, n, and g = drying constants, t = drying time [32,38,40–45]. Instead of using the moisture ratio, weighted samples were used in the equation. Values of correlation coefficient (R^2) and the root mean square error (RMSE) were used for model validation [46].

Concerning the fitting steps, the non-linear regression analysis was carried out to fit equations (6)–(13) presented to the experimental data and to determine the coefficients of the equations and statistical test parameters. This includes the coefficient of correlation represented by R^2, and the root mean square error, *RMSE*. The goodness of fit for the best model which describes the thin layer drying of mango slices was chosen according to the higher R^2 and the lower RMSE values were calculated using the following formula [32]:

$$R^2 = \frac{\Sigma_{i-1}^{N}\left(MR_i - MR_{pre,i}\right) \bullet \Sigma_{i=1}^{N}\left(MR_i - MR_{exp,i}\right)}{\sqrt{\left[\Sigma_{i=1}^{N}\left(MR_i - MR_{pre,i}\right)^2\right] \bullet \left[\Sigma_{i=1}^{N}\left(MR_i - MR_{exp,i}\right)^2\right]}} \tag{14}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2} \tag{15}$$

$MR_{exp,i}$ experimental moisture ratio, $MR_{pre,\,i}$ predicted moisture ratio, N number of observations and z, number of drying constants.

2.4. Colour

Colour measurements were taken on opposite sides of each mango fruit slice before, during and after hot air drying at given time intervals using a Minolta Chroma Meter (CR-400, Minolta Corp., Osaka, Japan). Six slices of dried samples were evaluated for each drying regime. Two colour measurements were taken on opposite sides of mango slices ($n = 12$). Based on measured colour parameters L^*, a*, and b*, colour intensity C^*, hue angle $h°$ that denotes the qualitative attribute of colour shades and the total colour difference between the fresh and the dried mango slices were calculated using equations (16)–(18):

$$C^* = \left(a*^2 + b*^2\right)^{½} \quad (16)$$

$$h^\circ = arctan\ (b*\ /\ a*) \quad (17)$$

$$TCD\ (\Delta E) = \sqrt{\left(L_0^* - L^*\right)^2 + \left(a_0^* - a^*\right)^2 + \left(b_0^* - b^*\right)^2} \quad (18)$$

where L^*_0, a^*_0 and b^*_0 are the colour parameters of the fresh cut mango fruit, while L^*, a^* and b^* are the colour values of the dried mango slices [47].

2.5. Statistical analysis

Data were analyzed using one-way analysis of variance, and mean values were tested using Fisher's LSD test at a level of significance of 95%. All data analyses were carried out using Statistica software (vr. 13, TIBCO-StatSoft Inc., Tulsa, OK, USA). The data obtained were presented as means ± standard error.

3. Results and discussion

3.1. Moisture ratio/content of 'Tommy Atkins' mango fruit

Fig. 2 presented, the moisture ratio versus drying time of 'Tommy Atkins' mango slices dried at 60 °C. Moisture of mango fruit was significantly influenced by the pre-treatments and the drying duration ($p < 0.05$). Moisture ratio of mango samples decreased continuously from initial value of 1% d.b at time 0–0.09% d.b, 0.14% d.b, 0.12% d.b and 0.17% d.b for AEW, AlEW, SMB, and control, respectively at drying time 10. The observed reduction of MR indicated that the internal mass transfer was caused by the water vapour pressure deficit between the fruit tissue centre and surface [10]. This implies that during the drying process, the heat was transferred from the surface of mango slices towards the inner part of the fruit, which increased the vapour pressure. This is also explained by the increasing energy of the water molecules during drying process, having the ability to escape easier and faster. Moreover, the decrease in the *MR* of samples treated both with electrolyzed water and sodium metabisulphite could be explained by slight rise from the slices temperature to drying temperature which enhances the migration of water vapour from mango slices to ambient air [10].

