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AIR-DRYING CHARACTERISTICS OF FRESH AND PRETREATED (AFRICAN OIL BEAN) *PENTACLETHRA MACROPHYLLA* BENTH. COTYLEDONS

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ABSTRACT
Processing of African Oil Bean Cotyledons (AOBC), a valuable source of protein has been a bottleneck because of the associated drudgery. In addition, the shelf life of the processed bean is very short; the cotyledon turns green shortly during storage due to putrefaction. On the basis of the above, there is a need to produce shelf-stable cotyledons which could be rehydrated when needed. Three portions were separately soaked in each solution of sodium chloride (3 %), sodium meta-bisulfite (300 ppm), ascorbic acid (300 ppm) for 1h, and one portion were subjected to natural fermentation for three days, while the other was used as control. All the samples (single and double cotyledons) were oven-dried at 50, 60, 70, and 80 ^{o}C to constant weight. The dehydration rate of AOBC decreased gradually until the water activity of the oil bean cotyledon reduced to less than one. Moisture diffusivity increased from 4.9061×10-10 – 2.091 × 10-9 m^2/s, and varied with drying temperature, thickness, and pretreatments. Midilli and Kucuk model (R^2 = 0.9702 - 0.9940) showed a better fit than other drying models. Effective moisture diffusivity is direct of the samples is reliant on air-drying temperature and can be described by the Arrhenius equation. The activation energy of drying of the African Oil Bean cotyledon was in the range of 10.29 – 27.12 kJ/mol. Finally, the addition of preservatives proved to be highly effective on the drying rate and the other studied parameters as well as the shelf stability of the AOBC.

Keywords: Modeling, legume, drying pretreatment, moisture diffusivity, drying rate
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INTRODUCTION

African oil bean (*PentaclethramacrophyllaBenth*) is of the family Fabaceae and sub-family Mimosoidae and it belongs to one of the biggest flowering plants (Keay, 1989; Orwa et al., 2009). It is wild cultivated however, few improved ones are cultivated in the rain forest of the West African coast. Each pod typically contains six to eight tasty, flat, polished brown seeds (Enujiugha et al., 2003). The seed contains the twenty essential amino acids and the quality of its protein is considered excellent and it is also rich in fatty acids which makes it a good source of calories and edible protein (Enujiugha and Agbede, 2003It is a low-cost protein source that can be used to combat protein-energy malnutrition in Sub-Saharan Africa. Usually, the seeds are

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

sorted, washed, boiled, sliced, fermented and packaged, before commercially sold in open markets. It has been noted that fermented and boiled seeds have a minimal shelf life, which causes putrefaction a few days after processing (Mbajunwa, 1993).

To date, the preparation of fermented seeds remains at the cottage level in a substantial part of its range, as the processing remains a family art with limited documented information. The available literature indicated variations in cooking time, fermentation duration and slice size (Enujiugha, 2000; Mbajunwa, 1993; Aju and Okwulehie, 2005). The storability of African oil bean seeds has been increased by various unit processes, including canning, fermentation, roasting, and temperature changes during storage (Enujiugha, 2000). However, processed products from these methods have not satisfied consumers' taste and convenience because of bulkiness and the short shelf life of the product. There is therefore the need to preserve the African oil bean product all-year-round using appropriate preservation techniques at relatively low cost. Drying of the boiled seeds and subsequently rehydrating it when needed is viewed as an appropriate technique for the maintenance of the preferred form and quality of the oil bean seeds while ensuring the extension of its shelf life.

Air drying is a suitable preservation technique in which water content of food materials is reduced by hot air to alter biochemical and microorganism deteriorations (Doymaz and Pala, 2003; Doymaz and Kocayigit, 2011; Guine and Fernandes, 2006; Olurin et al., 2012). Dehydration in low-cost mechanical dryers would ensure the appropriate level of moisture in foods and reduced susceptibility to microbial and biochemical deterioration. This gives the product better storage quality and enhances product distribution. The drying characteristics of a number of agro-product have been reported by some authors in the literature (Aguilera et al., 2009; Ayensu, 1997; Kumar et al., 2012; Doymaz and Ismail, 2011). A number of pre-treatments which include the addition of table salt and/or sugar and blanching have been reported to have minimized structural tissue disruption and to have enhanced moisture removal rate. Previous work has shown that sodium meta-bisulfite, potassium carbonate, ethyl ester emulsion, and ascorbic acid have been used as commercial pre-treatment in the drying of an agricultural commodity (Doymaz and Kocayigit, 2011; El-Beltagy et al., 2007). However, literature is sparse on the effects of pre-treatments and drying characteristics of African oil bean cotyledons. Thus, this investigation aimed to assess the effects of pre-treatments, cotyledon thickness, and drying air temperature on the drying characteristics of cotyledons in African oil beans.

MATERIALS AND METHODS

Materials

A Conservation Officer at Ilaro, South Western Nigeria (6.8954° N, 3.0126° E) sold matured African Oil Bean seeds (*Pentaclethra macrophylla* Benth). To remove the hard seed coats, a batch of the seeds was parboiled for 30 minutes at 103.42 kPa in a pressure cooker. Some cotyledons were cut in half to vary the thickness, while others were left whole. The two samples were steamed for 6 hours at 103.42 kPa (Enujiugha, 2003), and the cotyledons were washed in

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

five or more changes of freshwater for 2 hours (Enujiugha, 2000). After draining the water, the cotyledons were soaked in the solutions of the following food additives: sodium meta-bisulfite (300 ppm), ascorbic acid (300 ppm), and sodium chloride (3 %) for 1 hour at 30 ± 2 °C (Mbajunwa, 1993). Some of the samples were also fermented for three (3) days. The boiled cotyledons were wrapped in clean and sterile *Tectona gradis* leaves and allowed to ferment in a basket for three days at ambient temperature (Orwa et al., 2009). The cotyledons were removed from the pre-treatment solution at the expiration of the pre-treatment time and the solution was drained off.

