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# Synergy of ultrasound and osmotic dehydration in improving drying kinetics and quality of dried sweet potato (*Ipomea batatas* L.)

## *Synergieeffekte von Ultraschall und osmotischer Dehydrierung zur Verbesserung der Trocknungskinetik und der Qualität von getrockneten Süßkartoffeln (Ipomea batatas L.)*

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**Summary**

The effect of ultrasonic pretreatment and combined ultrasonic-osmotic dehydration using different pretreatment times (10, 20, 30, and 45 min) at 60°C was investigated. The aim of the present work was to shorten the total drying time and to improve the quality of sweet potato slices. The results showed that the moisture effective diffusivity increased when ultrasound was used as pretreatment to reduce the drying time, while the osmotic solution had no effect on moisture diffusivity. Among different ultrasound pretreatment timings, 30 min ultrasonically osmotic dehydrated treatment (US/GC-10%-3) proved the best in drying time reduction, which showed that ultrasound has a positive impact on osmotic dehydration. The drying kinetics of sweet potato slices were improved by sonication, which involves an improvement of mass transfer coefficient and drying rate. The logarithmic model showed the best fit to the experimental data for all treatments. For ultrasound treated samples, the parameters including enzyme inactivation, color, microstructure, mass transfer parameter had significant changes in comparison with distilled water treated and osmotically treated samples of sweet potatoes.

**Keywords:** Drying, mathematical modelling, osmotic dehydration, enzyme inactivation, color, Ultrasound

**Zusammenfassung**

Untersucht wurde der Effekt von Ultraschallvorbehandlung und ultraschallunterstützter osmotischer Dehydrierung mit unterschiedlichen Vorbehandlungszeiten (10, 20, 30 und 45 min) bei 60°C. Ziel der Studie war es, die Gesamttrocknungszeit zu verkürzen und die Qualität von Süßkartoffelscheiben zu verbessern. Die Ergebnisse zeigten, dass die Feuchtediffusionsfähigkeit zunahm, wenn Ultraschall als Vorbehandlung zur Verkürzung der Trocknungszeit eingesetzt wurde, während die osmotischer Dehydrierung keinen Einfluss auf die Feuchtediffusionsfähigkeit hatte. Unter den verschiedenen Ultraschall-Vorbehandlungszeitpunkten erwies sich die 30-minütige Ultraschallbehandlung mit osmotischer Dehydrierung (US/GC-10%-3) als die Beste in der Trockenzeitverkürzung. Dies zeigte, dass Ultraschall einen positiven Einfluss auf die osmotische Dehydrierung hat. Die Trocknungskinetik von Süßkartoffelscheiben wurde durch Ultraschall verbessert, was eine Verbesserung des Stoffübergangskoeffizienten und der Trocknungsrate mit sich brachte. Das logarithmische Modell zeigte für alle Behandlungen die beste Übereinstimmung mit den experimentellen Daten. Bei mit Ultraschall behandelten Proben zeigten die Parameter einschließlich Enzyminaktivierung, Farbe, Mikrostruktur und Stoffübergang im Vergleich zu mit destilliertem Wasser behandelten und osmotisch behandelten Proben von Süßkartoffeln signifikante Änderungen.

**Schlüsselwörter:** Trocknung, mathematische Modellierung, osmotische Dehydrierung, Enzyminaktivierung, Farbe, Ultraschall

## Introduction

Sweet potato (*Ipomoea batatas* L.) is herbaceous perennial, edible tuberous root plant of the *Convolvulaceae* family. Native to the South American continent, this plant has been extensively cultivated in China. In China, the annual production of sweet potato is 117 million tonnes, comprising about 90% of global sweet potato production (Abegunde et al., 2013). Sweet potato is a kind of tuber crop rich in carotenoids and contains higher levels of carbohydrates, minerals, protein, and vitamins than other vegetables (Rashid et al., 2019a).

Sweet potatoes are subject to rapid deterioration after harvest at ambient tropical temperatures and need curing period of 15 to 20 days at 27–34°C and 85–90% relative humidity prior to long-term storage (Lidster et al., 1988). Sprouting of the roots during storage above 10°C and chilling injuries below 10°C are some of the main hurdles for long-term storage of sweet potatoes and this can be avoided by drying them either by using the traditional drying or modern drying methods (Lidster et al., 1988).

Drying is one of the conventional methods of food preservation and extensively being used to increase the storage life of fruit and vegetables since from ancient times (Sarpong et al., 2018; Rashid et al., 2019b). Drying process provides long time storage of commodities by reducing water activity through decreasing water content that inhibits deterioration. Pretreatments of vegetables or fruits prior to drying process has been proven effective which not only help to reduce the laborious drying time and high cost but produces high-quality products as well. Pretreatments are often used to reduce the initial water content, accelerate the drying process, and improve products quality (Fernandes and Rodrigues, 2008; Ghavidel and Davoodi, 2009). The quality of any dried product can be accomplished by inhibiting enzyme activity, destroying microorganisms, effectively increasing the rate of water diffusion. Some of the common pretreatments include blanching, microwaves, and ultrasound.

The ultrasonic wave is a new kind of non-thermal technology, which is widely used in the food industry. Pretreatments with ultrasonic waves prior to drying of fruits and vegetables have been proven to be effective in improving drying rate and quality properties of dried products (Azoubel et al., 2010; Oliveira et al., 2011). In general, different kind of pretreatments, like ultrasonic pretreatment, osmotic dehydration, and mechanical dehydration are used to reduce the initial moisture content or modification in the structure of the fruit/vegetable tissues to reduce the total drying time (Fernandes et al., 2008; Uribe et al., 2011). The utilization of high-intensity ultrasound has been considered to improve the quality of different products such as dried papaya (Fernandes et al., 2008).

In this study, the effect of ultrasonic pretreatment time on drying kinetics, enzyme inactivation, color, and microstructures were evaluated. Again, different mathematical models were tested to predict the drying kinetics. A comparison with the osmotic dehydration pre-treatment was also carried out.

**Nomenclature**

| | |
|---|---|
| CRT | Control |
| D*eff* | Moisture effective diffusion |
| Eq | Equation |
| khz | Frequency |
| $M_r$ | Moisture ratio |
| $Mr_{exp}$ | Moisture experimental |
| $Mr_{pre,I}$ | Moisture predicted |
| POD | Peroxidase |
| PPO | Polyphenol oxidase |
| RMSE | Root Mean Square Error |
| US | Ultrasound |
| US/GC | Ultrasound/Glucose |
| UST | Ultrasound treatment |
| $W_d$ | Weight of solid loss |
| $W_o$ | Weight after drying |
| $W_w$ | Initial weight |
| WB | Wet Basis |

## Material and Methods

### Preparations of samples

Fresh sweet potatoes were bought from nearby market in Zhenjiang, China in September 2017 to the research laboratory of School of Food and Biological Engineering, Jiangsu University, China. Fundamental handling such as cleaning and peeling were done before cutting into slices of 3 mm thickness by using a cutting machine (SS-250, SEP Machinery Company Ltd, Guangzhou, China) prior to pretreatments and drying.

### Osmotic dehydration (OD)

The osmotic solution used in each experiment was prepared by mixing food grade glucose with distilled water to give a concentration of 10 and 20% (w/v). Samples were placed in the solution for 10, 20, 30 and 45 min before drained, blotted with filter paper to clean the remaining solution.

### Ultrasonication

Sweet potatoes samples were stacked into plastic packs and immersed in an ultrasonic bath manufactured by Meibo Biotechnology Co., Ltd (Zhenjiang, China). These samples were subjected to ultrasonic waves at 10, 20, 30 and 45 min. The frequency of the ultrasound was set at 20 kHz, with the intensity of 0.2 W/cm and temperature (25°C ± 2) was controlled by a water bath. The pulsed on-time (10 s) and off-time (3 s) with power density of 300 W/L were used, respectively. All the experiments were conducted in triplicate.

