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Research article

Effect of gum Arabic and ethanol pretreatments on drying kinetics and quality attributes of dried carrot slices

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ABSTRACT

Carrot is an important root vegetable to the food industry and consumers due to its nutritional and health benefits. Given the high moisture content and low shelf life of fresh carrots, preserving this highly demanded vegetable is vital. This current research modelled the drying kinetics and evaluated the quality of ultrasonic-assisted gum Arabic and ethanol pretreated and oven-dried carrot slices. Fresh carrots were processed into thin slices and immersed in 3% gum Arabic (GA), ethanol (99.9%), and distilled water (control), followed by ultrasonication (frequency: 50 Hz, power: 500 W, temperature: 25 °C) for 10 min and drying in a hot air oven at 50 °C. The loss of moisture from the carrots was periodically recorded, converted to moisture ratio before fitted to eleven semi-theoretical thin layer drying mathematical models. The effects of the pretreatments on the retention of bioactive compounds and carrots' physical and chemical properties were also evaluated. From the tested models, the Diffusion, Modified Henderson and Pabis, and Two-term models showed the best fitting (R^2 = 0.9944–0.9985; RSME = 0.0103–0.0227) to the experimental data from 3% GA and ethanol pretreated carrots, while control samples followed the Aghbasho model (R^2 = 0.9999; RMSE = 0.0033). Overall, the 3% GA pretreated carrot slices exhibited better colour (yellowness: 25.82–34.50; total colour differences: 8.12–13.06), water activity (0.37–0.44), total phenolic content (1.34–2.99 mg GAE/100 g DM), β-carotene (7.63–13.07 mg/100 g DM), and DPPH radical scavenging activity (5.67–8.02 mM AAE/100 g DM) than ethanol pretreated carrot slices and control samples. At the same time, 3 % GA pretreatment did not affect the drying rate of the carrot slices. The total soluble solids/titratable acidity ratio, rehydration capacity, and shrinkage ratio did not significantly ($p > 0.05$) vary among the treatments. The findings of this study can be used to develop an optimal drying protocol for pretreated carrot slices and to produce shelf-stable carrot products that can be used dried, rehydrated, or in combination with other products.

1. Introduction

Carrot (*Daucus carota* L.) is the most cultivated root vegetable worldwide, with an estimated global annual production of 36 million tonnes (Ramos-Andres et al., 2021). It is a crucial source of phytonutrients such as vitamins (A, B, C, D, E, and K), carotenoids, minerals (sodium, calcium, phosphorus, potassium, and iron), and bioactive compounds, as well as dietary fiber (Ahmad et al., 2019). These phytonutrients provide health benefits to humans, such as anticancer, plasma lipid modification, anti-tumour, and anti-inflammatory properties (Md Saleh et al., 2020; Da Silva Dias, 2014). Fresh carrots, which contain above 86% water, are seasonal, and their physical and nutritional quality can be largely degraded by storage temperature and microbial growth (Ramjan and Ansari., 2018). In addition, during storage, the physical and sensory properties such as firmness, colour, and taste deteriorate, affecting the consumers' acceptance of the product (Molnos and Vajda, 2019). Given the perishable nature of the root crop, an appropriate method of preservation is crucial to maintain its nutritional value for better commercialisation.

Drying has been used in the past to preserve and prolong the shelf-life of foods. The removal of water has been established to be sufficient in preventing microbial proliferation and food spoilage, because these activities are inhibited below a certain moisture and water activity level. Moreso, reducing the food product volume and weight makes transport

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and storage easier. Hot air drying has remained the most popular methods of reducing the moisture content of vegetables and fruits due to its cost-effectiveness. Nevertheless, hot air drying may provoke alterations in tissue structures, colour, texture, shrinkage, chemical composition, and nutritional variations, which negatively affect the quality of dried product and consumers' acceptability (Md Saleh et al., 2020). Literature has reported that pretreatment of vegetables and fruits before drying inactivates the enzymes and enhances the drying rate, thereby minimising quality degradation (Osae et al., 2020).

The use of edible coatings as a pretreatment before drying fruits and vegetables is a novel approach that can enhance the quality of the dried product. Animal and vegetable proteins, lipids, celluloses, and gums are the most common biological sources of edible coatings (Han et al., 2005). The edible coating material forms a thin layer on the food surface, providing a selective barrier against moisture, carbon dioxide, and oxygen consequently improving the nutritional, and physicochemical properties of the dried product (Han, 2014; Rahman et al., 2020). In addition, the edible coatings can also be used as a carrier of antioxidants to improve their protective effect by inhibiting the loss of bioactive phytochemicals during the drying and storage of vegetables and fruits. Gum Arabic is a cheap, and biodegradable polysaccharide-based biopolymer obtained from mature trees of *Acacia senegal* and *Acacia seyal* (Saleem et al., 2020). Among others, gum Arabic is one of the most used biopolymers in fruits and vegetables. Alone or combined with other components the biopolymer has been used to provide an active edible packaging on various fruits and vegetables including guavas, tomatoes, plums, bananas, strawberries, avocadoes, apples, and sweet cherries (Tahir et al., 2019). In addition, gum Arabic has been successfully used as a pretreatment for dried fruits and vegetables. In a study by Lago Vanzela et al. (2013), dried pumpkin slices pretreated with an edible coating showed better retention of phytonutrients than untreated samples. Also, Eltoum and Babiker (2014) reported improved retention of colour properties and antioxidant compounds in gum Arabic pretreated and dried tomato slices. Meanwhile, the application of ethanol as a pretreatment method prior to drying has been widely reported in the literature (Wang et al., 2022).

Ethanol is easily accessible, volatile, and designated as a "Generally Recognized as Safe" (GRAS) substance (Burdock and Carabin, 2004). In addition, no residues of ethanol have been reported in ethanol pretreated and dried food products. Furthermore, in the food matrix ethanol evaporates before the water and the flow channels it creates remain as pores, which may facilitate water evaporation, improved drying, and better retention of the bioactive compounds in the dried plant material (De Freitas et al., 2021). Recently, Rojas et al. (2020) reported a lower drying time, faster rehydration capacity, and higher carotenoid retention for ethanol pretreated pumpkin slices. To enhance the edible coating effect, ultrasonication can be used to break the cells of fruits and vegetables, creating channels that improve the transfer of the coating material into the cells. Additionally, ultrasonication is included within the "Green Food Processing" concept, which refers to food processing technologies that consume less energy and water and are more sustainable and environmentally friendly (Astráin-Redín et al., 2021). Combining ethanol and ultrasonication as a pretreatment reduced the drying time of pineapple slices (De Freitas et al., 2021). Considering that pretreatment and ultrasonication have a remarkable effect on the drying process of the fruits and vegetables, modelling the kinetics of the drying process is therefore essential. Also, each food matrix has a typical structure and composition, which might affect the mass transfer from the intracellular matrix.