Drying procedure

Prepared samples were weighed, and dried at different temperatures (50, 60, 70, and 80 °C). During drying, samples were weighed hourly intervals until equilibrium was achieved but, initial 30 minutes reading was captured at10 minute intervals after which the next reading was 30 minutes. On reaching equilibrium, samples were further dried in the oven at 100 °C for 24 hours (Doymaz, 2007) to obtain the dry solids (bone dry weight). Initial, instantaneous, and equilibrium moisture contents were calculated from the (Hii et al., 2008).

Determination of effective moisture diffusion coefficient

Dehydration of food materials occurs in the declining moisture removal rate and moisture transfer during drying is controlled by internal moisture migration (Sacilik, 2007; Sobukola, 2009; Kaleemullah and Kailappan, 2006). Fick's diffusion equation as shown in Eq. 2, for a lab, assuming one-dimensional moisture transfer, void of shrinkage, at isotherm, diffusivity coefficients, and negligible external resistance has been widely used to describe the drying process during falling rate period for all agriculture produce is as follow:

$$MR = \frac{m_t - m_e}{m_o - m_e} \qquad \ldots 1$$

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

Where MR denotes moisture ratio, m_t denotes moisture content at time, t (kg water/kg dry matter), m_e denotes moisture content at equilibrium (kg water/kg dry matter), m_o denotes initial moisture content (kg water/kg dry matter), L denotes half-thickness of African oil bean cotyledons (m), and D_m denotes moisture diffusivity. By assuming that the first term of the series was significant, the linear solution of Equation 2 was achieved. Using Equation's natural logarithm:

$$\ln MR = \ln \frac{8}{\pi^2} - \left(\frac{-\pi^2 D_m t}{4L^2} \right) \qquad \ldots 3.$$

Moisture diffusivity (Dev et al. 2008) was determined to compute the slope of the graph of the natural logarithm of moisture ratio (ln MR) versus time (t).

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

$$slope = \frac{\pi^2 D_m}{4L^2} \quad \ldots 4$$

2.5. Determination of activation energy

Plotting the effective moisture diffusion coefficient data (Dev et al., 2008) against the inverse of absolute temperature (1/Tabs) allowed for the estimation of the activation energy, as determined through the use of the existing diffusion model (Simal et al., 2005; Lee & Kim, 2009; Dev et al., 2008; Rosselló et al., 1997).

$$D_m = D_o \exp - \frac{E_a}{RT_{abs}} \quad \ldots 5$$

This can be linearized by applying logarithms as:

$$\ln D_m = \ln D_o - \frac{E_a}{RT_{abs}} \quad \ldots 6$$

$E_a$was obtained from the slope of the plot:

$$Slope = -\frac{E_a}{R} \quad \ldots 7$$

Where,
E_a is the activation energy in (kJ/mol),
R is the universal gas constant (8.3143 J.mol^{-1} K^{-1}), and
T_{abs} is the absolute temperature (K).

Modelling drying characteristics

Moisture ratios of the *Pentaclethra macrophylla* cotyledons during the thin layer drying experiments were estimated using Equation 1 (Tunde-Akintunde and Oke, 2012), four thin layer drying models as shown in Table 1 were selected for fitting the experimental data obtained from drying the samples at 50; 60; 70; 80 ^{o}C drying air temperature. The goodness of fit of each model was evaluated using the coefficient determination (R^2), the mean relative per cent error (P), the root mean square error ($RMSE$) and the reduced chi-square (χ^2) as the mean square of the deviation between

the experimental and predicted observations for the drying models (Tarigan et al., 2007; Guiné et al., 2011; Ertekin and Yaldiz, 2004). The parameters of all the models were estimated using Data fit software version 8.2 by Oakdale Engineering.

$$R^2 = \frac{\sum_{i=1}^{n}\left(MR_{\exp,i} - MR_{pre,i}\right)\sum_{i=1}^{n}\left(MR_{pre,i} - MR_{\exp,i}\right)}{\sqrt{\left[\sum_{i=1}^{n}\left(MR_{\exp,i} - MR_{pre,i}\right)\right]^2\left[\sum_{i=1}^{n}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]}} \quad \ldots 8$$

$$P = \frac{100}{N}\sum_{i=1}^{N}\frac{MR_{\exp,i} - MR_{pre,i}}{MR_{\exp,i}} \quad \ldots 9$$

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{pre,i} \right)^2 \right]^{\frac{1}{2}} \quad \ldots 10$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{pre,i} \right)^2}{N - n} \quad \ldots 11$$

Where, $MR_{exp,i}$ is the i^{th} experimentally observed moisture ratio, $MR_{pre,i}$ is the i^{th} predicted moisture ratio, N is the number of observations and *n* is the number of constants. The higher the values of R^2 (closeness to one), the least values of χ^2 and *RMSE* (closeness to zero) determines the fitness of the data.