### Experimental design

Four sets of pretreatments including Ultrasound (US) only, glucose (GC) only, Ultrasound combined with glucose (US/GC) and distilled water used as control (CRT). For OD, samples were pretreated with two concentrations (10 and 20%) of glucose in all the treatment. All pretreatments lasted for 10, 20, 30 and 45 min as shown in Table 1.

### Drying with the humidity control convective hot-air dryer

The drying process was performed on a laboratory scale air dryer's humidity control capability as reported by Sarpong et al. (2018) with a temperature at 60°C, 25% relative humidity and 1.5 m/s air velocity. The drying system runs for about 30 min to obtain a stable drying condition before spreading the sample in a single layer of stainless steel wire grid and placed in a drying chamber. Samples were weighed at 20, 40, 60 and 90 min in the beginning and subsequent hours respectively until the desired moisture content was achieved at <5% WB.

### Drying kinetics

Dry matter moisture Ratio (MR) of sweet potato slices was expressed as an empirical model using Eq. (1).

$$MR = \frac{M - M_e}{M_0 - M_e} \quad \text{(Eq. 1)}$$

Where M is the water content at any time, $M_e$ is the equilibrium water content, $M_0$ is the initial moisture content. $M_e$ was assumed to be zero for analysis of *MR* according to Sarpong et al. (2018)

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The drying rate (DR) of sweet potato slices at a specific time period was calculated as follows:

$$DR = \frac{M_{t1} - M_{t2}}{t_1 - t_2} \quad \text{(Eq. 2)}$$

Where $t_1$ and $t_2$ are the drying times (min) at a different time during the drying process; $M_{t1}$ and $M_{t2}$ are the moisture content of the samples (kg water/kg dry matter)

### Mathematical Modeling of Drying Data

Different mathematical models (i.e. Newton, Page, Henderson and Pabis and Logarithmic models) were used to test the drying kinetics of ultrasound pretreated sweet potato to represent the drying behavior. The equations corresponding to these models are:

Newton Model: $MR = \exp(-kt)$ (Eq. 3)

Page Model: $MR = exp(-kt^n)$ (Eq. 4)

Handerson and Pabis: $MR = a\exp(-kt)$ (Eq. 5)

Logarithmic: $MR = a\exp(-kt) + c$ (Eq. 6)

### Non-linear regression analysis

Regression analysis of the drying rate was conducted by means of Sigma plot 14.0. The coefficient of determination $R^2$, root mean squared error (RMSE) and the reduced $\chi^2$ values were calculated from the following equations:

$$R^2 = \frac{N\sum_{i=1}^{N} MR_{pred,i} MR_{expt,i} - \sum_{i=1}^{N} MR_{pred,i} \sum_{i=1}^{N} MR_{expt\,x,i}}{\sqrt{\left(N\sum_{i=1}^{N} MR_{pred,i}^2 - \left(\sum_{i=1}^{N} MR_{pred,i}\right)^2\right)\left(N\sum_{i=1}^{N} MR_{expt,i}^2 - \left(\sum_{i=1}^{N} MR_{expt,i}\right)^2\right)}} \quad \text{(Eq. 7)}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{expt,i} - MR_{pred,i}\right)^2} \quad \text{(Eq. 8)}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{expt,i} - MR_{pred,i}\right)^2}{N - z} \quad \text{(Eq. 9)}$$

Where $MR_{expt,i}$ and $MR_{pred,i}$ are the experimental and predicted dimensionless $MR$ respectively, $N$ is the number of observations, and $z$ is the number of constants. The best model to describe the drying kinetics of sweet potato slices was chosen as the one with highest $R^2$ and least $RMSE$ and $\chi^2$ (Sarpong et al., 2019).

### Calculation of Moisture effective diffusion ($D_{eff}$)

The effective diffusivity $D_{eff}$ ($m^2/s$) was calculated from diffusion equation (Eq. 10) for slab geometry on the assumption of constant diffusivity, uni-dimensional moisture movement, constant temperature and negligible external resistance an analytical solution for linear diffusion in an infinite slab of thickness L (Crank 1975).

$$MR = \frac{8}{\pi^2}\sum_{n-1}^{\infty}\frac{1}{(2n-1)^2} exp\left[-\frac{(2n-1)^2\pi^2 D_{eff}\, t}{4L^2}\right] \quad \text{(Eq. 10)}$$

Where $D_{eff}$ is the constant effective diffusivity ($m^2/s$). $L$ and $t$ represent half the thickness of the sweet potato slices and the drying time $t$ (s), $n$ is the positive integer, respectively. However, according to Lopez et al., (2000), only the first term of the equation can be applied for long drying times from Eq. (11).

$$MR = \frac{8}{\pi^2} exp\left(-\frac{\pi^2 D_{eff}\, t}{4L^2}\right) \quad \text{(Eq. 11)}$$

The slope ($k_0$) was calculated by plotting in MR against time as given below:

$$k_0 = \frac{\pi^2 D_{eff}}{4L^2} \quad \text{(Eq. 12)}$$

### Mass transfer ratio

The mass transfer ratio of sweet potatoes was carried out for the osmotic dehydration process on different timings (10, 20, 30 and 45 min). The parameters of mass transfer weight gain (WG) and solid loss (SL) were expressed by equations 13 and 14.

$$\text{Weight gain } (\%) = \frac{W_o - W_w}{W_w} \times 100 \quad \text{(Eq. 13)}$$

$$\text{Solid Loss } (\%) = \frac{W_d}{W_o} \times 100 \quad \text{(Eq. 14)}$$

Where $W_o$ is the mass in gram (g) of the sweet potatoes sample after ultrasound treatments, $W_w$ is the initial mass (g) of the fresh sweet potatoes samples prior to treatments and $W_d$ is the mass (g) of solid lost into the water after ultrasound treatments. The solid loss was determined after ultra-sonication at 105°C for 12 h till the constant weight obtained.

### Enzyme extraction

Enzyme extraction was done with some modification into the method reported by Jiang (1999). A finely ground powder of sweet potato slices (1 g) was mixed with 5 mL extraction solution (0.2 M phosphate buffer at pH 6.5, 1% (v/v), Triton X-1 and 4% polyvinylpolypyrrolidone). This was continuously stirred for 3 min and kept for 4 h at 4oC. The mixture was centrifuged at 7000×g for 10 min at room temperature and supernatant collected and filtered through a 0.45 µm filter membrane to be analyzed as crude enzyme extract.

### Enzyme Assays

#### *Polyphenol Assays (PPO)*

The activity of polyphenol oxidase (PPO) was determined according to the spectrophotometric method of Jiang (1999) with minor changes. A 0.5 ml of PPO extract was made by adding 200µl (0.1 m) catechol and 1.5 mL of 0.1 M sodium phosphate buffer (PH 7.0). The absorbance at 420 nm was recorded continuously at 25°C for 5 min using (TU-1810; Purkinje universal Instrument Co., Ltd., Beijing, China). The blank samples were containing only the extract mixture solution and devoid of enzyme extract.

#### *Peroxidase (POD) activity*

The POD activity was determined as per used by Zhang et al., (2017) with minor modifications and was measured at 470 nm spectrophotometry using guaiacol as a phenolic substrate with hydrogen peroxide. The reaction mixture contains 0.15 mL of 4% (v/v) guaiacol, 0.15 ml of 1% (v/v) $H_2O_2$, 2.66 mL of 0.1 m phosphate buffer (PH 7) and 40µl enzyme extracts. The blank sample contains the same mixture solution without the enzyme extract.