Understanding the drying kinetics of vegetables and fruits is vital for the drying process designing, optimisation, and control (Briki et al., 2019). Thin layer drying models can be categorised as empirical, theoretical, or semi-theoretical. Semi-theoretical models are popular and are suitable for modelling fruits and vegetables drying kinetics. These include Newton, Henderson, and Pabis, Agbashlo, diffusion, and other models (Babalis et al., 2006). In a study by Seiiedlou et al. (2010), the drying behaviour of apple slices was investigated in a thin layer hot-air dryer (temperature: 50–70 °C, air velocities: 0.6–1.8 m/s), and the Aghbashlo model was the most suitable to describe the thin-layer drying behaviour of apple slices. Sonmete et al. (2017) studied the drying kinetics of ultrasonicated (65, 75, and 85 W for 10, 20, and 30 °C) carrot slices and established that the Midilli model could be applied to predict the moisture content and drying characteristics of the carrot slices. The two-term model adequately described the drying kinetics of figs dried (55–85 °C and 0.5–3 m/s) in a tunnel dryer (Babalis et al., 2006).

Despite the current advancement in using ultrasound techniques to pretreat fruits and vegetables before drying, ultrasonication to improve edible coatings' performance in food drying is still limited. Therefore, the present study aimed (i) to model the drying kinetics of ultrasonic-assisted gum Arabic and ethanol pretreated carrot slices; and (ii) to investigate the effect of ultrasonic-assisted pretreatment with gum Arabic and ethanol on the physical, phytochemical, and antioxidant properties of oven-dried carrot slices.

2. Materials and methods

2.1. Plant material and sample processing

Fresh carrots were purchased from the local fresh produce market in Johannesburg, South Africa. Free from mechanical damage, good-quality carrots were washed, peeled, and cut into uniform slices (25mm: diameter and 5 mm: thickness).

2.2. Pretreatments and oven drying

Carrot slices (300 g) were each submerged in 250 mL 3% GA w/w (Sigma Aldrich Co., France), 99.9% ethanol (Kimix, Johannesburg, South Africa), distilled water, and sonicated in an ultrasonic bath (705, Labotec, Johannesburg, Gauteng, South Africa) (internal dimension: 500 mm × 300 mm x 150 mm) equipped with a maximum power of 600 W, and 50 Hz frequency for 10 min at 25 °C. The excess water on the carrots slices was removed by blowing using a fan for 10 min (GDF-16YA, Goldair, China). The carrots slices were oven-dried (277, Labotec, South Africa) at 50 °C, and a 1.0 m/s constant airflow rate. The hot air oven was adjusted to be the selected temperature an hour before starting the drying process to achieve the steady-state conditions. The average initial moisture content varied from 81-89% (w/w). The moisture loss of the samples was recorded at a 1 h interval until the change in moisture content was less than 8%. The initial moisture content of the pretreated carrot slices was measured using a moisture analyser (KERN DBS 60-3, Berlin, Germany) at 105 °C. The dried and cooled carrot slices were packed in clear polyethylene bags and kept at -20 °C until further analysis.

2.3. Mathematical modelling

The drying kinetics was determined based on mass losses of the pretreated (3% GA, and ethanol) carrot slices and the control samples. Respectively, moisture content (MC) and ratio (MR) were calculated using Eqs. (1) and (2) (Roy et al., 2021).

$$MC\ (\%) = \left(\frac{M_0 - M_t}{M_0}\right) \times 100 \quad (1)$$

$$MR = \frac{M_t}{M_0} \quad (2)$$

where, MC is the moisture content, M_o is the initial moisture content, and M_t is the moisture content at time t.

Different models (equations 3-13) were tested to predict the pretreated carrot slices and the control samples drying behaviour and kinetics (Table 1). The Python Software Version 3.10.0 was used to perform non-linear regression analysis and curve fitting using the selected model equations. The predicted models were evaluated based on

Table 1. Models used for the mathematical description of the oven drying (50 °C for 9 h) process of pretreated (3% gum Arabic and ethanol), carrot slices and the control samples.

Model number	Model name	Model equation	
1	Aghbashlo et al.	MR = exp [- $k_1t/(1 + k_2 t)$]	(3)
2	Diffusion	MR = aexp (−kt) + (1 − a) exp (−kbt)	(4)
3	Henderson and Pabis	MR = aexp (-kt)	(5)
4	Logarithmic	MR = aexp (-kt) + c	(6)
5	Midilli et al.	MR = aexp ($-kt^n$) + bt	(7)
6	Modified Henderson and Pabis	MR = aexp (−kt) + bexp (−gt) + cexp (−ht)	(8)
7	Modified Page	MR = exp [$-(kt)^n$]	(9)
8	Newton Equation	MR = exp (-kt)	(10)
9	Page	MR = exp ($-kt^n$)	(11)
10	Two-term	MR = aexp (-kt) + bexp ($-k_1t$)	(12)
11	Wang and Singh	MR = 1 + at + bt^2	(13)

Abbreviations: MR, moisture ratio (dimensionless); a, b, c, g, h, k_1, k_2, drying constants; t, time (min).

statistical parameters such as the coefficient of determination (R^2) and root mean square error (RMSE). The R^2 and RMSE were calculated using equations 3 and 4, respectively (Roy et al., 2021).

$$R^2 = 1 - \frac{\Sigma_{i-1}^{n}\left(MR_{exp} - MR_{pred}\right)^2}{\sum_{i-1}^{n}\left(MR_{exp} - \overline{MR}\right)^2} \quad (14)$$

$$RMSE = \sqrt{\frac{\Sigma_{i-1}^{n}\left(MR_{exp} - MR_{pred}\right)^2}{N}} \quad (15)$$

where, MR_{exp} is the experimental dimensionless moisture ratio, MR_{pre} is the predicted dimensionless moisture ratio, and N is the number of observations.

The models with the lowest RMSE value and the highest value of R^2 were considered the best-fitted model (Horecki et al., 2018).

2.4. Drying rate

The drying rate (DR) at a particular time was calculated according to Eq. (16).

$$DR = \frac{M_{t1} - M_{t2}}{t_2 - t_1} \quad (16)$$

where, t_1 and t_2 are the drying times (min) at different times during drying; M_{t1} and M_{t2} are the moisture content of samples (g min^{-1}).

2.5. Determination of physicochemical properties

2.5.1. Water activity

The water activity (a_w) was determined using a Novasina electronic dew point water activity meter CH 8853 (Lachen, Switzerland).

2.5.2. Colour

A calibrated CR-10 chromameter (Konica Minolta, Osaka, Japan) was used to measure the colour parameters yellowness (b*), lightness (L*), and redness (a*) of the carrot slices during and after the drying period. According to Adetoro et al. (2021), the total colour difference (ΔE) was calculated using Eq. (17).

$$\Delta E = \left(\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}\right)^{1/2} \quad (17)$$

where, L*, a*, and b*represent lightness, redness, and yellowness, respectively, at the hourly drying time. The L*, a*, and b* values of fresh samples were used as the control.

2.5.3. Hardness

Hardness was measured using a texture analyser (1173XX, Agrosta, Calib, France). The maximum force (N) at the first compression was recorded as hardness.

2.5.4. Shrinkage ratio

The shrinkage ratio was measured using an electronic micrometre (705–1229, RS PRO, Midrand, South Africa) with a range of 0–25 mm.