Fruit processing which includes cutting generally leads to a significant decline in *MR*, because the surface area for mass transfer is greater in the minimally processed fruit in comparison to the whole fruit [48]. According to Talens et al. the heat generated during the hot air-drying process, is transported from the surrounding air of the product into the core resulting in a slower diffusion of heat transfer occurred, which slows down the water migration [49]. The results observed in our study agree with the reports of Jokić et al. [50]. The air-drying temperature used in our study caused a greater slope of the moisture. Studies by Lopez et al. revealed that moisture removal from fresh produce occurs from the centre to the surface of the material followed by the surface to the environment which is parallel to the diffusion of moisture [51]. This process leads to a decrease of relative humidity on the surface material, promoting surface evaporation during drying [51].

Also, during the drying process, surface evaporation rates improved, which accelerates moisture diffusion from the centre to the surface. These findings were in agreement with another study that found that increase in the air drying temperature was responsible for the shorter drying time [52] in fresh produces. Furthermore, to date, no studies have investigated the effects of electrolyzed water on the drying kinetics of dried fruit slices. The decline in MR as the drying progresses in this study is corroborated by other studies in

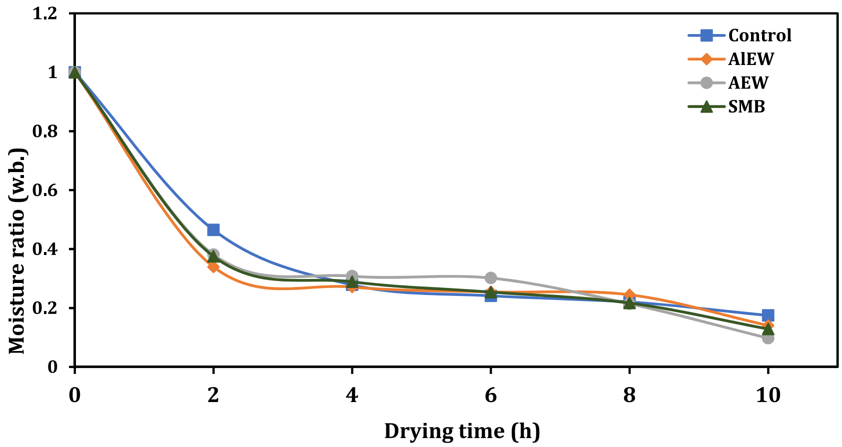

Fig. 2. Moisture ratio of mangoes cv. 'Tommy Atkins' pre-treated with sodium metabisulphite (SMB), acidic electrolyzed water (AEW), alkaline electrolyzed water (AlEW) and dehydrated at 60 °C.

literature studies such as the drying of garlic [53], carrot [54], eggplants [55], fresh 'Washington' potatoes and 'Australian' carrots [56]. Ramesh et al. [57] demonstrated during the drying of 'Kalocsa 622′ paprika berries at 60 °C, in a laboratory scale crossflow dryer that considerable amount of heat was transferred to the tissue surface, while another portion of heat circulates towards the core of the fruit. The remaining heat energy is then employed in moisture evaporation from the product surface.

Similarly, in our experiment, *MR* decreased for all treated and untreated dehydrated mango slices throughout the drying process. Studies conducted by Schiffmann [58] revealed that convective hot air could be effective in getting rid of free water close to the surface of the sample. Thus, thin layer drying and moisture movement within biological material or food produce is governed by diffusion as described by Fick's second law of diffusion [59]. Overall, the moisture ratio of dehydrated 'Tommy Atkins' mango slices could be credited to the moisture evaporation via convective drying from the surface of the samples.

3.2. Drying rate

Experimental drying rate (DR) of 'Tommy Atkins' mango pre-treated with acidic and alkaline EW and SMB is presented in Fig. 3. During the initial period of drying from 0 to 2 h, the DR was decreased from the initial value of 1.0 g/h at time 0–0.30 g/h for AEW, 0.33 g/h for AlEW, SMB 0.31 g/h and 0.26 g/h control sample). This drying phase is regarded as the falling rate period. This first falling rate period occurs when the drying rate declines as the proportion of surface areas is no longer saturated with moisture [29]. The pre-treated samples had slightly higher drying rate compared to the untreated mango slices. Moreover, during drying, no constant rate period was recorded. Furthermore, the results showed a continuous increase in drying rate as the time progresses from 2 h to 10 h in all samples treated with AEW (from 0.30 to 0.05 g/h), AlEW (from 0.33 to 0.05 g/h), SMB (from 0.31 to 0.04 g/h) and the untreated (control) sample (from 0.26 to 0.02 g/h).