One unit of enzyme activity (U/min/mL) was defined as the amount of the enzyme which caused a change of 0.001 in absorbance unit per min under the conditions of the assay for PPO and POD. The enzymes residual activity was calculated as the residual enzyme‘s activity (RA)

$$Relative\ activity\ (\%) = \frac{Current\ Enzyme\ activity}{Initial\ Enzymes\ activity} \times 100 \quad \text{(Eq. 15)}$$

### Color

The sweet potato slices color variable was measured according to the CIE Lab system, using a colorimeter (DC-P3, Beijing, China). The total color difference (ΔE) was calculated by Eq. (16) (Ramallo and Mascheroni, 2012).

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad \text{(Eq. 16)}$$

### Microstructure evaluation with scanning electron microscopy (SEM)

The microstructure of dried sweet potatoes samples was examined by using scanning electron microscope (electronic JSM-5800lv, Tokyo, Japan). A small portion from samples dried powder was attached on a stainless stub with double sticky tape, sputtered immediately with a gold target in approximately 10 nm. Observations were performed at an acceleration voltage of 20 KV. The samples were subsequently viewed under the microscope.

### Statistical analysis

The experimental results were conducted in triplicates. The data were processed with the Origin Pro 9.2 (Origin Laboratories Company, Northampton, MA, USA) and presented as means ± standard deviation. The effects of pretreatment on drying data, enzyme inactivation and color were compared by means of One-way Analysis of Variance (ANOVA) and Tukey test at $p<0.05$. All the analyses were done in triplicate.

## Results and Discussion

### Drying kinetics

The hot air-drying of sweet potato slices pretreated with distilled water, glucose and US was carried out at a stable air temperature of 60oC. At the beginning of the process, the relatively high water loss was observed, because of excessive moisture content led to rapid moisture removal on the product surface (Xiao et al., 2010). This certainly affects the distribution of moisture, resulting in shrinkage of the sample (Fig. 1). The moisture content decreased gradually when samples were immersed for 45 min pretreated in distilled water, osmotic solution and US. The time taken to achieve the ≃5% moisture content was different among all pretreated samples such as 450 min for CRT-1, 420 min for GC-10%-4, 480 min for GC-20%-4, 390 min for US/GC-10%-4 and 420 min for US/GC-20%-4 were recorded. The results showed that drying time was decreased with samples treated with ultrasound pretreatments (Fig. 1). These results were similar to what was observed by Oliveira et al., (2011) in the drying of Malay apples. The shortest time to achieve ≃5% moisture content in combined ultrasound and osmotic dehydrated samples US/GC-10-3 was 300 min (Fig. 1e), which showed that pretreatment of ultrasound had a positive impact on hot air-drying of sweet potato slices. Similar findings were reported by Fernandes and Rodrigues, (2008) using different ultrasound pretreatments for drying of papaya and pineapple. The results for the combined ultrasound-and osmotic dehydration showed that the total drying time increased with increasing glucose concentration. Since the samples pretreated with osmotic dehydration process at a low concentration of glucose (10%) did not reduce the drying time as compared to the high level of glucose concentration (20%). The results were in agreement with Rodrigues and Fernandes, (2007) and Fernandes et al., (2008) who observed 30 min of ultrasound pretreatment as the optimum time to reduce the hot air-drying time of pineapple.

**TABLE 1:** *Values of statistical constants and coefficients of different thin layer drying models of sweet potatoes.*

| Models / Treatments | Samples | Coefficients | | | | | RMSE |
|---|---|---|---|---|---|---|---|
| | | K | a/n | c | $R^2$ | $\chi^2$ | |
| **Logarithmic** | | | | | | | |
| Control | CRT-1 | 0.013 | 0.842 | 0.016 | 0.994 | 1.05E-09 | 3.1E-05 |
| | CRT-2 | 0.012 | 0.844 | 0.132 | 0.994 | 2.58E-09 | 4.86E-05 |
| | CRT-3 | 0.010 | 0.893 | 0.085 | 0.996 | 2.17E-11 | 4.46E-06 |
| | CRT-4 | 0.010 | 0.900 | 0.089 | 0.997 | 1.11E-10 | 1.01E-05 |
| US (D.W) | USW-1 | 0.012 | 0.822 | 0.140 | 0.989 | 2.08E-09 | 4.36E-05 |
| | USW-2 | 0.006 | 0.895 | 0.025 | 0.967 | 2.94E-10 | 1.64E-05 |
| | USW-3 | 0.005 | 0.868 | 0.049 | 0.964 | 1.16E-09 | 3.26E-05 |
| | USW-4 | 0.005 | 0.927 | 0.007 | 0.971 | 2.37E-09 | 4.66E-05 |
| Glucose | GC-10%-1 | 0.015 | 0.831 | 0.154 | 0.997 | 9.09E-12 | 2.89E-06 |
| | GC-10%-2 | 0.014 | 0.815 | 0.156 | 0.991 | 1.51E-11 | 3.73E-06 |
| | GC-10%-3 | 0.136 | 0.819 | 0.142 | 0.989 | 1.07E-09 | 3.14E-05 |
| | GC-10%-4 | 0.011 | 0.870 | 0.108 | 0.977 | 8.59E-10 | 2.81E-05 |
| | GC-20%-1 | 0.013 | 0.783 | 0.168 | 0.980 | 8.84E-10 | 2.85E-05 |
| | GC-20%-2 | 0.169 | 0.847 | 0.139 | 0.988 | 7.56E-10 | 2.63E-05 |
| | GC-20%-3 | 0.013 | 0.836 | 0.127 | 0.988 | 1.2E-09 | 3.31E-05 |
| | GC-20%-4 | 0.011 | 0.867 | 0.108 | 0.978 | 3.71E-10 | 1.84E-05 |
| US and Glucose | US/GC-10%-1 | 0.011 | 0.828 | 0.122 | 0.984 | 1.52E-10 | 1.18E-05 |
| | US/GC-10%-2 | 0.009 | 0.889 | 0.066 | 0.985 | 2.39E-10 | 1.48E-05 |
| | US/GC-10%-3 | 0.010 | 0.856 | 0.103 | 0.989 | 2.95E-11 | 5.2E-06 |
| | US/GC-10%-4 | 0.007 | 0.894 | 0.047 | 0.984 | 4.69E-10 | 2.07E-05 |
| | US/GC-20%-1 | 0.012 | 0.826 | 0.137 | 0.990 | 3.07E-09 | 5.31E-05 |
| | US/GC-20%-2 | 0.012 | 0.831 | 0.136 | 0.990 | 0.001413 | 0.035993 |
| | US/GC-20%-3 | 0.013 | 0.801 | 0.162 | 0.989 | 3.11E-11 | 5.34E-06 |
| | US/GC-20%-4 | 0.013 | 0.811 | 0.145 | 0.987 | 1.18E-09 | 3.29E-05 |
| **Page** | | | | | | | |
| Control | CRT-1 | 0.033 | 0.729 | | 0.996 | 2.57E-05 | 0.004852 |
| | CRT-2 | 0.02 | 0.744 | | 0.996 | 1.5E-05 | 0.003704 |
| | CRT-3 | 0.018 | 0.836 | | 0.997 | 5.3E-07 | 0.000697 |
| | CRT-4 | 0.017 | 0.853 | | 0.995 | 2.41E-05 | 0.004695 |
| US (D.W) | USW-1 | 0.036 | 0.705 | | 0.994 | 1.49E-06 | 0.001169 |
| | USW-2 | 0.021 | 0.763 | | 0.975 | 0.000162 | 0.012199 |
| | USW-3 | 0.022 | 0.732 | | 0.974 | 0.00012 | 0.010858 |
| | USW-4 | 0.016 | 0.807 | | 0.975 | 0.000127 | 0.010808 |
| Glucose | GC-10%-1 | 0.043 | 0.683 | | 0.994 | 7.07E-05 | 0.008051 |
| | GC-10%-2 | 0.044 | 0.672 | | 0.997 | 1.58E-05 | 0.003807 |
| | GC-10%-3 | 0.042 | 0.680 | | 0.996 | 3.48E-06 | 0.001787 |
| | GC-10%-4 | 0.022 | 0.799 | | 0.975 | 1.24E-05 | 0.003377 |
| | GC-20%-1 | 0.049 | 0.638 | | 0.996 | 6.63E-07 | 0.00078 |
| | GC-20%-2 | 0.048 | 0.677 | | 0.993 | 0.000109 | 0.009991 |
| | GC-20%-3 | 0.041 | 0.695 | | 0.995 | 3.26E-06 | 0.001728 |
| | GC-20%-4 | 0.022 | 0.797 | | 0.977 | 5.06E-06 | 0.002155 |
| US and Glucose | US/GC-10%-1 | 0.033 | 0.715 | | 0.993 | 8.31E-06 | 0.002759 |
| | US/GC-10%-2 | 0.021 | 0.807 | | 0.990 | 4.14E-05 | 0.006163 |
| | US/GC-10%-3 | 0.024 | 0.772 | | 0.994 | 8.24E-06 | 0.002748 |
| | US/GC-10%-4 | 0.018 | 0.807 | | 0.988 | 0.000115 | 0.010256 |
| | US/GC-20%-1 | 0.036 | 0.706 | | 0.995 | 1.59E-06 | 0.001208 |
| | US/GC-20%-2 | 0.036 | 0.710 | | 0.996 | 0.000151 | 0.011773 |
| | US/GC-20%-3 | 0.044 | 0.662 | | 0.996 | 5.36E-06 | 0.002217 |
| | US/GC-20%-4 | 0.042 | 0.677 | | 0.996 | 8.97E-09 | 9.07E-05 |