2.5.5. Rehydration capacity

The rehydration rate was measured according to Adetoro et al. (2021). Briefly, dried carrot samples (5 g) were immersed in distilled water (100 mL) at room temperature for 30 min. The water was drained, and excess water from the rehydrated carrots was removed using a paper towel. The rehydration ratio was calculated according to Eq. (18).

$$\text{Rehydration ratio} = \frac{W_t - W_d}{W_d} \quad (18)$$

Where, W_t is the weight of wet carrot slices at time t, and W_d is the initial weight of dry carrot slices.

2.5.6. Total soluble solids/titratable acidity ratio

To measure total soluble solids and titratable acidity the dried carrots were ground to fine powder using a coffee grinder under liquid nitrogen. About 5 g of the powder was dissolved in distilled water (15 mL) in triplicates. The solution was vortexed (3 min) and sonicated in a 705 ultrasonic bath (Labotec, Johannesburg, Gauteng, South Africa) (internal dimension: 500 mm × 300 mm x 150 mm) at a frequency of 50 Hz, 500W, and temperature of 25 °C for 10 min. The samples were then centrifuged (D-37520, Thermo Fisher Scientific, Stratos, United Kingdom) at 8400 Xg for 10 min. Total soluble solids (TSS, Brix %) were measured using a PT-32 refractometer (Atago, Tokyo, Japan). Titratable acidity (TA, % citric acid) was measured using a titrator (Orion Star T910, Thermo Fischer Scientific, Chelmsford, USA). In brief, 2 mL of the supernatant was diluted in 90 mL of distilled water and titrated with 0.2 N sodium hydroxide to a pH of 8.2. The TSS and TA values were used to calculate the TSS/TA ratio.

2.6. Microstructure analysis

The microstructures of pretreated carrot slices and control samples were studied using a scanning electronic microscope (SEM) (Tescan Vega 3, Borno, Czech Republic). Briefly, the samples were placed on adhesive tape and then coated with a fine layer of gold through sputter coating attachment of balzers. The coated samples were then examined at 2500X magnification.

2.7. Determination of phytochemical properties and radical scavenging activity

2.7.1. β-carotene content

In triplicate, 2 g of carrot powder (ground under liquid nitrogen) were added to a glass pill vial, and a 10 mL mixture of ethanol and hexane (1:1) containing 0.02% 2,6-di-ter-butyl-*p*-cresol (BHT) was added. The solution was vortexed, sonicated in an ultrasonic bath (705, Labotec (PTY) LTD, Gauteng, South Africa) at a frequency of 50 Hz, 500 W and temperature of 25 °C for 10 min and centrifuged (D-37520, Thermo Fisher Scientific, Stratos, United Kingdom) at 8400 Xg for 5 min. The absorbance of the samples was measured using UV spectrophotometry (SP-UV 300, Spectrum Instruments, Shanghai, China) at 470 nm under dim light

conditions. A β-carotene standard curve (0–0.01 mg/mL; $R^2 = 0.958$) was used to determine the β-carotene concentration, and the results were expressed as milligram β-carotene/100 g dry matter (mg β-carotene/100 g DM).

2.7.2. Total phenolic content

The dried carrot slices' total phenolic content was determined using the Folin–Ciocalteau reagent, according to Nurkhoeriyati et al. (2021). Briefly, 2 g of carrot powder (ground under liquid nitrogen) were mixed with 10 mL of distilled water, vortexed and then centrifuged (D-37520, Thermo Fisher Scientific, Stratos, United Kingdom) at 8400 Xg for 5 min. Each extract's supernatant (50 μL), 450 μL of 50% methanol, Folin–Ciocalteau reagent (500 μL), and 2% sodium carbonate solution (2.5 mL) were incubated in darkness at room temperature for 40 min. The absorbance of the samples was measured using a UV spectrophotometer (SP-UV 300, Spectrum Instruments, Shanghai, China) at 725 nm under dim light. A 50% methanol was used as a blank. A gallic acid standard curve (0–0.1 mg/mL; $R^2 = 0.9825$) was used, and the final results were reported as mg gallic acid equivalent per 100 g dry matter (mg GAE/100 g DM).

2.7.3. Radical scavenging activity

The radical scavenging activity (RSA) of the carrot samples was determined using the 2.2-diphenylpicrylhydrazyl (DPPH) assay, according to Adetoro et al. (2021). Triplicated samples of carrot powder (2 g) were mixed with 10 mL of distilled water. The mixture was vortexed and then centrifuged (D-37520, Thermo Fisher Scientific, Stratos, United Kingdom) at 8400 Xg for 5 min. The supernatant (15 μL) was mixed with 50% methanol (375 μL) and DPPH (750 μL), and the mixture was incubated in darkness at room temperature for 30 min. The absorbance of the samples was then measured using a UV spectrophotometer (SP-UV 300, Spectrum Instruments, Shanghai, China) at 517 nm under dim light. The RSA of the samples was calculated using the ascorbic acid standard curve (0–2.0 mM, $R^2 = 0.999$), and final results were reported as ascorbic acid (mM) equivalent per gram dry matter (mM AAE/100 g DM).

2.8. Statistical analysis

All experiments were carried out in triplicate and subjected to statistical analysis using STATISTICA (Statistica 13.0, StatSoft Inc., Tulsa, OK, USA). Data were analysed using a one-way analysis of variance (ANOVA) and the Duncan's multiple range tests was used to separate the differences between the treatment means ($p < 0.05$). All the results were expressed as mean ± standard error. The Microsoft Excel software version:16.0.13029.20344 (Microsoft Cooperation, Washington, USA) was used to produce graphs. The moisture ratio curves obtained were fitted with eleven mathematical models to describe the drying characteristics of pretreated carrot slices and control samples. The Python Software Version 3.10.0 was used to perform non-linear regression analysis.

3. Results and discussion

3.1. Drying characteristics

The change in moisture ratio (MR) versus the drying time for the control, 3% GA, and ethanol pretreated carrot slices is shown in Figure 1a. It can be observed that the MR decreased as the drying time increased. Previous studies reported similar observations of MR changes in hot air and infrared drying of pumpkin and pomegranate arils samples, respectively (Rojas and Augusto, 2018; Briki et al., 2019). The curves indicate that for the first 2 h of oven-drying, water loss was almost linear and then it steadily decreased until it reached a constant after 5 h. However, the control and 3% GA pretreated samples took longer (5 h) to