RESULTS AND DISCUSSION

Effect of temperature, pre-treatment and thickness on moisture content, moisture ratio and drying rate

Dimensionless moisture ratio was computed from the result generated during drying of the African Oil bean cotyledons. The result of a representative sample was presented in Figure 1. The effect of pre-treatments on the moisture profile of the African oil bean cotyledons over drying time are shown in Figures 1-2. Moisture ratio reduced in a similar manner to that which was observed in the moisture profile graph (Fig. 2). Similar trends have been observed for the drying of untreated and other pre-treated samples. Figures 3 & 4 present the effect of drying temperature on moisture content and moisture ratio of African oil bean cotyledons. The constant rate was not detected in the drying experiment. This demonstrates the diffusion-controlled process, where moisture diffuses from the product's core to its surface, limiting the pace of moisture loss. Similar trends for candle and Asian white radish slices were found by Tarigan et al. (2007) and Lee and Kin (2009). The moisture content of the samples also decreased with increasing drying time as shown in Figure 3. The drying air temperature had a significant influence on the drying time. From a range of drying experiments, the longest and shortest drying times were recorded at 50^{o}C and 80^{o}C, respectively. The drying time taken to reach equilibrium moisture content was 34, 26, 24 and 20thhour at drying air temperatures of 50, 60, 70 and 80^{o}C, respectively, for 3 % NaCl treated samples (Figure 3). The drying time was reduced by 58.82% when the air-drying temperature was raised from 50^{o}C to 80^{o}C. Again, the time required to reduce the moisture ratio to any given level was dependent on the drying temperature, the highest at 50^{o}C (34 hours) and lowest at 80 ^{o}C (20 hours) (Figure 4). A similar trend was observed in the drying of untreated (14 hours), fermented (15 hours) and ascorbic acid (14 hours) treated samples at 80^{o}C. The result above is in accordance with previous studies reported by Doymaz and Ismail (2011); Guiné et al. (2011) for drying of sweet cherry and pumpkin respectively.

Various pre-treatments applied prior to the drying of African oil bean cotyledons affected the drying time.Pre-treatments reduce the resistance to moisture diffusion and invariably increasing the drying rate. Samples pretreated with sodium meta-bisulfite were found to have a shorter drying time compared to control, fermented and other pre-treatments (sodium chloride and ascorbic acid). Similar findings were reported by Dev et al. (2008) dipping of Cape gooseberry fruits in chemical pre-treatment increased water loss rate during drying.

The influence of cotyledons thickness of the African oil bean on drying time was determined at a fixed drying air temperature of 60 ^{o}C as shown in figure 5. The average thickness of single and double cotyledon was 5.0 ± 0.03 mm and 9.0 ± 0.04 mm, respectively. Drying time of single cotyledon was 133.33% higher than double cotyledons. The higher drying time of the double cotyledons could be due to increased resistance to greater distance moisture travelled from the core of the cotyledons to the surface. The resistance to moisture movement is relatively higher in thicker cotyledons than in thinner ones. Also, the lower drying time for samples with single cotyledon could be attributed to decreased resistance of the internal movement of moisture in the samples which facilitated faster moisture diffusion from the samples which invariably influenced moisture removal rate. Thus, single cotyledon dried faster due to the shorter distance of moisture diffusion, the moisture travels and increased surface area exposed for a given number of samples. This is in agreement with previous studies by Ertekin and Yaldiz (2004) on drying of eggplant; Falade et al. (2007) on drying of yam slices; Sobukola (2009) on drying of okra slices. Generally, it is observed that the time required to reduce the moisture content of samples to any required moisture level was dependent on the drying conditions that are influenced by drying parameters (drying air temperature, pre-treatment and cotyledon thickness).

The changes in the drying rate (kg H_2O/kg dry matter-hour) of the samples with the moisture content (kg H_2O/kg dry matter) are shown in Figures 6 and 7. The rate of moisture removal was significantly affected moisture content-temperature interaction. The higher the drying air temperatures, the steeper drying rate curves, this could be attributed to the shorter drying time recorded by samples dried at higher temperatures. Steepest drying rate curve was obtained at 80 ^{o}C which was the highest drying temperature used in the study. Likewise, the pre-treatments also have a pronounced influence on the drying rate of the sample. Sodium meta-bisulphite and sodium chloride treated samples showed the highest and least drying rates, respectively. The results obtained are consistent with those reported in literatures (Babalis et al., 2006; Kaleta and Gornicki, 2010; Giri and Prasad, 2007; Falade and Abbo, 2007; El-Beltagy et al., 2007) in which air temperature is considered the most important factor affecting drying rate.

Effect of pre-treatment, temperature and thickness on moisture diffusivity of African oil bean cotyledons during drying

Non-dimensional moisture ratio for the samples was plotted in semi-logarithmic graph ln*MR*–*t* in order to determine the mechanism of water transport during drying and to calculate effective diffusion coefficients (Tunde-Akintunde and Oke, 2012). Linear lines were obtained for all samples to confirm that diffusion is a mechanism for removal of water during drying of African oil bean cotyledons. The plots were found to satisfactorily describe the drying behaviour over the

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

moisture ratio range ($0 \leq MR \leq 1.0$), a range that represents the bulk of the drying process, as straight lines were obtained by regression analysis with high correlation coefficients (R^2 = 0.9915- 0.9955). Figure 8 shows the plot of ln*MR* versus time for the samples at the different drying temperatures (50 – 80^{o}C) for sodium meta-bisulfite treated samples.

It is worthy to note that diffusion controls the falling rate period, the effective diffusion coefficients (Devet al.,2008) were calculated using Equation 4. From the curves, slopes of the lines were determined by regression analysis and D_m values were calculated and reported in Table 2. Due to the presence of high moisture content before drying, an increased shrinkage of the African oil bean samples was noticed during the process of drying. Hence, dimension is defined with the assumption that shrinkage was negligible during moisture removal.