Fresh produce dries in constant rate and subsequent falling rate periods and stops after reaching the equilibrium. During the drying period, the dominant diffusion mechanism is the surface diffusion and some factors such as the physical form of product, the relative humidity, the drying temperature and air velocity and the direction of air flow play an essential role. Moreover, during the drying process, moisture is transported from the inside of the solid to the surface through capillary forces and drying rate may still be constant until the critical moisture content has been reached with evidence of appearance of dry spots on the surface implying decrease in moisture. This period explains clearly the first falling rate and unsaturated surface drying begins. The drying rate falls while the rate per unit wet solid surface area remains constant [60]. In this drying period, liquid diffusion occurs. After evaporation of the surface film of the liquid, the subsequent falling rate period start where the dominant diffusion mechanism occurring is known as vapour diffusion [61]. Agricultural products usually have a high moisture content; therefore, no constant rate period is seen in the drying processes [62].

In the second falling rate period, the movement of internal tissue moisture controls the drying rate of mango samples during that period regarded. The same pattern was observed for 'Dasehari' mangoes pre-treated by blanching in 1% potassium metabisulphite solution and dried at 60 °C and drying occurred in falling rate period via diffusion with internal mass transfer to the surface [63]. The authors also confirmed no constant rate period was observed. Furthermore, the air temperature played a crucial role during drying of raw 'Dasehari' mango slices [63]. A study by Doymaz [64] on the drying of apricot samples pre-treated with potassium metabisulphite and alkaline ethyl oleate solutions at 55 °C revealed that the prevalent mechanism governing moisture movement was diffusion. In another study the authors defined internal diffusion as the process liable for the moisture loss during drying [29,65]. In this study, the pre-treatments slightly increased the drying rate in comparison to the untreated (control) samples.

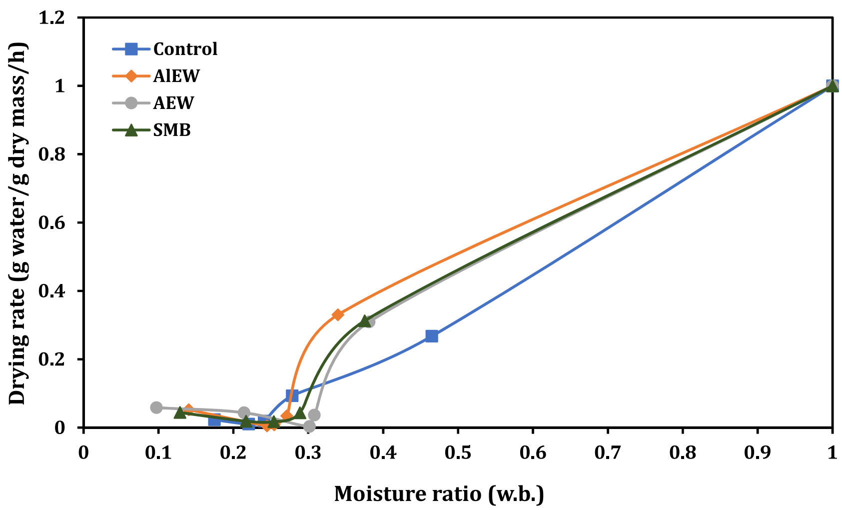

Fig. 3. Drying rate of mangoes cv. 'Tommy Atkins' pre-treated with acidic electrolyzed water (AEW), alkaline electrolyzed water (AlEW), sodium metabisulphite (SMB) and dehydrated at 60 °C.