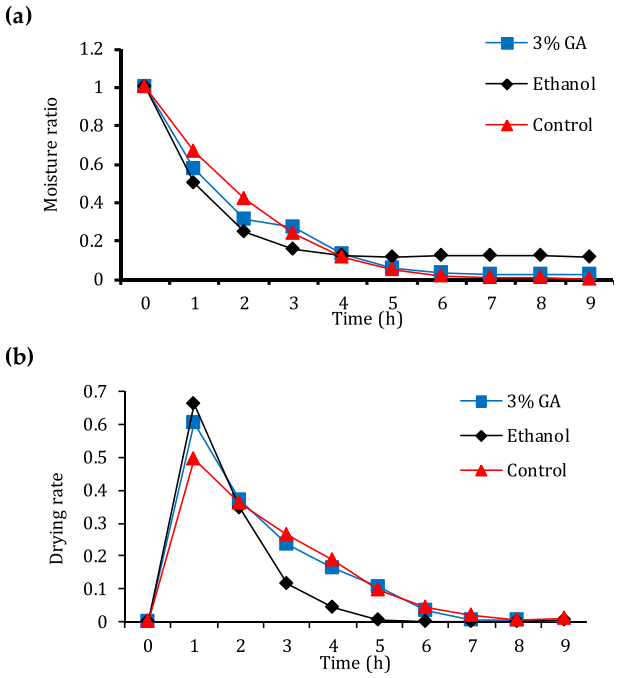

Figure 1. (a) Moisture ratio, and (b) drying rate vs. time of control, 3% GA, ethanol pretreated and oven-dried (50 °C for 9 h) carrot slices. Control samples were dipped in distilled water. GA, gum Arabic.

reach equilibrium conditions than the ethanol pretreated samples (3 h). At the end of the 9 h drying time, ethanol pretreated carrot slices had higher MR (0.12) than 3% GA pretreated and the control samples (0–0.03), despite the increased reduction in MR.

Figure 1b presents the curve drying rate (DR) versus the drying time for the carrot samples. Overall, the DR declined with the increase in drying time in all the samples. From Figure 1b, it is apparent that the mass transfer was faster in ethanol pretreated carrot slices than in 3% GA and control samples. Ethanol pretreatment of carrot slices shortened the drying time by 28% compared to 3% GA pretreated and control samples. Similarly, Da Cunha et al. (2020) observed that ethanol pretreated melon slices took shorter time to reach the equilibrium condition when compared with the control samples. Different mechanisms have been proposed to explain the higher DR in ethanol pretreated plant samples. Given that ethanol has higher vapour pressure than water, the gradient surface tension could have promoted moisture migration from the interface to the surface of the carrot slices during the drying process due to the Gibbs-Marangoni effect, a phenomenon based on the mass transfer at the interface between two fluids with different surface tensions (Wang et al., 2022). In addition, ethanol pretreatment of carrot slices could have altered the cell wall structure through the dissolution of the polysaccharides on the cell wall, thereby enhancing the porosity and DR. Gomes et al. (2022) also reported increased DR in ethanol (99.8%) pretreated uvaia fruit. In addition, Rojas et al. (2020) established that ethanol (>90%) pretreatment of apple slices decreased the convective drying time by 21%.

The combination of ultrasonication and ethanol in the present also contributed to the reduced drying time (Rojas et al., 2020; Da Cunha et al., 2020). Meanwhile, the 3% GA pretreated and control samples showed insignificantly different and lower DR. These findings suggest that pretreating the carrot slices with 3% GA before drying may not significantly affect the DR and energy requirements. Comparable results were reported from previous studies in which coating papaya and pineapple slices with pectin did not influence the DR (60 and 70 °C) (Silva et al., 2015; Garcia et al., 2014). However, coating papaya slices with 3%

starch showed slower moisture loss than uncoated samples. The authors attributed the lower moisture loss to the protective barrier provided by starch (Islam et al., 2019). It was interesting to observe that despite having higher DR the ethanol pretreated carrot slices reached equilibrium moisture content faster than the ethanol and control samples and also showed higher MR after 4 h of drying. It is not clear was caused the ethanol pretreated samples to reach equilibrium moisture content faster than the 3% GA pretreated and control samples.

3.2. Model analysis

The experimental data of control, 3% GA, and ethanol pretreated samples were converted into MR expressions and the curves were fitted to the eleven selected thin layer drying models to describe the drying characteristics of the carrot slices (Table 1). The statistical calculation results of the thin layer model selection criteria (R^2 and RMSE) and model constants are presented in Table 2. It was observed that most of the

Table 2. Estimated various model parameters for control, 3% gum Arabic, ethanol, and oven-dried (50 °C for 9 h) carrot slices.

Pretreatment	Model	k_0	k/k_1	k_2	a	b	c	n	g	h	R^2	RMSE
3% GA	1		1.537×10^{-4}	5.739×10^{-6}							0.9940	0.0236
	2		**6.021×10^{-4}**		**9.700×10^{-2}**	**2.200×10^{-1}**					**0.9944**	**0.0227**
	3		1.436×10^{-4}		9.900×10^{-1}						0.9936	0.0243
	4		1.478×10^{-4}		9.840×10^{-1}		0.009				0.9938	0.0239
	5		2.746×10^{-4}		9.990×10^{-1}	-5.952×10^{-8}		0.929			0.9942	0.0230
	6		**6.023×10^{-4}**		**9.800×10^{-2}**	**4.510×10^{-1}**	**0.451**		**1.328×10^{-4}**	**1.328×10^{-4}**	**0.9944**	**0.0227**
	7		1.477×10^{-4}					0.933			0.9942	0.0230
	8		1.449×10^{-4}								0.9937	0.0246
	9		2.650×10^{-4}					0.934			0.9942	0.2303
	10	**1.33×10^{-4}**	**6.020×10^{-4}**		**9.024×10^{-1}**	**9.800×10^{-2}**					**0.9944**	**0.0227**
	11				-8.790×10^{-5}	1.860×10^{-4}					0.9587	0.0742
Ethanol	1		2.886×10^{-4}	8.661×10^{-5}							0.9870	0.0310
	2		**2.270×10^{-4}**		**9.300×10^{-1}**	**-8.300×10^{-2}**					**0.9985**	**0.0104**
	3		1.580×10^{-4}		9.650×10^{-1}						0.9600	0.0750
	4		2.500×10^{-4}		8.940×10^{-1}		0.112				0.9967	0.0185
	5		2.280×10^{-4}		1.001×10^{0}	4.270×10^{-6}		0.987			0.9942	0.0230
	6		2.474×10^{-4}		8.950×10^{-1}	5.600×10^{-2}	0.056		1.129×10^{-11}	1.129×10^{-11}	**0.9975**	**0.0136**
	7		2.012×10^{-4}					0.542			0.9723	0.0454
	8		1.649×10^{-4}								0.9665	0.0758
	9		9.607×10^{-3}					0.546			0.9723	0.0454
	10		**-1.900×10^{-5}**	**2.280×10^{-4}**		**7.000×10^{-2}**	**0.934**				**0.9985**	**0.0103**
	11				-9.310×10^{-5}	2.160×10^{-9}					0.8760	0.1158
Control	**1**		**1.037×10^{-4}**	**-2.009×10^{-5}**							**0.9999**	**0.0033**
	2		1.329×10^{-4}		1.000×10^{0}	9.870×10^{-1}					0.9953	0.0287
	3		1.358×10^{-4}		1.026×10^{0}						0.9945	0.0272
	4		1.209×10^{-4}		1.058×10^{0}		-0.042				0.9967	0.0185
	5		1.934×10^{-5}		9.960×10^{-1}	-2.946×10^{-7}		1.208			0.9993	0.0084
	6		1.358×10^{-4}		9.550×10^{-1}	3.500×10^{-2}	0.035		1.358×10^{-4}	1.358×10^{-4}	0.9945	0.0273
	7		1.272×10^{-4}					1.226			0.9992	0.0095
	8		1.329×10^{-4}								0.9953	0.0287
	9		1.670×10^{-5}					1.226			0.9992	0.0095
	10	1.541×10^{-4}	3.700×10^{-2}		1.186×10^{0}	-1.930×10^{-1}					0.9978	0.0169
	11				-8.520×10^{-5}	1.740×10^{-9}					0.9868	0.1158