Regardless of pre-treatment type and a number of seed cotyledons increased drying temperature brought about an increased effective diffusivity (Tables 2). The effective moisture diffusivity, D_m of African oil bean cotyledons increased from 4.9061×10^{-10} – 2.091×10^{-09} m^2 s^{-1} as the thin layer drying temperature increase from 50 to 80 ^{o}C, for both single and double cotyledons. Moisture diffusivities gotten in the study were noticed to be within the general range of $10^{-11}$to 10^{-09} m^2/s for food materials (Mirzaee et al., 2009; Dinrifo, 2012) and similar with values stated by Mittal et al. (2009) for peas (3.1 - 6.6×10^{-10} m^2/s) and for soybean (1.304×10^{-10} m^2/s). In this study, the major factors that influenced diffusivities effectiveness were observed to be pre-treatment and temperature. The ascorbic acid-treated samples had the least effective diffusivity (4.9833×10^{-10} - 1.1686×10^{-09} m^2/s), while the sodium meta-bisulfite treated sample had the highest effective diffusivity (1.3541×10^{-09} – 2.091×10^{-09}).

Drying at high temperatures, especially at 80 ºC, seemed to be effective on moisture removal, possessing effective diffusivity of 1.01– 2.091×10^{-09} m^2/s. Findings that correlates with the effects of air temperature and pre-treatment on the effective moisture diffusivity were reported by Dinrifo (2012) for sweet potatoes; Doymaz (2007) for pumpkin; Kaleemullah and Kailappan (2006) for red chillies. The concentration of pre-treatments showed a significant effect ($p<0.05$) on the effective diffusivities of dried African oil bean seeds. Double cotyledons showed lower effective diffusivity than single cotyledon, and resultant longer drying time and lower drying rate. This is likely to happen because the migration of moisture gets highly difficult as distance in which moisture migrate increases during drying. Whereas, for single cotyledons, distance in which moisture will transfer were shorter which make its effective moisture diffusivity higher than those of double cotyledons. The moisture diffusivity values were in comparison to previous research reported by Guine and Fernandes (2006) on drying of chestnut; Hii et al. (2009); Rosselló et al. (1997) for greenbean; Olurin et al. (2012) on drying of blanched field pumpkin.

Effect of pre-treatment, pre-treatment concentration and thickness on the activation energy of African oil bean cotyledons during drying

The activation energy (kJ mol-1) is the energy required to remove one mole of moisture from a particular material and is thus affected by material-moisture bonding (Baini & Langrish, 2007;

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

Guine & Fernandes, 2006). An overview of the mechanisms of moisture migration within the product is as follows: capillary water migration, liquid diffusion due to concentration gradients, surface diffusion, and water vapour diffusion in air-filled products pores, flow due to pressure gradient and flow due to vapourisation-condensation sequence (Barbosa-Cánovas and Vega-Mercado, 1996; Mittal, 1999; Moreira et al., 2011). Since the drying of the African oil bean cotyledons exhibited only falling rate curve as reported above with negligible shrinkage, diffusion of water vapour through the sample pore is assumed. Mittal (1999) stated that for the diffusion of moisture to be initiated, a certain amount of energy is needed which is also linked to the temperature dependence of diffusivity. The activation energy (E_a) was calculated from Equation 6. The activation energy obtained is reported in Table 3. The activation energy of African oil bean cotyledons showed high coefficients of determination (R^2 =0.8098 – 0.9980) indication of a good fit (Table 3). As expected, the E_a varied with the number of cotyledons and pre-treatments. The activation energy for drying ranged from 10.29 to 27.12 kJ/mol for untreated, fermented, sodium chloride treated, and sodium meta bi-sulfite treated African oil bean cotyledons, Higher E_a in sodium chloride treated samples could be attributed bound binding of molecular moisture to the salt. Single cotyledon consistently recorded lower E_a values (10.29to 18.73 kJ/mol) than double cotyledons (12.50 to 27.12 kJ/mol). This is likely to happen because during drying the physical structure becomes denser and harder making the migration of moisture to be highly difficult. This correlates with studies previously carried out by Moreira et al. (2011) for chestnut (17.3–35.4 kJ/mol) and Doymaz and Kocayigit (2011) for green peas (26.86-30.99 kJ/mol). The activation energy responsible for moisture removal in African oil bean cotyledon dried fell within the range (12.7–110 kJ/mol) previously reported for various food materials (Zogsas et al., 1996).

Modelling of drying kinetics of African oil bean cotyledons

The drying curves of African oil bean cotyledons obtained from experiments, M = f(t) (moisture content as a function of drying time), were converted to non-dimensional moisture ratio (MR), theoretical, and fitted to four models shown in Table 1. Regression analyses were conducted using the Data fit 8. 2 (Oakdale Engineering). Following statistical tests were used to evaluate the performance of the models: coefficient of determination (R^2), a mean relative percentage deviation (P), root mean square error ($RMSE$) and reduced chi-square (χ^2). To adequately describe the thin-layer drying characteristics of African oil bean cotyledon, the adequate model chosen was the one with the *highest* R^2 *values*, while the χ^2, *RMSE* and P –values are the lowest. Generally, the Midilli and Kucuk model gave the highest R^2 and least P, *RMSE* and χ^2 values. Thus, it was selected to represent the thin layer drying kinetics of African oil bean cotyledons. A validation test was performed to validate the Midilli and Kucuk models by comparing projected and experimental moisture ratios at various drying air temperatures. Figure 8 shows an acceptable connection between the observed and predicted moisture ratio values, as both were positioned around the straight line for the Midilli and Kucuk model. The Midilli and Kucuk model might thus be utilized to describe the drying characteristics of African oil bean

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

cotyledons. This finding corroborates the findings of Hi et al. (2008) for thin-layer drying kinetics of cocoa beans and Ertekin and Yaldiz (2004) for eggplant drying kinetics. The parameters ‘k’ (drying rate constant) obtained from the regression analyses of experimental data obtained from drying characteristics of African oil bean cotyledons using selected models (Newton, Page, Henderson &Pabis and Midilli&Kucuk) for all the pre-treatments in Tables 4-11 varied with increasing drying air temperature, however, it decreases with increasing cotyledon thickness. A higher drying rate constant ‘k’ exhibited by higher drying air temperature signifies faster drying due to increased moisture diffusion due to an improved collision of the water molecule in the core African oil bean samples. This correlates with the analysis by Sobukola (2009) and Olurin et al. (2012). In addition, there is variation in the drying rate constant ‘k’ with pre-treatment and drying air temperature. Expectedly, sodium meta-bisulfite treated samples exhibited a higher drying rate constant (2.2868) than other pre-treatments. This can be attributed to the lower drying time displayed by sodium meta-bisulfite treated samples. However, no clear pattern was revealed by the drying coefficient ‘n’ value due to its dependency on further processing conditions. It is in tandem with the findings of Dinrifo et al. (2012) and Olurin et al. (2012).