3.3. Fitting of drying curve

Moisture ratio data for the dehydrated 'Tommy Atkins' mango slices were fitted into the Lewis, Page, Henderson & Pabis, Logarithmic, Aghbashlo et al. Verma et al., Midilli-Kucuk, Wang & Singh models. Using non-linear regression approach various model parameter values were obtained, and the correlation coefficient (R^2) and the root mean square error (RMSE) obtained are presented in Tables 1–4. It can be demonstrated that the models derived from Fick's second law including the Logarithmic as well as Henderson and Pabis models can adequately describe drying curves of 'Tommy Atkins' mango dried slices compared to previous studies [66,67]. In our study, most suitable model(s) describing the thin-layer drying characteristics of untreated and pre-treated 'Tommy Atkins' mango was based on the highest R^2 and lowest RMSE values. Thus, Henderson & Pabis model, and Logarithmic model were the most suitable with R^2 values greater than 0.90. The values of drying constant of k, coefficients of an as shown in Table 1 for the Logarithmic model ranging from 0.8000 to 0.8002, and 19.6707 to 27.2497, respectively for all treatments. The k parameter, described as a kinetic parameter, is considered as a pseudo-diffusivity [68]. According to Ah-Hen et al., the k coefficients could be related to the ease of moisture removal from the sample, and its values are related to effective moisture diffusivity [69]. The fitting procedure indicated that the results obtained from the Henderson & Pabis and Logarithmic models could be used to model the drying behavior of 'Tommy Atkins' mango slices and to estimate the moisture content at any time with hot air at 60 °C with an acceptable accuracy. Similar results were observed by Doymaz for 'Hacihaliloglu' apricots where the logarithmic model gave the highest values of R^2 and the lowest values of RMSE [64]. Contrarily to this study, the experimental results obtained by de Medeiros et al. after pre-treating 'Tommy Atkins' mango fruit slices in two stages showed that the two-term exponential model was most suitable with high R^2 value [67]. The differences observed could be related to the pre-treatment, which influenced the R^2 values. Moreover, Kabiru et al. revealed that Page model adequately illustrated the drying behavior of mango slices (constant thickness) dried at 60, 70 and 80 °C with R^2 value of 0.990 in comparison to Henderson & Pabis, Newton, and Modified Page [70]. In another study, among all the six thin-layer drying models, the Page model also sufficiently described the drying behavior of raw pre-treated (1% potassium metabisulphite solution) 'Dasehari' mango slices dried at 55, 60 and 65 °C [63]. The graph representing each model with each treatment is shown in Supplementary-Figs. 1–4 for AEW, AlEW, and SMB treated samples, as well as the untreated (Control). These figures shows the comparison of the experimental and predicted moisture values by the different models. The consistency of the model and relationship between the coefficients and drying variables was evident with the R^2.

3.4. Colour

Colour is one of the essential characteristic traits for consumers and fruit processing industry [71]. It is a measure of quality deterioration in fruit subjected to thermal processes [72]. In this study, changes observed visually are summarized in Fig. 4. Measured and calculated colour parameters of fresh and dried mango slices 'Tommy Atkins' at different stages are presented in Table 5. Dried mango samples pre-treated with AEW, AlEW and SMB were significantly different in L^* value compared to the fresh-cut samples ($p < 0.05$). Samples treated with SMB showed highest stability (65.1 ± 0.09) compared to AEW (61.6 ± 0.19), AlEW (63.1 ± 0.11) and untreated control (63.7 ± 0.85) treatments after 10 h of drying. The low L* value in the untreated dried mango slices at the end of storage could be attributed to the occurrence of enzymatic and non-enzymatic browning [73]. Thanimkarn et al. [74] demonstrated in their study that the maillard reaction, which is a non-enzymatic browning reaction, was inhibited during the drying temperature. Various studies have described a positive correlation between declining L^* values and enhanced browning in food products [75,76]. However, the major cause of colour changes (from the typical mango yellow orange to slightly bleached) under AEW-treated samples with the lowest L^* and ΔE, could be attributed to low level of pH, high ORP, and free available chlorine content of the treatment. This resulted in slightly bleached mango tissue colour.

Furthermore, a^* values for pre-treated samples were significantly higher than the untreated (control) fresh-cut mango ($p < 0.05$). Among all the treatments applied, the fruit treated with SMB indicated a higher a^* value (3.4 ± 0.79) compared to the AEW (3.3 ± 0.85) which were higher than the AlEW (2.3 ± 0.13) treatment. Studies by Pott et al. [77] indicated that increased redness of dried 'Kent' mango was associated with the intensive browning, which was undesirable. Another study revealed that darkening in samples could be associated with oxidative reactions catalyzed by enzymes peroxidase and polyphenoloxidase, which transform quinones to a dark-colour pigment called melanin [78].