*Where, $R^2$ = Coefficients of determination, RMSE = Root mean square error, a/n = 'a' is a coefficient of Logarithmic model and 'n' is a coefficient of Page model.*

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Throughout the drying process, the higher internal temperature was observed in sweet potato slices pretreated with the combined US and osmotic samples of US/GC-10%-3 which shorten the drying process (Fig. 2). The internal temperature of sweet potato slices accounted for the various drying rates as shown in Fig. 3. The highest drying rate was peaked in treatment UST-2 at 120 min for 20 min in US pretreated samples (Fig. 3b) followed by the US osmotically pretreated sample for 30 min at 150 min (Fig. 3e) which was maintained for a shorter period of time and then decreased gradually.

## Mathematical modelling of thin layer drying of sweet potatoes slices

The models were evaluated by measuring the coefficient ($R^2$), Chi-Square ($\chi^2$) and root mean square error (RMSE) and the best model was chosen based on maximized $R^2$ and minimal $\chi^2$ and RMSE. The results obtained indicate that the Logarithmic model was found to be the best, followed by the Page model for drying of sweet potatoes (Table 1). Whereas, Newton & Handerson and Pabis models were found not suitable and fit for drying of sweet potatoes and hence data is not shown here. In all cases, the Logarithmic

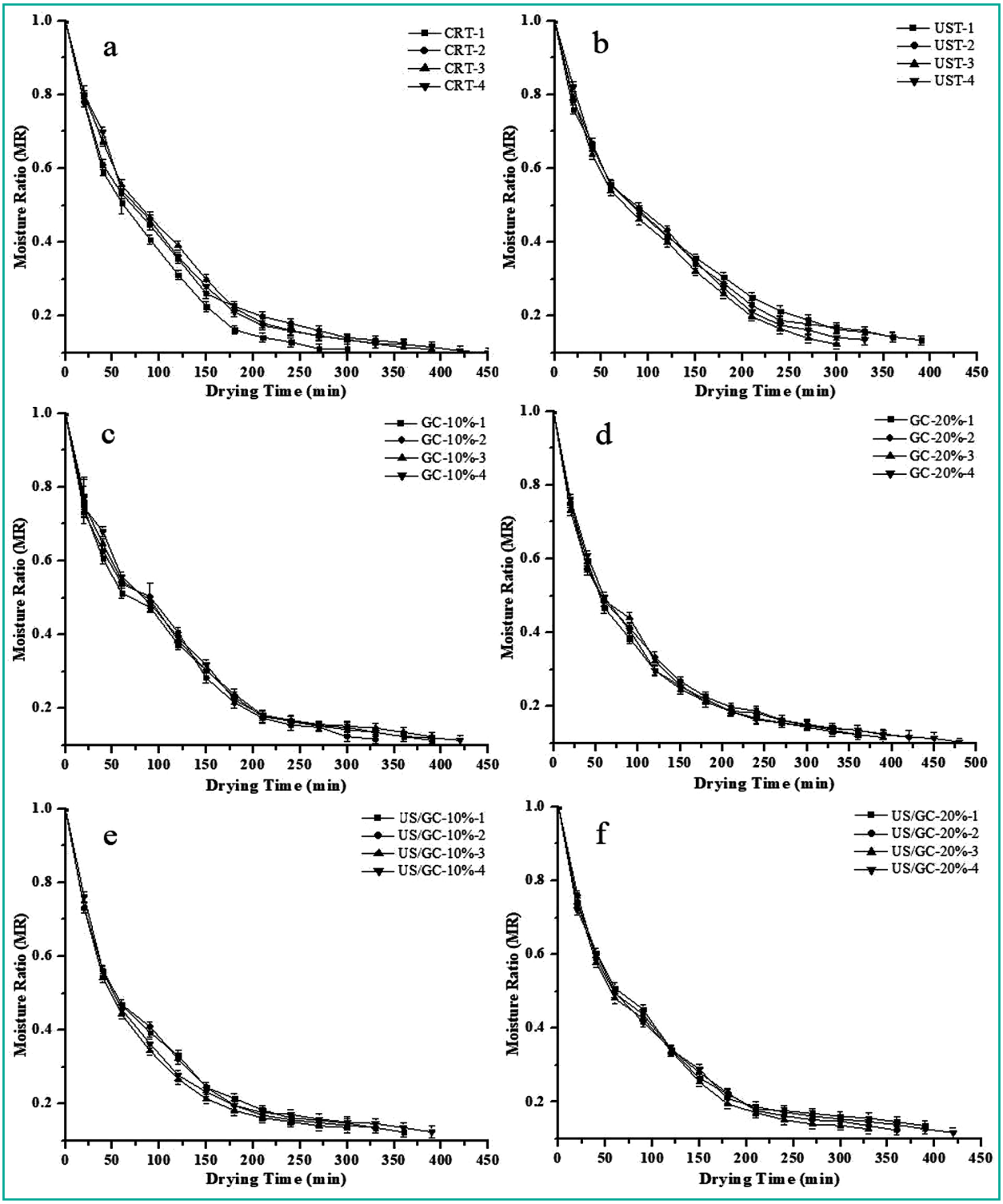


**FIGURE 1:** *Moisture loss in sweet potato samples, (A) samples treated with distilled water, control; (B) US; (C) 10% GC; (D) 20% GC; (E) 10% GC/US; (F) 20% GC/US.*

values of $R^2$ varied from 0.985 to 0.998, which was considered to the closest fit to the drying experiments with the lowest RMSE (≤5.2E-06) and $\chi^2$ values ($9.09\times10^{-12}$). The fitted drying curve based on the logarithmic model provided a very suitable experimental data for the kinetic data for all drying curves, as shown in Fig. 1. In this manner, they can be utilized satisfactorily for describing the drying behavior of ultrasound pretreated and combined ultrasound-osmotically pretreated samples of sweet potatoes in hot air-drying. Similarly, the logarithmic and Page models found suitable for button mushrooms slices and pomegranate (Başlar et al., 2014; Zhang et al., 2016), respectively.