1, Aghbashlo et al.; 2 Diffusion; 3, Henderson and Pabis; 4, Logarithmic; 5, Midili et al.; 6, Modified Henderson and Pabis; 7, Modified Page; 8, Newton Equation; 9, Page; 10, Two-term; 11, Wang and Singh. Abbreviations: GA, gum Arabic; RMSE, root mean square error; k_0, k,k_1,k_2,b,c,a, n,g, and h, drying constants; k/k_1, k or k_1 constants, R^2, coefficient of determination. Models in bold were the best fitting models.

Table 3. Colour attributes and water activity of control, 3% GA, ethanol pretreated, and oven dried (50 °C for 9 h) carrot slices.

Parameter	3% Gum Arabic	Ethanol	Control
L*	45.46 ± 0.51[a]	43.46 ± 2.43[a]	48.16 ± 0.70[a]
a*	34.12 ± 0.85[b]	35.32 ± 0.63[b]	26.00 ± 0.82[a]
b*	34.50 ± 0.87[a]	30.88 ± 0.26[b]	25.82 ± 0.68[c]
ΔE	8.12 ± 0.36[c]	10.69 ± 0.63[b]	13.06 ± 0.78[a]
a_w	0.37 ± 0.005[c]	0.44 ± 0.003[a]	0.40 ± 0.011[b]

Abbreviations: L*, lightness; a*, redness; b*, yellowness; ΔE, total colour differences; a_w, water activity; GA, gum Arabic. Control samples were dipped in distilled water. Values represent the mean ± SE of triplicate determinants. Values in each row and followed by different superscript letters are significantly different ($p < 0.05$).

models tested showed a good fit in all the treatments ($R^2 > 0.98$; RMSE<0.04) except for the Henderson and Pabis, Modified Page, Newton Equation, and Wang and Singh models (RMSE>0.04). De Jesus Junqueira et al. (2021) also reported that Henderson and Pabis and Wang and Singh models were the least compatible models to describe the drying kinetics of ethanol pretreated taioba leaves. In the present study, the diffusion, modified Henderson and Pabis, and two-term models could adequately describe the drying kinetics of 3% GA and ethanol pretreated carrot samples ($R^2 = 0.9944–0.9985$, RMSE = 0.0103–0.0227), whereas the Aghbashlo model could adequately describe the drying behaviour of the control samples ($R^2 = 0.9999$, RMSE = 0.0033). In contrast to the present study, Mahapatra and Tripathy (2018) observed that the Wang and Singh model adequately described the drying behaviour of unpretreated carrot slices. Factors such as the drying method, cultivar, and geographical location among others, could be implicated in the variation of the results. In the study of Santos et al. (2022) the diffusion model was established as the most adequate to describe the diffusion process during the drying of ethanol and ultrasonication pretreated strawberries. Similar findings were reported by Garcia et al. (2014). They observed that the Diffusion model was most suitable for predicting the drying kinetics of pectin-coated and hot-air dried papaya samples. Meanwhile, Rahimi et al. (2013) observed that the Page model described the drying behaviour of carboxyl methyl cellulose coated and dried apple slices than the Newton model.

3.3. Physicochemical properties

3.3.1. Colour and water activity

Consumer acceptance of a food product could be based on the product's physical characteristics, such as colour; therefore, colour retention during the drying process is important. The colour parameters of the dried carrot samples, including L*, a*, b*, and ΔE, are represented in Table 3. The carrot samples pretreated with 3% GA and ethanol showed a significantly ($p < 0.05$) higher b* value (34.50 and 30.88, respectively) compared to the control samples (25.82). Islam et al. (2019) reported comparable results; they observed higher b* values in potato starch coated and hot air-dried papaya slices. This phenomenon suggests that pretreatment of carrot slices with 3% GA and ethanol preserved carotenoids, which are the pigments responsible for imparting the orange colour in carrots. The absence of a protective layer on control samples could have exposed the conjugated double bond system in carotenoids to oxidation, reducing its light absorption properties and the typical orange colour of carrots (Kaseke et al., 2021). Also, enzymatic oxidation, browning, and formation of brown pigments during oven drying could be implicated in the loss of colour in the control samples (Md Saleh et al., 2020; Saengrayap et al., 2016). The polyphenol oxidase and peroxidase enzymes could have catalysed the hydroxylation of phenolic compounds and oxidation of the diphenols to quinones to produce brown pigments, consequently reducing the orange colour of the control samples (Briki et al., 2019). Similarly, a* values were significantly higher in 3% GA and ethanol pretreated carrot slices than in the control samples.

With regards to ΔE, the 3% GA and ethanol pretreated carrot slices exhibited significantly lower ΔE (1.2–1.6-fold lower) than the control samples. Similar results were observed by Islam et al. (2019) and Song et al. (2018) on papaya and pumpkin slices coated with starch, respectively. Despite the insignificant differences in the L* of the carrot samples ($p > 0.05$), visible and distinguishable differences in the colour of the dried carrot slices were observed (Table 1). Insignificant differences ($p > 0.05$) in L* was observed in ethanol pretreated and infrared-hot air dried scallion (*Allium fistulosum*) when compared to the control samples (Wang et al., 2019). On the other hand, Da Cunha et al. (2020) observed reduced L* values from ethanol pretreated and hot air-dried melon samples, while Granella et al. (2022) reported improved colour in ethanol pretreated and hot air-dried banana slices. The variation in the colour results demonstrate that the plant materials respond differently to the pretreatments given their varied tissue structures and composition.

Water activity (a_w) is essential for the stability of food products during storage. In the present study, pretreatment significantly affected ($p < 0.05$) the dried carrots' a_w which ranged between 0.37 and 0.44 (Table 3). The 3% GA pretreated carrot slices exhibited significantly lower a_w (0.37) than ethanol (0.44) pretreated carrot slices and the control samples (0.40). Though not clear, 3% GA pretreatment of the carrot slices was effective in reducing a_w when compared to the control samples. Unlike in the present study, Dadan and Nowacka (2021) reported lower a_w (0.25–0.27) from ethanol pretreated and hot air dried carrot slices. The variation in a_w could be ascribed to differences in cultivar, ethanol pretreatment time and the drying temperature and time, among other factors. In the study of Santos et al. (2022) ethanol and ultrasonication pretreatment of strawberries significantly reduced the a_w (0.37–0.57). It is assumed that a_w below 0.6 inhibit biochemical chemical activities such as microbial growth, enzymatic, and nonenzymatic reactions in food (Dadan and Nowacka et al., 2021). It can therefore be hypothesised that all the dried carrot samples could be stable during storage.