Pre-treatments applied had no significant effect on the yellowness of dried mango slices, as no significant difference was observed in the b^* value ($p > 0.05$). However, pre-treatments had significant impact on hue angle ($h°$) values for the mango slices ($p < 0.05$). Highest $h°$ values (91.2 ± 1.19) were recorded in the control samples (Table 5). Chroma (C^*) values were not influenced by the type of pre-treatment applied. However, at the end of drying C^* value was significantly different from the fresh-cut samples ($p > 0.05$). Higher C^* values were recorded in samples pre-treated with SMB (57.6 ± 1.15) followed by control (57.0 ± 1.19), AlEW (56.7 ± 1.38) and AEW (55.8 ± 1.34) pre-treated samples ($p < 0.05$). According to literature, high C^* values indicate a better retention of colour [79]. The result in this study suggests that SMB pre-treatments before drying led to better colour retention in dried mango slices. Similar research findings on the retention of colour for dried peppers soaked in SMB prior to drying were reported by Sigge et al. [80]. Logarithmic and Henderson and Pabis model gave better co-relation between the moisture content and drying time, during which, the product to dry is thin, the air velocity is high, while both temperature and RH are constant [34]. Therefore our results showed that the models provided a good fitness of colour degradation of mango.

For total colour difference (ΔE), relatively high values were recorded for untreated samples (15.4 ± 2.48) as compared to AEW (11.5 ± 3.23), AlEW (12.4 ± 4.75) and SMB (12.8 ± 5.35) treated samples. Total colour difference is used to classify differences in colour perception. Overall, for all dried samples ΔE significantly increased ($p < 0.05$) in comparison to the fresh-cut mangoes. The

Table 1
Curve fitting criteria for eight mathematical models and parameter for 'Tommy Atkins' mango slices pre-treated with AEW and dehydrated at 60 °C.

Parameters	Mathematical models							
	Lewis	Page	Verma et al.	Midilli-Kucuk	Henderson & Pabis	Logarithmic	Wang and Singh	Aghbashlo et al.
k	0	0	0.8008	1.8311	0.8001	0.8001	NA	NA
K_1	NA	NA	NA	NA	NA	NA	NA	1.2221
K_2	NA	NA	NA	NA	NA	NA	NA	1.3344
a	NA	NA	19.6915	19.6688	19.6707	19.6707	1	NA
b	NA	NA	NA	0	NA	NA	2	NA
c	NA	NA	NA	NA	NA	NA	NA	NA
n	NA	0.5370	NA	75.9711	NA	NA	NA	NA
g	NA	NA	11.8672	NA	NA	NA	NA	NA
R^2	0.8878	0.8878	0.2389	0.4286	**0.9415**	**0.9415**	0.8878	0.8511
RMSE	6.4800	6.4800	5.9039	2.1961	**0.0015**	**0.0015**	6.4800	6.4672

Table 2
Curve fitting criteria for eight mathematical models and parameter for 'Tommy Atkins' mango slices pre-treated with AlEW and dehydrated at 60 °C.

Parameters	Mathematical models							
	Lewis	Page	Verma et al.	Midilli-Kucuk	Henderson & Pabis	Logarithmic	Wang and Singh	Aghbashlo et al.
k	0	0	0.8002	1.8312	0.8000	0.8000	NA	NA
K_1	NA	NA	NA	NA	NA	NA	NA	1.2160
K_2	NA	NA	NA	NA	NA	NA	NA	1.3493
a	NA	NA	22.0840	22.0789	22.0800	22.0800	1	NA
b	NA	NA	NA	0	NA	NA	2	NA
c	NA	NA	NA	NA	NA	0	NA	NA
n	NA	0.6876	NA	75.9711	NA	NA	NA	NA
g	NA	NA	11.8672	NA	NA	NA	NA	NA
R^2	0.8878	0.8878	0.2283	0.4286	**0.9415**	**0.9415**	0.8878	0.8511
RMSE	7.3299	7.3299	6.6660	2.4647	**0.0018**	**0.0018**	7.3299	7.3120

Table 3
Curve fitting criteria for eight mathematical models and parameter for 'Tommy Atkins' mango slice pre-treated with sodium metabisulphite and dehydrated at 60 °C.