CONCLUSION

Thin-layer drying of African oil bean cotyledons was investigated. Inner diffusion of moisture was the major controlling factor in the drying rate of the African oil bean where the effective diffusion coefficient showed a temperature dependency in an Arrhenius way. When the temperature is increased, moisture diffusivity coefficients generally increase. The effective moisture diffusivity, D_m of African oil bean cotyledons increase from $4.9061\times10^{-10} – 2.091 \times 10^{-9} m^2/s$ as the thin layer drying temperature increase from 50 to 80^{o}C. The time required to dry single cotyledon was lesser as compared to double cotyledon. Moisture diffusivity was higher in single cotyledon than in double. The Midilli and Kucuk model was discovered to be more suitable in the description of the African oil bean cotyledons drying kinetics.

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Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

APPENDICES

Table 1. Mathematical models used to describe the drying kinetics

No.	Model name	Model	References
1.	Newton	$MR = \exp(-kt)$	(Ayensu, 1997)
2.	Page	$MR = \exp(-kt^{n})$	(Agrawal and Singh, 1977)
3.	Henderson &Pabis	$MR = a\exp(-kt)$	(Westermanet al., 1973)
4.	Midilli and Kucuk	$MR = a\exp(-kt^{n}) + bt$	(Midilli and Kucuk, 2003)

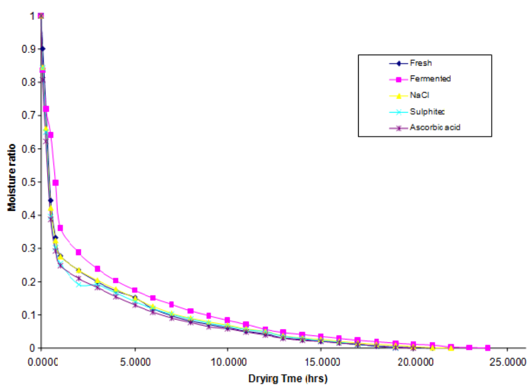

Fig. 1: Effect of pretreatments on moisture ratio of African oil bean cotyledons

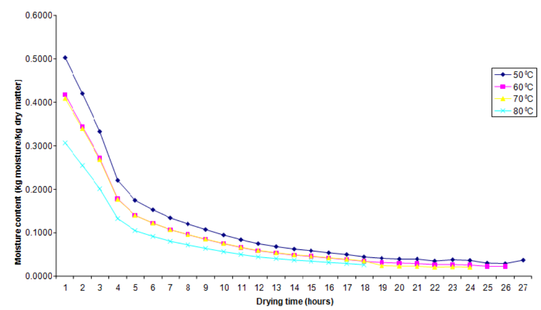

Fig. 3: Effect of drying air temperature on moisture profile of 3% NaCl treated African oil bean cotyledons

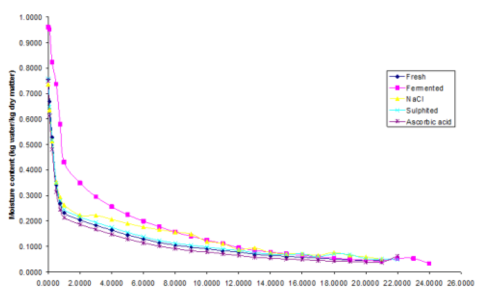

Fig. 2: Effect of pretreatments on moisture profile of African oil cotyledons

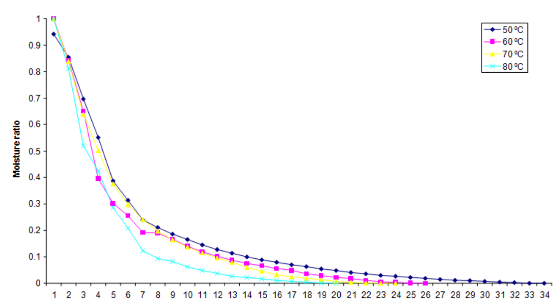

Fig. 4: Effect of drying air temperature on moisture ratio of 3% NaCl treated African oil bean cotyledons

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 24 .

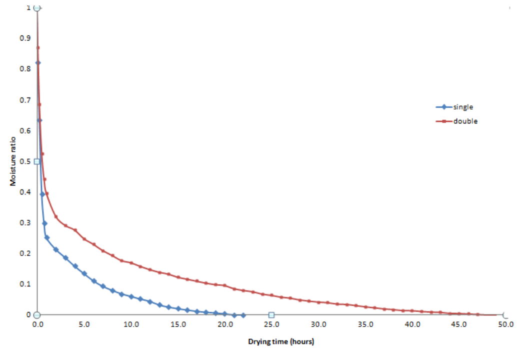

Fig. 5: Effect of slice thickness on the moisture ratio untreated African oil bean slices