### Effective moisture diffusivity ($D_{eff}$)

The average values of $D_{eff}$ ranged from $1.02\times10^{-8}$ m²/s to $9.89\times10^{-9}$ m²/s, very similar to report for different fruits and vegetables ($10^{-12}$ m²/s to $10^{-8}$ m²/s) (Table 2). The moisture diffusivity of sweet potato samples treated with the US was significantly ($p<0.05$) higher than control, whereas there were no significant differences between control, GC and US/GC samples. As per findings obtained by Ozuna et al., (2011), the $D_{eff}$ values in potatoes increased by 19% and 41% at 30W and 60W, when dried at 40°C. Whereas in the case of eggplants drying, the $D_{eff}$ values increased by 91% and 211% at 20W and 60W (García-Pérez et al., 2011). This phenomenon shows that ultrasound can significantly enhance the water diffusion ability in the hot air-drying process of food products. In addition, sonication can weaken the adhesion of water in the micro-capillary tunnel and may increase the fluidity of internal moisture (Liu et al., 2017) and may result in reducing the internal moisture diffusion. The combined effect of glucose concentrations

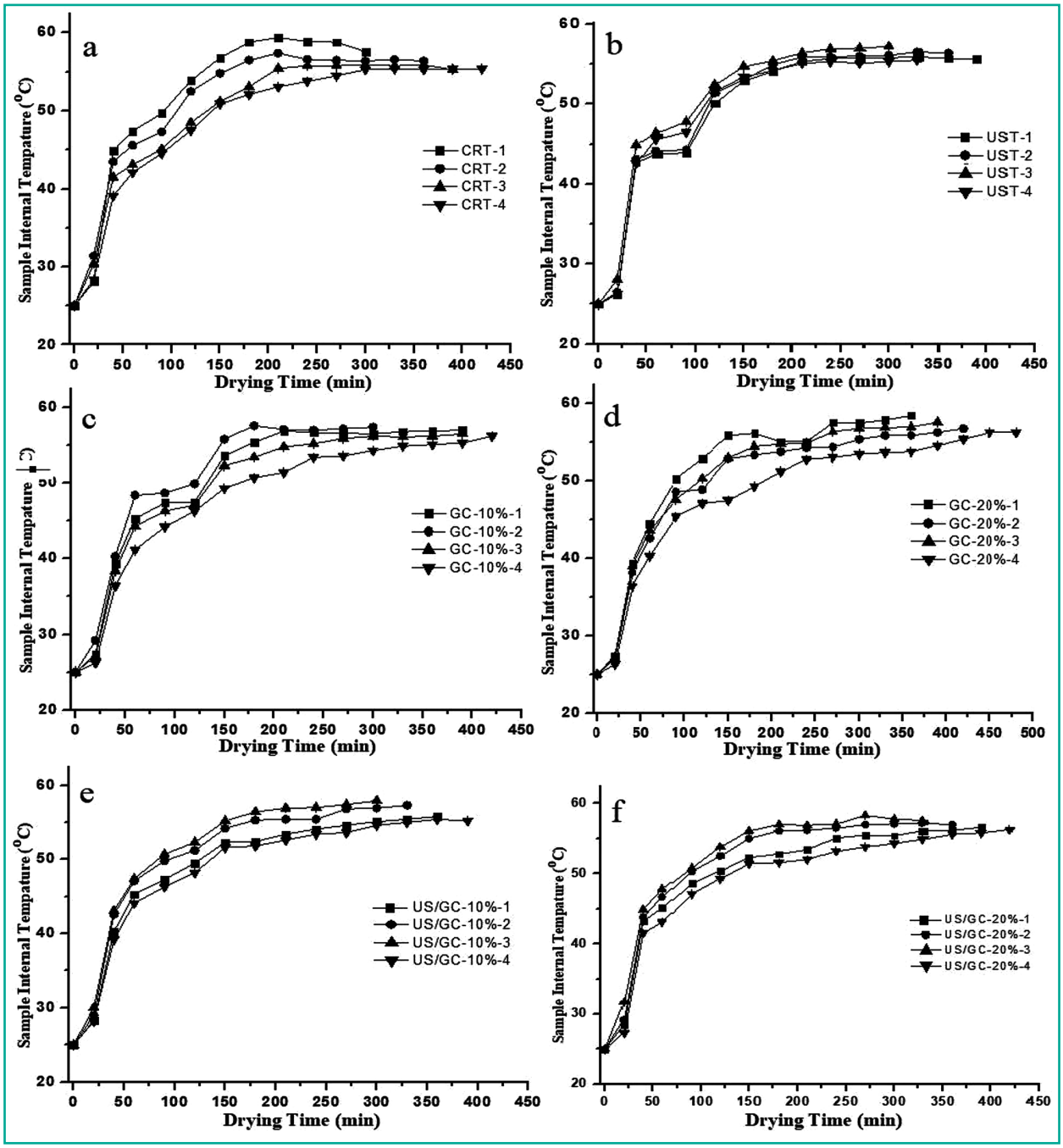


**FIGURE 2:** *Internal temperature of sweet potato samples, (A) samples treated with distilled water, control; (B) US; (C) 10% GC; (D) 20% GC; (E) 10% GC/US; (F) 20% GC/US.*

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and ultrasound (US/GC) resulted with lower moisture diffusivity than the US pretreated samples alone, which shows that the combination of glucose with the US has no effect on moisture diffusivity. The above fact is in harmony with the findings of Alvarez et al., (1995) who reported that the glucose-osmotic impregnation has no effect on moisture diffusivity during air drying of strawberries.

### Mass transfer ratio

The weight gain of sweet potato slices increased as the time increased in each treatment (i.e.10, 20, 30, and 45 min). Statistically, significant weight gain was observed in control samples at 45 min (16.72%) while the lowest was seen in US/GC-20%-1 treatment at 10 min (5.05%). The observed changes are mainly due to the absorption