Parameters	Mathematical models							
	Lewis	Page	Verma et al.	Midilli-Kucuk	Henderson & Pabis	Logarithmic	Wang and Singh	Aghbashlo et al.
k	0	0	0.8001	1.8312	0.8002	0.8002	NA	NA
K_1	NA	NA	NA	NA	NA	NA	NA	1.2207
K_2	NA	NA	NA	NA	NA	NA	NA	1.3377
a	NA	NA	20.1659	20.1689	20.1697	20.1697	1	NA
b	NA	NA	NA	0	NA	NA	2	NA
c	NA	NA	NA	NA	NA	0	NA	NA
n	NA	0.6876	NA	75.9711	NA	NA	NA	NA
g	NA	NA	11.8672	NA	NA	NA	NA	NA
R^2	0.8878	0.8878	0.2364	0.4286	**0.9415**	**0.9415**	0.8878	0.8511
RMSE	6.6557	6.6557	6.0620	2.2503	**0.0007**	**0.0007**	6.6557	6.6418

Table 4
Curve fitting criteria for eight mathematical models and parameter for untreated 'Tommy Atkins' mango slices and dehydrated at 60 °C.

Parameters	Mathematical models							
	Lewis	Page	Verma et al.	Midilli-Kucuk	Henderson & Pabis	Logarithmic	Wang and Singh	Aghbashlo et al.
k	0	0	0.8000	1.8316	0.8002	0.8002	NA	NA
K_1	NA	NA	NA	NA	NA	NA	NA	1.2051
K_2	NA	NA	NA	NA	NA	NA	NA	1.3760
a	NA	NA	27.2431	27.2499	27.2497	27.2497	1	NA
b	NA	NA	NA	0	NA	NA	2	NA
c	NA	NA	NA	NA	NA	0	NA	NA
n	NA	0.6876	NA	75.9711	NA	NA	NA	NA
g	NA	NA	11.8675	NA	NA	NA	NA	NA
R^2	0.8878	0.8878	0.2125	0.4286	**0.9415**	**0.9415**	0.8878	0.8511
RMSE	9.1546	9.1546	8.3009	3.0401	**0.0006**	**0.0006**	9.1546	9.1258