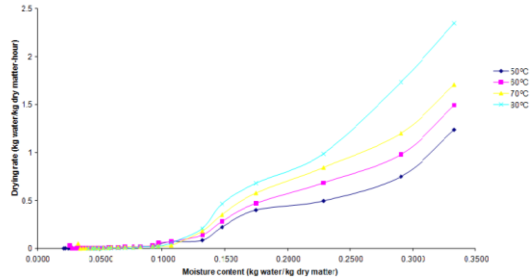

Fig. 6: Effect of temperature on the drying rate of ascorbic acid treated African oil bean cotylecons (single)

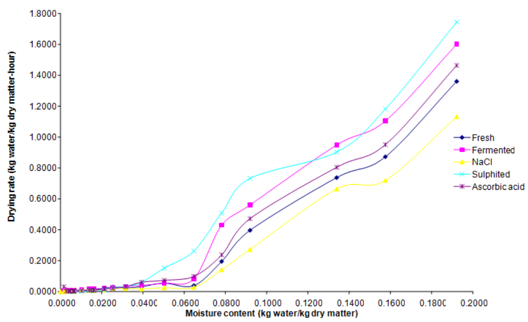

Fig. 7: Effect of pretreatment on the drying rate of fresh & pre-treated African oil bean cotyledons dried at 60 °C

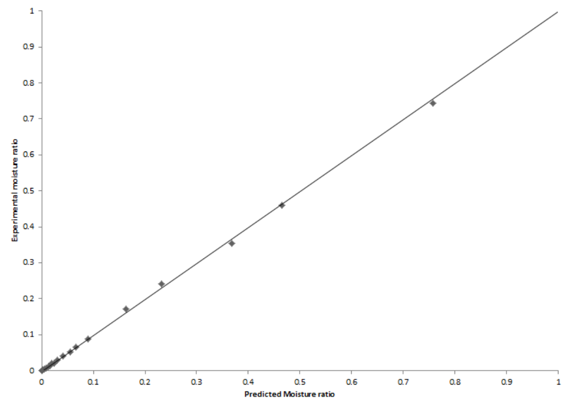

Fig. 8: Experimental Moisture Ratio vs. Predicted Moisture Ratio generated by Midilli and Kucuk Model at 80 °C

Table 2. Effect of pre-treatment and thickness (number of cotyledons) on effective diffusivity of African oil bean at different drying temperatures conditions.

Number of cotyledon	Pre-treatments	Effective diffusivity (m^2 s^{-1})			
		50°C	60°C	70°C	80°C
1	Control	8.3175E-10	9.2560E-10	1.0161E-09	1.4913E-09
1	Fermented	9.3283E-10	9.9794E-10	1.1147E-09	1.7497E-09
1	NaCl	8.2894E-10	9.2364E-10	1.0171E-09	1.5332E-09
1	$NaHSO_3$	1.5131E-09	1.7101E-09	1.9136E-09	2.0910E-09
1	$C_6H_8O_6$	8.3394E-10	9.3158E-10	9.9642E-10	1.1686E-09
2	Control	4.9542E-10	8.3361E-10	9.1528E-10	1.0100E-09
2	Fermented	8.6608E-10	9.3050E-10	1.2802E-09	1.5773E-09
2	NaCl	4.9061E-10	8.3833E-10	9.4192E-10	1.2174E-09
2	$NaHSO_3$	1.3541E-09	1.6516E-09	1.6784E-09	2.0170E-09
2	$C_6H_8O_6$	4.9822E-10	8.3889E-10	9.4411E-10	1.0565E-09

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

Table 3. Effect of pre-treatment and cotyledons thickness of African oil bean cotyledons on moisture diffusion during air drying.

Pre-treatment	Single cotyledon (kJ mol^{-1})	R^2	Double cotyledon (kJ mol^{-1})	R^2
Control	17.35	0.8615	21.39	0.8402
Fermented	18.73	0.8098	20.00	0.9448
NaCl	18.55	0.8971	27.12	0.9303
$NaHSO_3$	10.29	0.9980	12.50	0.9232
$C_6H_8O_6$	10.31	0.9690	19.74	0.8671

Table 4. Statistical results from various thin-layers Models at 50 ^oC (single cotyledon)

Pre-treatment/Model	K	n	A	B	R^2	P	RMSE	χ^2
Control								
Newton	0.7927				0.9832	0.6730	0.2447	2.84E-08
Page	0.7798	0.5050			0.9832	0.6730	0.2447	2.84E-08
Henderson &Pabis	0.4234		0.8242		0.9046	0.4922	0.1789	2.85E-08
Midilli&Kucuk	0.8257	0.4775	1.0431	3.10E-04	0.9843	0.0173	0.0063	5.00E-06
Fermented								
Newton	0.8932				0.9602	0.6730	0.0239	0.0003
Page	0.8237	0.5122			0.9832	0.0293	0.0021	0.0001
Henderson &Pabis	0.5919		0.8296		0.8934	0.7167	0.2360	0.0592
Midilli&Kucuk	0.8327	0.4930	1.0484		0.9804	0.7167	0.2360	0.1619
NaCl				3.39E-06				
Newton	0.7493				0.9106	0.6644	0.2188	0.0509
Page	0.8866	0.4831			0.9805	0.3708	0.1221	0.0169
Henderson &Pabis	0.6519		0.8385		0.8967	0.6655	0.2405	0.0596
Midilli&Kucuk	0.8728	0.4903	0.9874		0.9857	0.0385	0.0139	0.0002
$NaHSO_3$								
Newton	1.6028			5.57E-05	0.9857	0.0385	0.0139	0.0002
Page	1.1071	0.5091			0.9866	0.0181	0.0066	4.87E-05
Henderson &Pabis	1.4027		0.8347		0.9113	0.8641	0.2776	0.0448
Midilli&Kucuk	1.1446	0.4865	1.0405		0.9773	0.0809	0.0194	0.0004
$C_6H_8O_6$								
Newton	0.7979				0.9156	0.9022	0.2169	0.0508
Page	0.7854	0.4653		1.42E-04	0.9780	0.0492	0.3586	0.1446
Henderson &Pabis	0.4546		0.9291		0.9858	0.0275	0.0083	0.0004
Midilli&Kucuk	0.8298	0.4568	1.0307		0.9846	0.0674	0.0203	0.0508
				1.58E-04				

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

Table 5. Statistical results from various thin-layers Models at 60°C (single cotyledon).