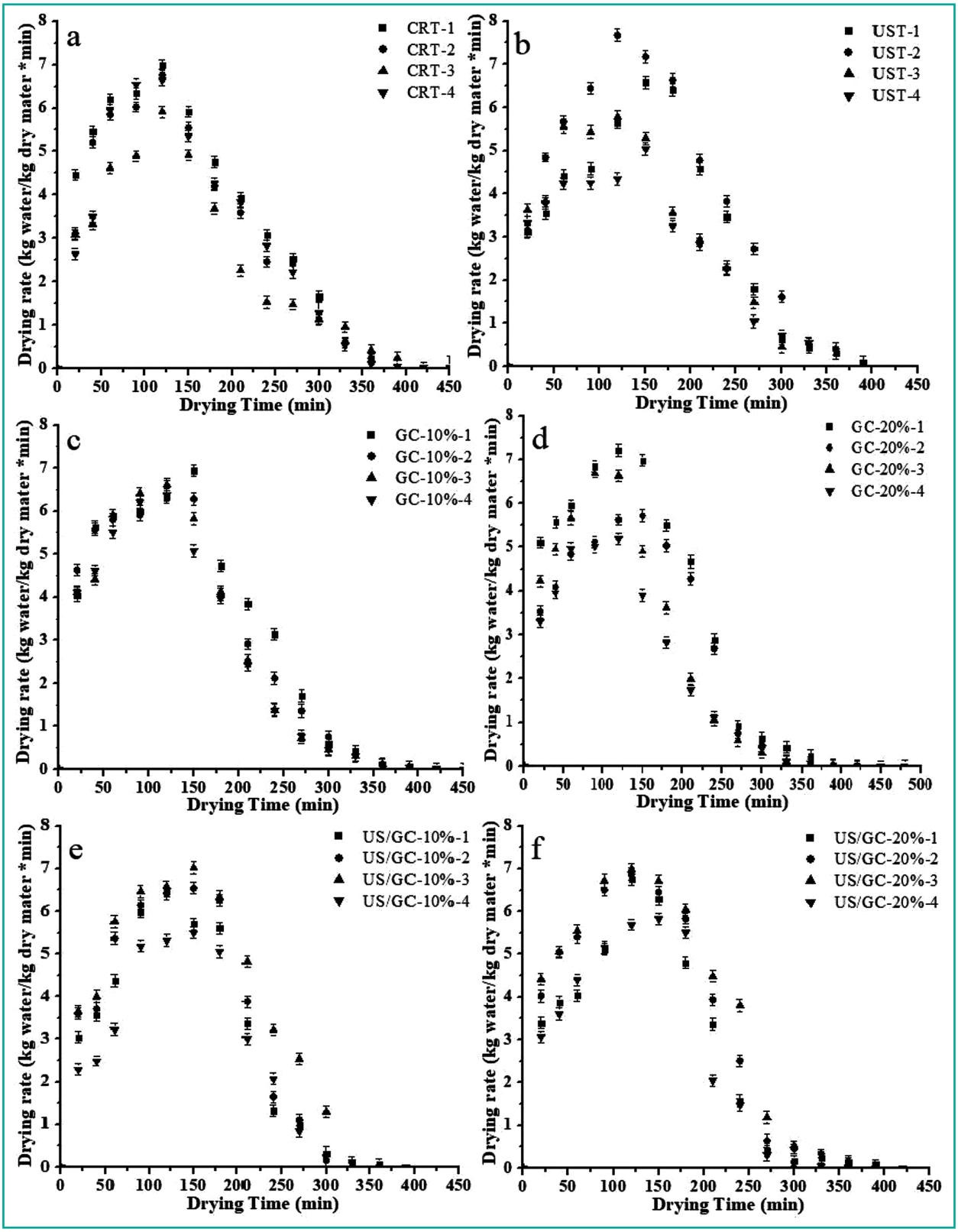


**FIGURE 3:** *Drying rate of sweet potato samples, (A) samples treated with distilled water, control; (B) US; (C) 10% GC; (D) 20% GC; (E) 10% GC/US; (F) 20% GC/US.*

of moisture from the conveying medium (distilled water). Similarly, weight gain in Malay apples (Oliveira et al., 2011) and melons (Fernandes et al., 2008) were 12% and 8%, respectively before drying was performed. The osmotic dehydration carried out at 20% glucose concentration at 10 and 20 min showed a higher solid loss from sweet potato slices, whilst also resulted in the highest water loss. This phenomenon was observed by Oliveira et al., (2011) in the drying of Malay apples where higher solid losses were recorded in comparison with control samples. The mass transfer of solid gain in sweet potato slices was enhanced by ultrasonication is presented in Table 2.

**TABLE 2:** *Values of statistical constants and coefficients of different thin layer drying models of sweet potatoes.*

| Treatments | Pretreatment Time (min) | Samples | Weight gains (%) | Solid loss (%) | Moisture diffusivity ($m^2/s$) | $R^2$ |
|---|---|---|---|---|---|---|
| Control | 10 | CRT-1 | $11.72^{h}$ | $14.86^{de}$ | $1.05\times10^{-8} \pm 0.24^{f}$ | 0.96 |
| | 20 | CRT-2 | $14.61^{d}$ | $21.24^{bc}$ | $1.04\times10^{-8} \pm 0.32^{f}$ | 0.96 |
| | 30 | CRT-3 | $16.81^{b}$ | $20.27^{c}$ | $1.09\times10^{-6} \pm 0.18^{f}$ | 0.98 |
| | 45 | CRT-4 | $16.72^{b}$ | $22.41^{bc}$ | $1.12\times10^{-8} \pm 0.14^{f}$ | 0.97 |
| Ultrasound | 10 | USW-1 | $12.84^{f}$ | $21.00^{bc}$ | $9.89\times10^{-9} \pm 0.16^{a}$ | 0.94 |
| | 20 | USW-2 | $15.26^{c}$ | $21.56^{bc}$ | $3.73\times10^{-9} \pm 0.21^{d}$ | 0.92 |
| | 30 | USW-3 | $16.86^{b}$ | $19.30^{de}$ | $8.45\times10^{-9} \pm 0.11^{c}$ | 0.98 |
| | 45 | USW-4 | $19.84^{a}$ | $23.69^{bc}$ | $9.41\times10^{-9} \pm 0.10^{b}$ | 0.98 |
| Glucose | 10 | GC-10%-1 | $6.88^{m}$ | $22.00^{bc}$ | $1.02\times10^{-8} \pm 0.06^{f}$ | 0.96 |
| | 20 | GC-10%-2 | $10.04^{j}$ | $21.42^{bc}$ | $1.04\times10^{-8} \pm 0.11^{f}$ | 0.94 |
| | 30 | GC-10%-3 | $10.22^{j}$ | $20.82^{bc}$ | $1.05\times10^{-8} \pm 0.19^{c}$ | 0.95 |
| | 45 | GC-10%-4 | $11.16^{i}$ | $21.12^{bc}$ | $1.07\times10^{-8} \pm 0.14^{f}$ | 0.94 |
| | 10 | GC-20%-1 | $6.00^{n}$ | $25.39^{f}$ | $1.02\times10^{-8} \pm 0.28^{f}$ | 0.97 |
| | 20 | GC-20%-2 | $6.88^{m}$ | $29.02^{a}$ | $1.05\times10^{-8} \pm 0.21^{f}$ | 0.92 |
| | 30 | GC-20%-3 | $6.94^{m}$ | $18.72^{de}$ | $1.08\times10^{-8} \pm 0.15^{f}$ | 0.95 |
| | 45 | GC-20%-4 | $6.99^{m}$ | $11.52^{e}$ | $1.09\times10^{-8} \pm 0.14^{f}$ | 0.94 |
| Ultrasound and Glucose | 10 | US/GC-10%-1 | $8.36^{k}$ | $20.93^{bc}$ | $1.04\times10^{-8} \pm 0.13^{f}$ | 0.96 |
| | 20 | US/GC-10%-2 | $12.08^{g}$ | $18.31^{d}$ | $1.05\times10^{-8} \pm 0.19^{f}$ | 0.98 |
| | 30 | US/GC-10%-3 | $11.22^{i}$ | $21.79^{bc}$ | $1.06\times10^{-8} \pm 0.27^{f}$ | 0.97 |
| | 45 | US/GC-10%-4 | $13.00^{e}$ | $24.12^{b}$ | $1.17\times10^{-8} \pm 0.23^{e}$ | 0.98 |
| | 10 | US/GC-20%-1 | $5.05^{o}$ | $23.89^{b}$ | $1.02\times10^{-8} \pm 0.24^{f}$ | 0.96 |
| | 20 | US/GC-20%-2 | $7.76^{l}$ | $23.55^{bc}$ | $1.03\times10^{-8} \pm 0.26^{f}$ | 0.96 |
| | 30 | US/GC-20%-3 | $11.14^{i}$ | $21.59^{bc}$ | $1.04\times10^{-8} \pm 0.26^{f}$ | 0.95 |
| | 45 | US/GC-20%-4 | $10.18^{j}$ | $24.16^{b}$ | $1.07\times10^{-8} \pm 0.28^{f}$ | 0.95 |

*Means on the same column with different superscript letters are significantly different at p<0.05. Means ± standard deviation.*

## Enzyme inactivation

The relative activities of PPO and POD decreased in all the samples at 60°C in Fig. 4 & 5. However, the higher reduction was recorded in both PPO and POD at 30 min in all treatments, especially in the US 10%. Meanwhile, the lowest reduction was observed in PPO in GC-20% at 20 min (Fig. 4) and GC-10% at 10 min & CRT and USW at 20 min in the case of POD (Fig. 5). The decrease in residual activity of these enzymes at the high temperature indicated the sensitivity of these enzymes to GC/US treatments. Likewise, Rodrigues et al., (2017b) found a decreased in the relative activity of PPO at 60°C in the US assisted hot air-drying of apples. Statistically, the results show that US/GC treated samples enzyme inactivation was better when compared to US and control samples.