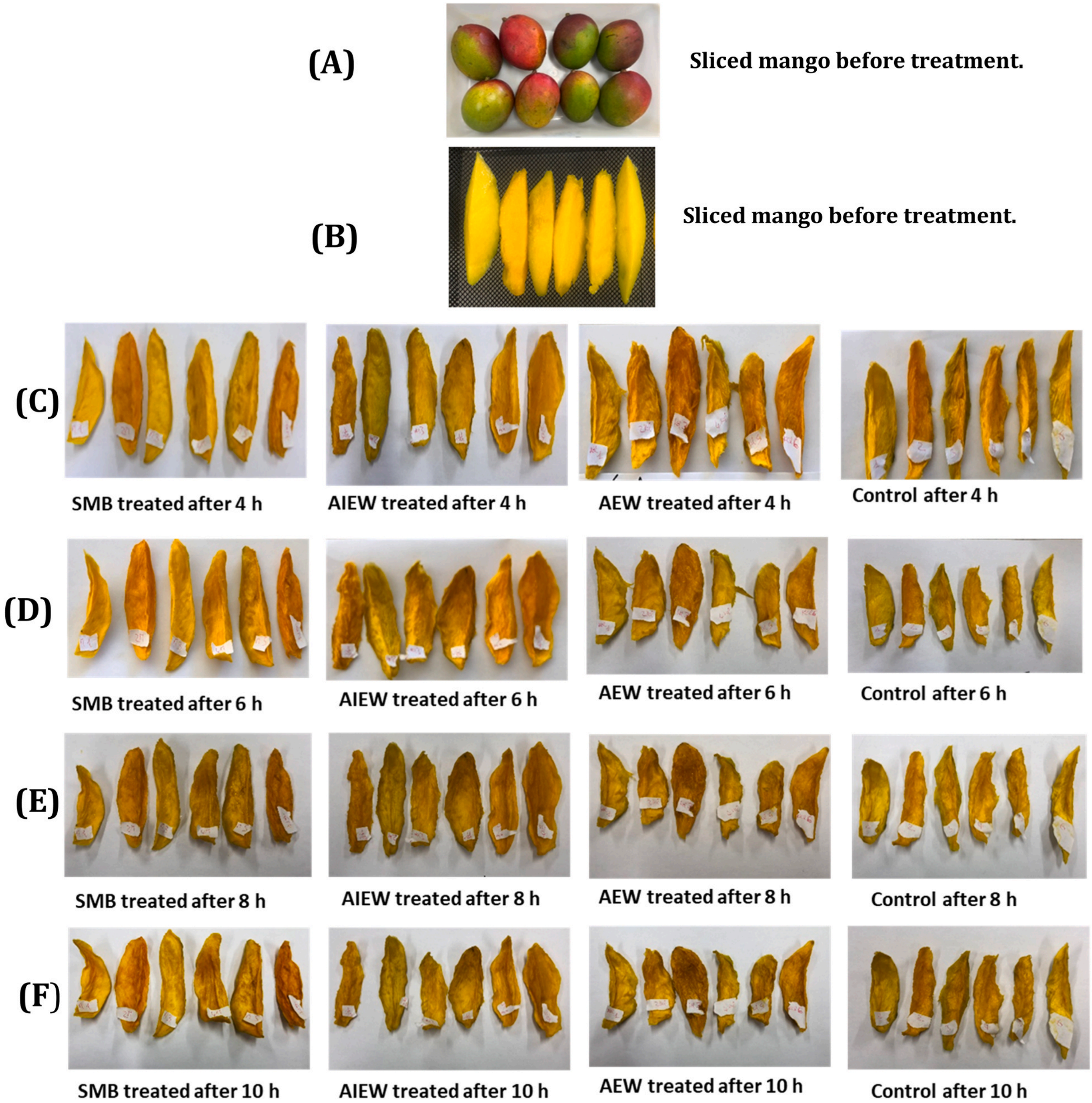

Fig. 4. Samples of 'Tommy Atkins' whole mangoes (A), fresh-cut into slices (B), and pre-treated with Sodium metabisulphite (SMB), acidic electrolyzed water (AEW) and alkaline electrolyzed water (AlEW) hot air-dried at 60 °C and captured after 4 h (C), 6 h (D), 8 h (E), and 10 h (F).

Table 5
Effects of pre-treatment and hot air drying on colour quality index of 'Tommy Atkins' mango slices and dehydrated at 60 °C.

Pre-treatment	Parameters					
	*L**	*a**	*b**	*c**	*h*°	TCD
Control untreated fresh cut 0 h	64.7 ± 1.04 A	−4.55 ± 2.47 B	53.0 ± 2.06 B	53.4 ± 1.25 B	93.4 ± 1.97 A	0
Control untreated dried 10 h	63.7 ± 0.85 A	−0.6 ± 1.11C	56.6 ± 1.23 A	57.0 ± 1.19 A	91.2 ± 1.19 A	15.4 ± 1.48 A
Treated sodium metabisulphite dried 10 h	65.1 ± 0.99 A	3.4 ± 0.79 A	57.3 ± 1.06 A	57.6 ± 1.15 A	86.6 ± 0.81 B	12.8 ± 1.35 A
Treated AlEW dried 10 h	63.1 ± 1.11AB	2.3 ± 0.93 A	56.4 ± 1.39 A	56.7 ± 1.38 A	87.8 ± 0.98 B	12.4 ± 1.75 A
Treated AEW dried 10 h	61.0 ± 1.09 B	3.3 ± 0.85 A	55.4 ± 1.36 A	55.8 ± 1.34AB	86.4 ± 0.95 B	11.5 ± 0.23 B

Data presented are means ($n = 12$) ± standard error, and different upper-case letters in columns represent significant differences ($p \leq 0.05$) in colour attributes.

changes in dried sliced mango fruit colour (yellowish orange) could be associated with the high drying temperature (60 °C). This thermal condition can induce degradation of pigments and non-enzymatic browning reactions such as the Maillard reaction [81,82]. Based on Bellary et al. [83] findings, distinct samples from visual perception are represented with a TCD corresponding to 1.50 < TCD >3 [84]. Since the changes in fruit colour can negatively influence consumer acceptance, it is important to have quantifiable matrix instead of sole depending on subjective assessment.