Pre-treatment/Model	K	N	A	b	R^2	P	RMSE	χ^2
Control								
Newton	1.2605				0.9160	0.8211	0.2165	0.0506
Page	0.9638	0.5204			0.9684	0.1160	0.0305	0.0003
Henderson	1.1614		0.9608		0.9172	0.8339	0.2198	0.0543
&Pabis	1.0263	0.5095	1.0403	4.16E-	0.9702	0.0446	0.0118	0.0002
Midilli&Kucuk				04				
Fermented	0.8011				0.9286	0.8659	0.2084	0.0476
Newton	0.9810	0.5002			0.9811	0.0599	0.0320	0.0003
Page	1.2320		0.9345		0.9097	0.8701	0.2039	0.0309
Henderson	1.0599	0.4903	1.0598		0.9803	0.0394	0.0273	0.0002
&Pabis				3.62E-				
Midilli&Kucuk	0.9238			04	0.9080	0.9449	0.2317	0.0559
NaCl	1.0637	0.4715			0.9696	0.1121	0.0749	0.0008
Newton	1.3844				0.9102	0.9748	0.2391	0.0619
Page	1.1555	0.4681			0.9708	0.0506	0.0124	0.0002
Henderson								
&Pabis	1.6028			4.43E-	0.8064	0.9047	0.2362	0.0579
Midilli&Kucuk	1.1071	0.4717		04	0.9752	0.0665	0.0174	0.0003
$NaHSO_3$	1.4027		0.9481		0.9008	0.9243	0.2413	0.0628
Newton	1.1446	0.4575	1.0385		0.9761	-1.519	0.3967	0.1929
Page								
Henderson	1.3777				0.9113	0.8641	0.2776	0.0448
&Pabis	1.0078	0.4653		3.74E-	0.9773	0.0809	0.0194	0.0004
Midilli&Kucuk	1.1712		0.9249	05	0.9156	0.9022	0.2169	0.0508
$C_6H_8O_6$	1.0484	0.4568	1.0360		0.9780	-1.492	0.3586	0.1446
Newton								
Page								
Henderson								
&Pabis				1.58E-				
Midilli&Kucuk				04				

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

Table 6. Statistical results from various thin-layers Models at 70 °C (single cotyledon).

Pre-treatment/Model	K	N	A	b	R^2	P	RMSE	χ^2
Control								
Newton	1.0728				0.9587	0.5784	0.8340	0.0165
Page	1.0506	0.6192			0.9781	0.1908	0.7568	0.0019
Henderson	1.1783		0.9568		0.9605	0.6180	0.8388	0.0198
&Pabis	1.0237	0.6248	1.0283	1.08E-	0.9796	0.0630	0.0873	0.0002
Midilli&Kucuk				03				
Fermented	1.1093				0.9479	0.6945	0.8297	0.0129
Newton	0.9981	0.5320			0.9802	0.0259	0.0093	0.0010
Page	1.0321		0.8919		0.9401	0.6932	0.1903	0.0204
Henderson	0.9907	0.5873	1.0045		0.9801	0.0482	0.0012	1.01E-
&Pabis				2.07E-				05
Midilli&Kucuk	1.1966			04	0.9166	0.7534	0.1767	
NaCl	0.9783	0.5139			0.9166	0.0379	0.0089	0.0311
Newton	0.9094				0.9265	0.7594	0.1779	8.22E-
Page	0.9648	0.5122			0.9883	0.0326	0.0078	05
Henderson								0.0331
&Pabis	1.1643				0.9171	0.6299	0.8656	7.06E-
Midilli&Kucuk	0.9363	0.5114			0.9878	0.0308	0.6799	05
$NaHSO_3$	0.8182		0.8779		0.9340	0.6270	0.8653	
Newton	0.9729	0.5028	1.0258		0.9883	0.0196	0.6558	0.0259
Page								6.49E-
Henderson	1.0743				0.9221	0.6048	0.8705	05
&Pabis	0.9379	0.5312			0.9878	0.0296	0.6904	0.0269
Midilli&Kucuk	0.7882		0.8779		0.9340	0.6030	0.8703	2.88E-
$C_6H_8O_6$	0.9649	0.5122	1.0258		0.9883	0.0189	0.0169	05
Newton								
Page								0.0249
Henderson								6.22E-
&Pabis								05
Midilli&Kucuk								0.0258
								2.75E-
								05

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

Table 7. Statistical results from various thin-layers Models at 80 °C (single cotyledon).