3.3.2. Shrinkage ratio

The shrinkage ratio indicates the physical degradation of the carrot slices, which can be affected by several factors, including material microstructure, mechanical properties, and processing. Although the shrinkage ratio decreased over time for all the samples, 3% GA pretreated carrot slices and control samples showed a lower shrinkage ratio after 4 h

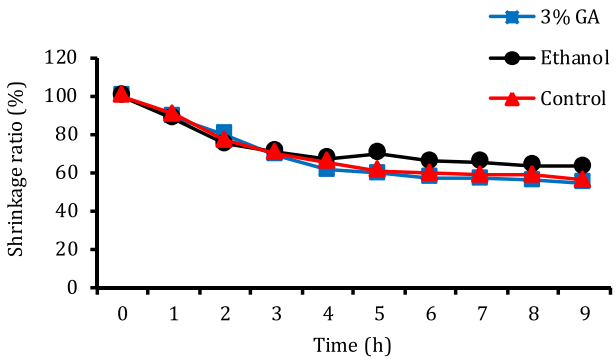

Figure 2. Shrinkage ratio of 3% gum Arabic (3% GA), ethanol pretreated and control samples of oven-dried (50 °C for 9 h) carrot slices. Control samples were dipped in distilled water.

of drying than samples pretreated with ethanol (Figure 2). At the end of the drying period, the shrinkage ratios were 62.94, 56.00, and 56.00% for the ethanol, 3% GA pretreated, and control samples, respectively. These findings suggest that 3% GA and ethanol did not have a significant impact on the shrinkage ratio of the carrot slices' during the drying process, despite the structural changes induced by ethanol pretreatment on the cell walls (Figure 5). The present results are in contrast with those reported from the drying of papaya and quince pretreated with edible coatings (Udomkun et al., 2014; Islam et al., 2019). Pretreatment of banana slices with ethanol did not significantly affect the shrinkage ratio; however, when ethanol pretreatment was combined with ultrasonication the shrinkage ratio significantly decreased (Granella et al., 2022).

3.3.3. Hardness and rehydration capacity

The effect of pretreatment on the hardness of the dried carrot slices is represented in Figure 3a. The carrot slices pretreated with 3% GA were 3–4 times harder than the ethanol pretreated and control samples suggesting that 3% GA delayed tissue softening and maintained the carrots' textural integrity (Li et al., 2017). A significant increase in hardness of papaya slices pretreated with edible starch coating was also reported (Islam et al., 2019). Varied results were reported by Rahimi et al. (2013) who reported that carboxymethyl cellulose coated apple slices required less energy to break than the control samples. Hardness can be related to the force performed by mastication during eating. Therefore, the higher hardness in 3% GA pretreated samples implies that the carrot slices require more energy to bite and chew than the ethanol and control samples. The findings suggests that the 3 % GA pretreated carrot slices may be best used as rehydrated or powdered food. According to Amanor-Atiemoh et al. (2019), gumminess, hardness, and chewiness decrease with an increase in a_w. This relationship could not be established in the present study as 3 % GA pretreated carrot slices which exhibited the highest hardness was characterised by the least a_w (Table 3).

The rehydration characteristics of a dried food product are used as a quality index. It determines the amount and rate of water absorption, which influences the sensorial properties and preparation time. A higher rehydration ratio suggests a good quality dried product as the pores allow water to re-enter the cells easily. As illustrated in Figure 3b, the rehydration ratio of the dried carrot slices insignificantly differed ($p > 0.05$), despite the significant variation in hardness among the carrot samples (Figure 3a). Generally, the rehydration ratio of the carrot slices increased linearly with time to about 90 min, after which it became almost constant. The rehydration ratio of the carrot slices varied insignificantly from 4.29-4.49 at the end of the rehydration experiment (270 min). Contrarily, varied results have been reported in literature. For instance, Rojas et al. (2020) observed higher rehydration capacity in ethanol pretreated and convective dried (50 °C) pumpkin slices compared with unpretreated samples. In the study of Islam et al. (2019), the rehydration ratio of starch-coated samples was significantly lower than the control samples.

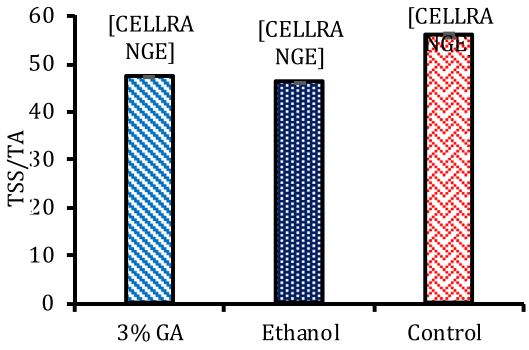

Figure 4. Total soluble solids/titratable acidity (TSS/TA) ratio of 3% gum Arabic (3% GA), ethanol pretreated and control samples of oven-dried (50 °C for 9 h) carrot slices. Control samples were dipped in distilled water. Bars with different letters are significantly different ($p < .05$). Vertical bars indicate the standard deviation of the mean.

3.3.4. Total soluble solids/titratable acidity ratio

The total soluble solids/titratable acidity is essential in providing a desirable taste in fruits and vegetables. Figure 4 shows an insignificant ($p > 0.05$) variation in the TSS/TA ratio of the carrot slices, indicating that edible coating pretreatment with 3% GA and ethanol did not significantly affect the balance of the total soluble solids and acidity in the carrot slices. The results indicate that 3% GA and ethanol pretreatment did not significantly alter the concentration of the organic acids and soluble components, suggesting minimum alteration of the sensory attributes, particularly taste. Overall, the TSS/TA ratio ranged between 46.20 and 55.95 (Figure 4).

3.3.5. Microstructure

The SEM analysis was important to determine the effect of edible coating pretreatment on the microstructures of the dried carrot slices. The SEM images of the dried carrot slices shown in the carrot slices pretreated with 3% GA showed a thin superficial layer on their surfaces, with smoother edges, illustrating good coating characteristics, which could have provided a protective barrier for the entry and exposure to atmospheric oxygen. Figure 5a also shows deposits of the coating on the fibrous layer, indicating the presence of gum Arabic. The finding can be used to explain the better retention of phenolic compounds, β-carotene, and radical scavenging activity in the 3% GA pretreated samples than in the ethanol pretreated and control samples (Figure 6). Nonetheless, transmission electron microscope imaging of coated and noncoated dried papaya samples showed that coating did not protect the papaya microstructures during drying (Garcia et al., 2014).