The activity of POD was generally higher in case of combined treatment of US/GC at 60°C than all the glucose treated samples without ultrasound treatments. These results are in complete agreement with Rodrigues et al., (2017b) who reported a partial deactivation of enzymes at 60°C in ultrasonic assisted hot air-drying on the activity of apples. The partial inactivation of this enzyme during the drying process of sweet potato slices using ultrasonic waves pretreatment at 60°C is an important finding observed in the current study. Similarly, both enzymes exhibited strong heat-resistant capacity, especially under 80°C (Yoruk and Marshall, 2003).

## Effect of glucose concentration and ultrasound pretreatments on the CIE Color variables of dried sweet potato slices

The highest $L^*$ value for US/GC treated samples increased with osmotic dehydration time which implies a higher product brightness and this may be as a result of a larger pigment leach as shown by the high absorbance value (Table 3). The impact of pretreatments (control) on color was similar with GC concentrated under osmotic condition. The reduction of $L^*$ value in osmotic dehydrated or glucose concentrated samples was mainly due to the enzymatic browning reaction in damaged tissues (Zhang and Chen, 2006). The color value of $a^*$ decreased for sweet potatoes after osmosis in GC treated samples but the combined use of GC/US showed similar values to the fresh samples. All treatments of GC/US samples showed a significantly higher value than that of GC osmotic dehydrated samples and fresh samples. Deng and Zhao, (2008) also found an increase of $a^*$ values in dried apples pretreated with ultrasound osmotic dehydration when compared to untreated samples.

**TABLE 3:** *Effect of different drying treatments on color variables of sweet potatoes.*

| Treatments | Samples | L* | a* | b* | ΔE |
|---|---|---|---|---|---|
| Fresh | Fresh | $82.00 \pm 0.90^{ab}$ | $8.14 \pm 0.76^{ab}$ | $39.64 \pm 0.93^{a}$ | – |
| Control | CRT-1 | $76.88 \pm 1.92^{defg}$ | $6.33 \pm 1.12^{abcdef}$ | $24.83 \pm 0.92^{bcde}$ | $15.44 \pm 0.10^{l}$ |
| | CRT-2 | $77.92 \pm 2.14^{cdefg}$ | $6.00 \pm 0.8^{bcdefg}$ | $22.52 \pm 1.77^{bcdefgh}$ | $17.41 \pm 0.10^{h}$ |
| | CRT-3 | $76.36 \pm 2.57^{defgh}$ | $7.44 \pm 0.25^{abc}$ | $26.41 \pm 2.71^{bc}$ | $14.08 \pm 0.08^{l}$ |
| | CRT-4 | $77.82 \pm 0.90^{cdefg}$ | $7.03 \pm 1.14^{abcd}$ | $22.00 \pm 2.50^{cdefghi}$ | $17.84 \pm 0.11^{g}$ |
| US (D.W) | USW-1 | $76.42 \pm 1.21^{defgh}$ | $7.56 \pm 0.87^{cdefg}$ | $21.80 \pm 1.06^{defghi}$ | $18.55 \pm 0.06^{g}$ |
| | USW-2 | $77.85 \pm 1.96^{cdefg}$ | $5.60 \pm 1.07^{cdefg}$ | $19.76 \pm 1.92^{fghijk}$ | $20.16 \pm 0.09^{f}$ |
| | USW-3 | $78.80 \pm 2.74^{bcde}$ | $8.68 \pm 1.99^{a}$ | $22.92 \pm 1.65^{bcdefg}$ | $16.71 \pm 0.11^{hi}$ |
| | USW-4 | $76.15 \pm 0.78^{efgh}$ | $5.60 \pm 1.89^{cdefg}$ | $18.72 \pm 3.20^{ghijkl}$ | $21.54 \pm 0.12^{e}$ |
| Glucose Conc. | GC-10%-1 | $75.13 \pm 0.86^{fgh}$ | $3.74 \pm 0.19^{g}$ | $17.05 \pm 0.61^{jkl}$ | $23.71 \pm 0.11^{bc}$ |
| | GC-10%-2 | $75.66 \pm 1.01^{efgh}$ | $4.47 \pm 0.599^{efg}$ | $16.06 \pm 2.03^{kl}$ | $24.37 \pm 0.11^{b}$ |
| | GC-10%-3 | $76.38 \pm 0.91^{defgh}$ | $4.02 \pm 0.88^{fg}$ | $18.21 \pm 2.15^{hijkl}$ | $22.23 \pm 0.09^{d}$ |
| | GC-10%-4 | $78.28 \pm 2.21^{cdefg}$ | $6.74 \pm 1.36^{abcde}$ | $20.79 \pm 2.07^{efghij}$ | $18.95 \pm 0.09^{f}$ |
| | GC-20%-1 | $79.15 \pm 0.45^{bcde}$ | $3.77 \pm 0.84^{g}$ | $16.33 \pm 1.83^{kl}$ | $23.93 \pm 0.66^{bc}$ |
| | GC-20%-2 | $72.91 \pm 0.955^{h}$ | $6.99 \pm 0.06^{abcd}$ | $17.85 \pm 0.16^{ijkl}$ | $23.31 \pm 0.10^{c}$ |
| | GC-20%-3 | $76.40 \pm 1.40^{defgh}$ | $4.22 \pm 0.699^{fg}$ | $14.97 \pm 2.72^{l}$ | $25.28 \pm 0.11^{a}$ |
| | GC-20%-4 | $74.79 \pm 0.716^{gh}$ | $5.92 \pm 0.56^{bcdefg}$ | $16.97 \pm 0.96^{jkl}$ | $23.57 \pm 0.09^{c}$ |
| US and Glucose Conc. | US/GC-10%-1 | $81.05 \pm 1.399^{abc}$ | $7.52 \pm 0.66^{abc}$ | $23.42 \pm 1.60^{bcdef}$ | $15.95 \pm 0.10^{kl}$ |
| | US/GC-10%-2 | $81.07 \pm 2.07^{abc}$ | $7.20 \pm 0.61^{abcd}$ | $23.83 \pm 1.55^{bcdef}$ | $15.56 \pm 0.11^{kl}$ |
| | US/GC-10%-3 | $79.74 \pm 1.03^{bcd}$ | $7.59 \pm 1.88^{abc}$ | $24.12 \pm 2.30^{bcdef}$ | $15.39 \pm 0.12^{l}$ |
| | US/GC-10%-4 | $80.68 \pm 1.08^{abc}$ | $7.28 \pm 0.69^{abc}$ | $25.87 \pm 0.81^{bcd}$ | $13.55 \pm 0.11^{mn}$ |
| | US/GC-20%-1 | $80.81 \pm 0.86^{abc}$ | $7.11 \pm 0.48^{abcd}$ | $26.44 \pm 1.90^{b}$ | $12.99 \pm 0.68^{n}$ |
| | US/GC-20%-2 | $78.53 \pm 0.80^{cdef}$ | $8.55 \pm 1.32^{a}$ | $23.82 \pm 1.16^{bcdef}$ | $16.19 \pm 0.11^{ij}$ |
| | US/GC-20%-3 | $80.42 \pm 1.53^{abc}$ | $8.27 \pm 0.82^{ab}$ | $28.91 \pm 1.66^{bcd}$ | $20.68 \pm 0.10^{f}$ |
| | US/GC-20%-4 | $82.56 \pm 1.299^{a}$ | $4.80 \pm 0.78^{defg}$ | $22.57 \pm 2.44^{bcdefgh}$ | $17.20 \pm 0.12^{h}$ |