3.5. Sulphur dioxide content

The commercial application of sulphite-based pre-treatment agents in dried fruit is largely due to its multipurpose role: (a) as anti-browning agent effective in controlling enzymatic and non-enzymatic reactions; (b) as antioxidant agent minimizing or preventing oxidation; and (c) as preservative agent retaining the colour, flavor, and retarding the growth of spoilage microorganisms. However, excessive exposure to sulphur dioxide could lead to various allergic irritations such as eye irritation, or respiratory tract irritation that results in swelling and sore throat in patients, and in acute cases digestive system irritation cumulating in vomiting and diarrhoea [85, 86].

The Sulphur content is significantly influenced by the amount of sulphur per mass of dried produce used in the sulphurization process and exposure/contact time [87]. The established limit (i.e., maximum permissible sulphite) according to CODEX General Standard for Food Additives (CODEX STAN 192–1995) [88] for dried mangoes is 2000 mg kg^{-1}. Similarly, the European Directive 95/2/EC (1995) on food additives other than colors and sweeteners declared 2000 mg kg^{-1} as the maximum permitted concentration of sulphur dioxide (SO_2) for dried fruits. The US and Australian allows for total SO_2 concentration of 3000 mg kg^{-1} on dried fruit. However, the US Food and Drug Administration and EU mandate that foods containing more than 10 mg kg^{-1} of sulfites must be labeled as such.

In this study, at the end of storage for sliced mango samples dipped in SMS the total SO_2 concentration of approximately 50 ± 1.14 mg kg^{-1}, while EW treated were below the detection limit. Crucial to note is the sensitivity of the SO_2 determination method used at very low SO_2 concentration still requires further investigation. Overall, there was a decline in SO_2 concentration in comparison to the freshly SMB treated sliced mangoes ≈105 mg kg^{-1}. The significant reduction in SO_2 level at the end of storage could be attributed to the impact of thermal degradation of free SO_2 from the fruit tissue during oven drying and extended storage period [24,89]. Furthermore, the initial SO_2 concentration for treated 'Tommy Atkins' mango slices (≈105 mg kg^{-1}) this study was lower than that reported for 'Amrapali' sliced mangoes (≈245.4 mg kg^{-1}) by Kumar et al. [89]. This difference could be attributed to varietal differences, the initial concentration of sulphite based dipping treatment and exposure time. It is suggested that initial SO_2 in dried fruits should target maximum residue limit to ensure storability and acceptance.

4. Conclusion

This study investigated the effects of different electrolyzed water pre-treatments and standard industry practice (sodium metabisulphite) on the drying kinetics and colour of slices of 'Tommy Atkins' mango dehydrated at 60 °C using hot air oven. The resulted demonstrated that the different pre-treatments resulted different moisture ratio of 'Tommy Atkins' mango. Comparing all the models, Henderson & Pabis and Logarithmic models with $R^2 = 0.94$ were the best performing models, that sufficiently described the drying kinetics of fresh-cut 'Tommy Atkins' mangoes. The model parameters and constants offer useful guide to simulating industrial scale hot air-drying process for sliced 'Tommy Atkins' mangoes to improve drying efficiency. Furthermore, based on measured colour parameter as quality matrix, pre-treatment of 'Tommy Atkins' mango slices with sodium metabisulphite prior to drying were comparable to alkaline electrolyzed water, which performed better than the untreated (control). Overall, this emphasizes the potential of electrolyzed water as an alternative to sulphur-based pre-treatment of fresh-cut mangoes. However, future study is required on the optimization of electrolyze water treatment (such as effective dipping concentration and duration), and long-term storage conditions for dried mangoes are required.

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Author contribution statement

Loriane A. Yanclo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Zinash A. Belay: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Gunnar O. Sigge: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Oluwafemi J. Caleb: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of interest's statement

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

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Appendix A. Supplementary data

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