Sakooei-Vayghan et al. (2020) obtained SEM images which showed that pectin coatings had no effect on the microstructure of both osmotic

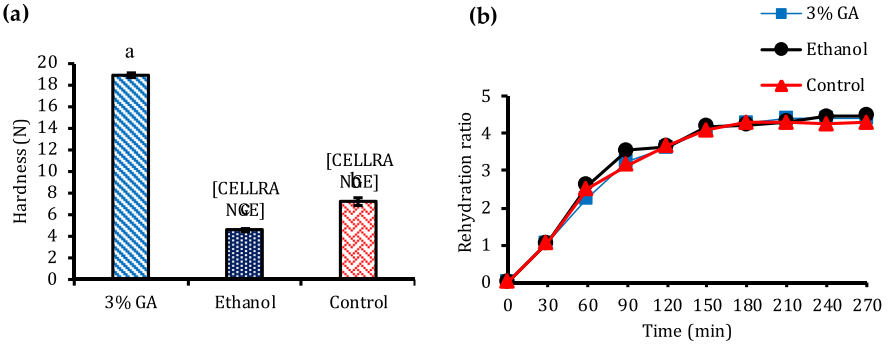

Figure 3. (a) Hardness and (b) Rehydration ratio vs. time of 3% gum Arabic (3% GA), ethanol pretreated and control samples of oven-dried (50 °C for 9 h) carrot slices. Control samples were dipped in distilled water. Bars with different letters are significantly different ($p < .05$). Vertical bars indicate the standard deviation of the mean.

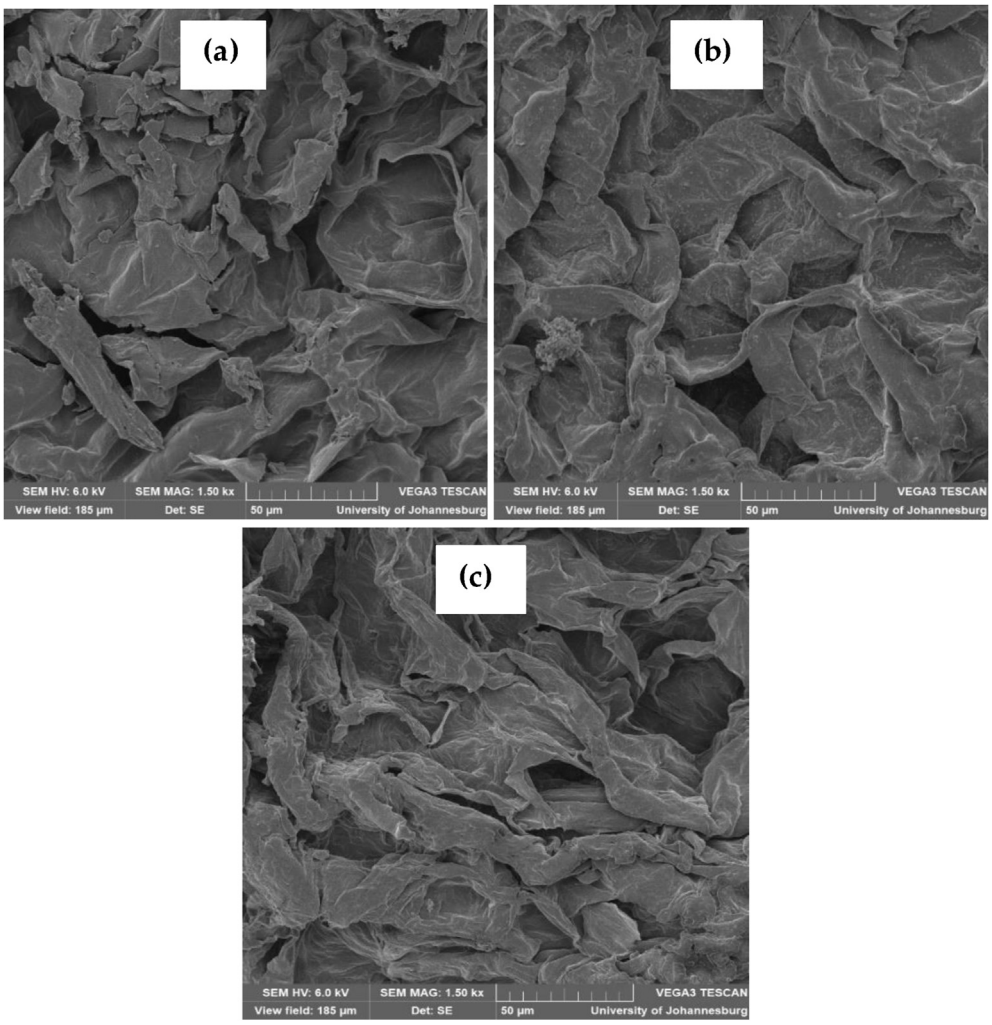

Figure 5. Scanning electron micrographs of (a) 3% GA, (b) ethanol pretreated, and (c) control oven-dried (50 °C for 9 h) carrot slices. Control samples were dipped in distilled water. GA, gum Arabic.

dehydrated and ultrasonic assisted osmotic dehydrated pretreated apricot samples. The variation in the effect of edible coating on the dried product microstructures could reflect differences in the functionality of the edible coating, the composition of the plant material cell walls, and the drying technique employed. Meanwhile, the carrot samples pretreated with ethanol exhibited cell disruption and microchannels in some parts of the tissue, which can be identified as white spots on the SEM micrographs of the ethanol pretreated samples (Figure 5b). Ethanol pretreatment of carrot slices could have altered the cell wall structure by dissolving polysaccharides on the cell wall, thereby affecting the integrity of the carrot tissues, which promoted shrinkage (Figure 3). Comparable results were reported by Wang et al. (2022) on ethanol pretreated pumpkin and potato slices and Santos et al. (2021) on ethanol pretreated carrot slices. As shown in Figure 5c the SEM images from the control samples revealed extensive destruction of the cell wall and tissue structure collapse due to the absence of a protective coating around the tissue cells (Song et al., 2018).

3.3.6. Total phenolic content and β-carotene content

Phenolic compounds have been linked to diverse biological activities, including anti-inflammatory and antioxidant properties; thus, eating polyphenol-rich foods may be linked to a lower risk of chronic diseases (Kaseke et al., 2021). Figure 6a shows that the TPC of the carrot samples ranged between 1.34 (control) and 2.99 mg GAE/100 g DM (3% GA), highlighting that edible coating pretreatment significantly affected the retention of phenolic compounds in the dried carrot slices. The carrot slices pretreated with 3% GA and ethanol preserved about 47–55% of the TPC during drying compared to the control samples. These results suggest that edible coating pretreatment positively affected the retention of the phenolic compounds during the drying process. The protective coating provided by the 3% GA protected the oxidation of the phenolic compounds. Thus the 3% GA pretreated carrot slices are a potential ingredient for the formulation of functional foods. The results from the present study concur with the findings of Chottanom et al. (2020), who pretreated (using cassava-modified starch) and vacuum dried Jerusalem artichoke. Higher retention of TPC was also observed in ethanol and ultrasonication pretreatment of strawberries and banana slices (Santos et al., 2022; Granella et al., 2022). The mechanism in which the ethanol pretreatment prevented the oxidation of the phenolic compounds is not clear. However, the application of ethanol could have assisted in dissociating the phenolic compounds from the carrot matrix, making their extraction for analysis easier (Kaseke et al., 2020). Da Cunha et al. (2020) reported different results when they studied the effect of ethanol pretreatment on dried melon samples. The authors observed no significant difference in the TPC between pretreated and unpretreated melon samples. The impact of ethanol pretreatment on TPC in the current study could have been enhanced by ultrasonication of the carrot samples compared to the previous research in which ultrasonication was not applied.