*Means on the same column with different superscript letters are significantly different at p<0.05. Means ± standard deviation.*

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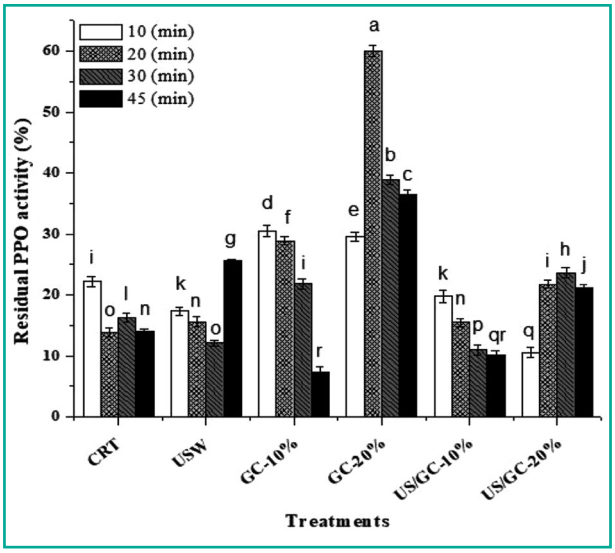


**FIGURE 4:** *Effect of ultrasound pretreatments and osmotically dehydrated samples on polyphenol oxidase inactivation (PPO) of sweet potato slices on different pretreatment timings (10, 20, 30, and 45).*

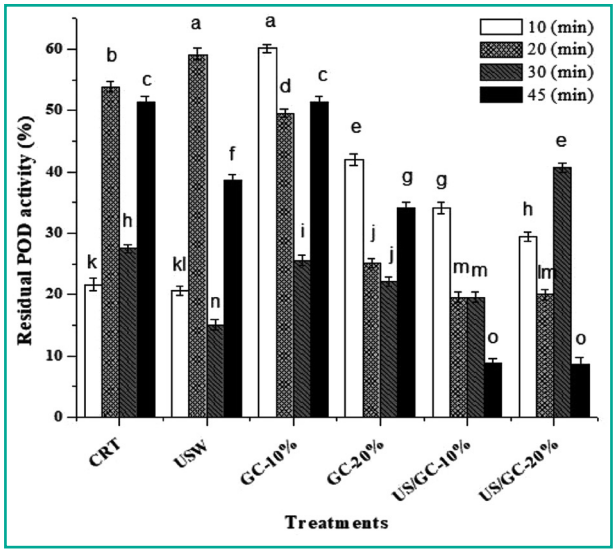


**FIGURE 5:** *Effect of ultrasound pretreatments and osmotically dehydrated samples on peroxidase inactivation (POD) of sweet potato slices on different pretreatment timings (10, 20, 30, and 45).*

In all pretreatments, a slight decrease in $b^*$ was observed as compared to fresh samples, which indicated that the samples become light bluer red in color after drying. The statistically significant difference $(p<0.05)$ was noted in samples of osmotically dehydrated under 20% glucose as compared to all other treatments while 10% glucose treatments presented a $b^*$ value that was closed to US pretreated samples (Table 3). Similarly, Kowalski and Mierzwa (2013) found glucose and fructose (used as an osmotic agent) as responsible for discoloring and lowering the quality of dried apples. The total color difference (ΔE) indicated the extent of color change as compared with a fresh sample. Osmotically GC had the highest impact on total color change, while samples treated with ultrasound assisted osmotically dehydrated US/GC had the lowest impact of total color change (Table 3). This work is in agreement with the findings of Kowalski and Szadzińska, (2014) who reported high-quality color and less color reduction in cherries by the application of ultrasound-assisted osmotic dehydration.

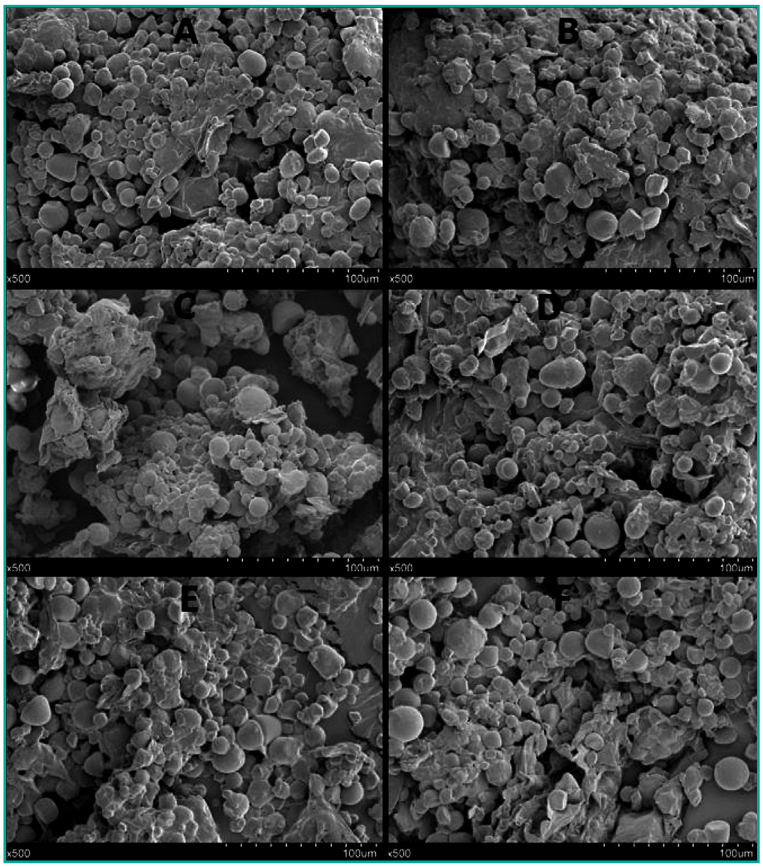


**FIGURE 6:** *SEM micrographs of sweet potato samples, (A) samples treated with distilled water, control; (B) US; (C) 10% GC; (D) 20% GC; (E) 10% GC/US; (F) 20% GC/US.*

### Microstructure

The major features of the microstructure of sweet potatoes treated with distilled water (control) were slightly well aligned with cell rupture (Fig. 6a). In comparison with control/distilled water samples, the microstructure of the sweet potatoes pretreated with the US had more cavities and rough structure appearance (Fig. 6b); in agreement with the previous report (Zhang et al., 2016). Meanwhile, the microstructure of the samples treated with 10% glucose concentration was destroyed by the micro-blasting of US and created micro channels (Fig. 6c). As per the findings of Nascimento et al. (2016b), the total cellular structure of passion fruit peel samples was greatly influenced by hot air drying in ultrasound assisted hot air-dried samples. In the case of 20% glucose concentration treated samples, the observed tissue arrangement were more similar to the control ones but the cells look more swollen cells with large intercellular spaces (Fig. 6d). The samples treated with 10% glucose in addition to ultrasound pretreatment showed less breakage of the internal structure of sweet potatoes than 10% glucose samples (Fig. 6e).

## Conclusion

The ultrasound combined with hot air-drying recorded shortest drying time and enhanced water diffu-

sivity and mass exchange coefficient of drying sweet potato slices. Among the distinctive models explored to show the drying kinetics, the Logarithmic model proved the best fit model followed by the Page model as demonstrated by highest $R^2$ and lowest RMSE and $\chi^2$ values. Combined ultrasound with hot air drying significantly inactivate PPO and POD enzymes activity and maintained the color features. The results obtained proved that ultrasound pretreatments resulted in reducing the drying time required for the osmotic dehydration. In conclusion, the utilization of ultrasound as a preparatory treatment before drying can significantly enhance the quality of dried sweet potato slices.

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## Conflict of interest

Authors declare no conflicts of interest.

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