While the consumption of carotenoids-rich foods such as carrots has been strongly linked to the prevention of cancers, cardiovascular

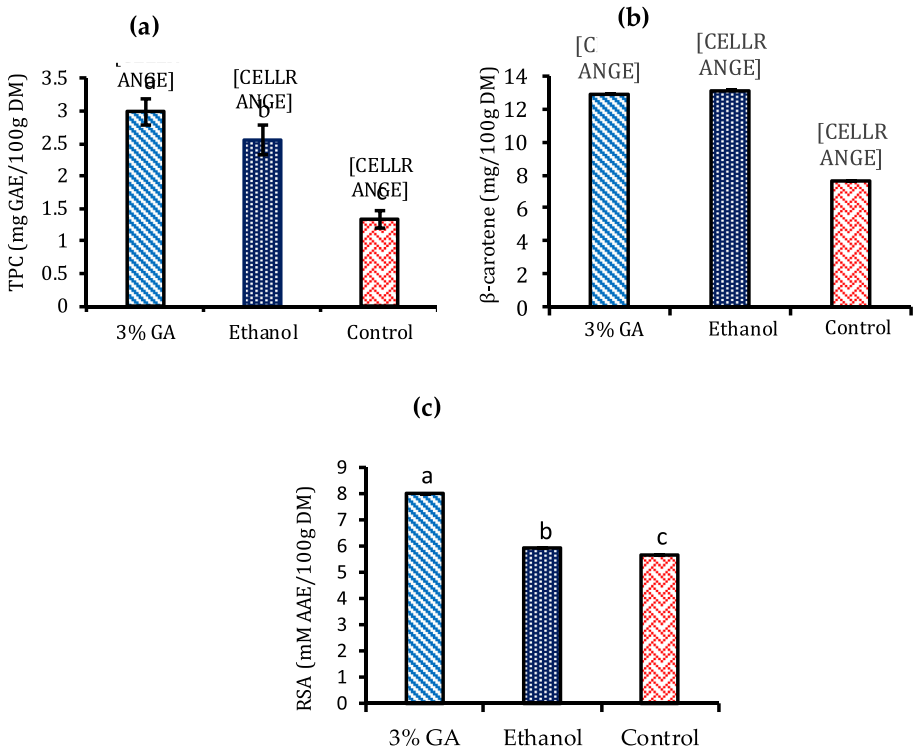

Figure 6. (a) Total phenolic content (TPC), (b) β-carotene content, and (c) radical scavenging activity (RSA) of 3% GA, ethanol pretreated and control samples of oven-dried (50 °C for 9 h) carrot slices. Control samples were dipped in distilled water. Bars with different letters are significantly different ($p < .05$). Vertical bars indicate mean and standard error. GA, gum Arabic.

diseases, and cataracts, these thermolabile bioactive compounds might be affected by processes such as drying (Kaseke et al., 2020). Therefore, minimum degradation of these antioxidant compounds during drying is essential. According to Figure 6b, carrot slices pretreated with 3% GA and ethanol exhibited β-carotene concentrations almost 2-fold higher than that of the control samples. However, no significant differences ($p > 0.05$) were observed between the β-carotene content of 3% GA and ethanol pretreated samples. These results affirm the need to preserve the degradation of this sensitive compound during processing. Dadan and Nowacka (2021) also reported a significant improvement in carotenoid content in ethanol pretreated and hot air dried carrot slices. The loss of β-carotene in control samples during the drying process corroborates the loss of the natural orange colour of carrots (Table 3). The present study's findings coincide with the study conducted by Lago-Vanzela et al. (2013) and Tonon et al. (2007) during the drying of pumpkin and tomato slices coated with starch, sucrose, and sodium chloride solutions, respectively. Meanwhile, ethanol and ultrasonication pretreatment of hot air-dried melon significantly reduced the carotenoids content (Da Cunha et al., 2020). The authors attributed the loss in carotenoids content to the microchannels created in the melon tissue which allowed the migration of the pigments into the ethanol solution during ultrasonication. The applied pretreatments provided an efficient barrier against oxygen and significantly reduced carotenoid loss compared to the control samples.

3.3.7. DPPH radical scavenging activity

The natural antioxidants operate as either reducing agents, quenchers of the singlet oxygen, free radical scavengers, or complexers of prooxidants metals (Kaseke et al., 2021). In the current study, the carrot samples' antioxidant activity was examined through their capacity to scavenge the DPPH radicals. The DPPH radical scavenging activity of the carrot slices significantly ($p < 0.05$) varied between 5.67 and 8.02 mM AAE/100 g DM, indicating that the radical scavenging activity of the carrot slices was dependent on the edible coating pretreatment. The 3% GA exhibited the highest DPPH radical scavenging activity (8.02 mM AAE/100 g DM), followed by ethanol pretreated samples (5.94 mM AAE/100 g DM). The control sample showed the lowest radical scavenging activity (5.67 mM AAE/100 g DM) (Figure 6c). This could be correlated to the level of TPC, and β-carotene recovered in the pretreated carrot samples (Figures 6a and Figure 6b). Positive correlation between TPC and the antioxidant activity was also observed in ethanol and ultrasound pretreated dried strawberries (Da Cunha et al., 2020). The mechanism in which the phenolic compounds scavenge the DPPH radical is by donating a hydrogen atom or an electron via its carbon atom with the highest electron density. The subsequent result is the abstraction of the hydrogen atom from the hydroxyl group (OH) to form a stable diamagnetic molecule in the form of 2,2-Diphenyl-1-picrylhydrazine (Koroleva et al., 2014). Wang et al. (2022) observed a decrease in apple slices' antioxidant capacity pretreated with ethanol in comparison to the control samples. The decrease in antioxidant activity was attributed to the increased cellular permeability.

4. Conclusions

In the present work, the effect of pretreating carrot slices with 3% GA and ethanol on the drying kinetics and quality of the dried carrot slices has been investigated. Based on the results obtained, 3% GA can be considered a better pretreatment method than ethanol and the control samples, as the carrot slices from the respective pretreatment exhibited better colour, water activity, TPC, β-carotene, and DPPH radical scavenging activity. At the same time, it did not affect the drying rate. These findings are important considering the possible application of the carrot slices (3% GA pretreated) in the formulation of functional foods. The thin layer modelling showed that the Diffusion, Modified Henderson and Pabis, and Two-term drying models could adequately describe and predict the drying kinetics of edible coating pretreated carrot slices. On the other hand, the Aghbasho model best described the drying kinetics of the

control samples. Given the potential of GA in retaining the quality and functional properties of dried carrot slices, future studies may focus on the sensory attributes and storability of GA pretreated dried carrot slices. Overall, this work provides a novel method for carrot slices' value addition and preservation.

Declarations

Author contribution statement

Zobabalo Progress Mina, Tafadzwa Kaseke, Tobi Fadiji, Olaniyi Amos Fawole:Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no competing interests.

Additional information

No additional information is available for this paper.

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