Pre-treatment/Model	K	n	A	B	R^2	P	RMSE	χ^2
Control								
Newton	1.8562				0.9904	0.3354	0.7249	0.0028
Page	1.6450	0.8265			0.9903	0.2912	0.7142	0.0023
Henderson	1.7874		0.9728		0.9911	0.3845	0.7354	0.0039
&Pabis	1.6648	0.8310	1.0038	1.25E-	0.9940	0.1262	0.0540	0.0005
Midilli&Kucuk				03				
Fermented	1.8202				0.9850	0.4391	0.7104	0.0093
Newton	1.4368	0.5672			0.9893	0.2345	0.7021	0.0032
Page	1.6249		0.9478		0.9909	0.3818	0.7249	0.0021
Henderson	1.6026	0.7898	1.0029		0.9929	0.1287	0.0209	0.0002
&Pabis				1.10E-				
Midilli&Kucuk	1.7978			03	0.9665	0.7174	0.7929	0.0087
NaCl	1.3605	0.6011			0.9898	0.3082	0.7316	0.0017
Newton	1.6301		0.9387		0.9702	0.7167	0.7928	0.0092
Page	1.4092	0.6080	1.0201		0.9910	0.1370	0.6772	0.0004
Henderson								
&Pabis	2.2868			1.14E-	0.9904	0.4674	0.7249	0.0028
Midilli&Kucuk	1.5089	0.8265		03	0.9932	0.4058	0.7142	0.0023
$NaHSO_3$	2.1899		0.9728		0.9911	0.4795	0.7268	0.0032
Newton	1.8534	0.8310	1.0038		0.9940	0.1837	0.0170	0.0005
Page								
Henderson	1.8562				0.9759	0.5246	0.7551	0.0061
&Pabis	1.6450	0.7332		1.25E-	0.9850	0.4085	0.7355	0.0039
Midilli&Kucuk	1.7874		0.9700	03	0.9768	0.5707	0.7618	0.0077
$C_6H_8O_6$	1.6648	0.7262	1.0216		0.9868	0.1517	0.0026	0.0006
Newton								
Page								
Henderson								
&Pabis				1.62E-				
Midilli&Kucuk				03				

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

Table 8. Statistical results from various thin-layers Models at 50 °C (double cotyledon).

Pre-treatment/Model	K	n	a	B	R^2	P	RMSE	χ^2
Control								
Newton	0.3380				0.9904	0.3354	0.7249	0.0028
Page	0.6132	0.8265	0.9728		0.9903	0.2912	0.7142	0.0023
Henderson	0.2840		1.0038		0.9911	0.3845	0.7354	0.0039
&Pabis	0.6700	0.8310		1.25E-	0.9940	0.1262	0.0540	0.0005
Midilli&Kucuk				03				
Fermented	0.2943				0.9850	0.4391	0.7104	0.0093
Newton	0.6032	0.5672			0.9893	0.2345	0.7021	0.0032
Page	0.2395		0.9478		0.9909	0.3818	0.7249	0.0021
Henderson	0.5981		1.0029		0.9929	0.1287	0.0209	0.0002
&Pabis		0.7898		1.10E-				
Midilli&Kucuk	0.4952			03	0.9665	0.7174	0.7929	0.0087
NaCl	0.6695	0.6011			0.9898	0.3082	0.7316	0.0017
Newton	0.2350		0.9387		0.9702	0.7167	0.7928	0.0092
Page	0.7224	0.6080	1.0201		0.9910	0.3082	0.0072	0.0004
Henderson								
&Pabis	0.8843			1.14E-	0.9904	0.4058	0.7249	0.0028
Midilli&Kucuk	0.8136	0.8265	0.9728	03	0.9932	0.4795	0.7142	0.0023
$NaHSO_3$	0.1927		1.0038		0.9911	0.0459	0.7268	0.0032
Newton	0.8617	0.8310			0.9940	0.4058	0.0009	0.0005
Page								
Henderson	0.3332				0.7979	0.3626	0.9542	0.0482
&Pabis	0.3775	0.4588	0.7194	1.25E-	0.9857	0.0388	0.8710	0.0006
Midilli&Kucuk	0.1530		1.0335	03	0.9008	0.2077	0.9328	0.0162
$C_6H_8O_6$	0.6835	0.4070			0.9896	0.0030	0.0051	3.62E-
Newton				8.58E-				06
Page				04				
Henderson								
&Pabis								
Midilli&Kucuk								

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

Table 9. Statistical results from various thin-layers Models at 60 °C (double cotyledon).

Pre-treatment/Model	K	n	A	B	R^2	P	RMSE	χ^2
Control								
Newton	0.8221				0.7186	0.8287	0.9858	0.2290
Page	0.7920	0.3864			0.9791	-0.0233	0.8545	0.0002
Henderson	0.1512		0.6451		0.8340	0.2797	0.9438	0.0266
&Pabis	0.8296	0.3427	1.0336	8.05E-	0.9832	0.0078	0.0178	2.14E-
Midilli&Kucuk				04				05
Fermented	0.8428				0.8043	0.7539	0.9218	
Newton	0.8029	0.3912			0.9799	-0.0219	0.8911	0.9236
Page	0.1623		0.6209		0.8926	0.1265	0.9721	1.92E-
Henderson	0.8311	0.3219	1.0934		0.9817	0.0023	0.0120	06
&Pabis				-7.90E-				0.0297
Midilli&Kucuk	1.1619			05	0.8487	0.8293	0.9681	4.09E-
NaCl	0.9074	0.4107			0.9797	0.0335	0.8367	05
Newton	0.7368		0.8524		0.8592	0.7809	0.9654	
Page	0.9489	0.3948	1.0394		0.9806	0.0228	0.0222	0.1284
Henderson								0.0002
&Pabis	0.9163			-9.03E-	0.8184	0.7785	0.9786	0.1165
Midilli&Kucuk	0.8346	0.4110		05	0.9770	0.0119	0.8279	0.0001
$NaHSO_3$	0.2860		0.7249		0.8464	0.4686	0.9589	
Newton	0.8812	0.3853	1.0446		0.9784	0.0163	0.0084	0.1595
Page								3.80E-
Henderson	0.8240				0.7568	0.8651	0.9850	05
&Pabis	0.8019	0.3957		-2.50E-	0.9680	0.0033	0.7837	0.0590
Midilli&Kucuk	0.1891		0.6756	04	0.8555	0.3586	0.9438	7.44E-
$C_6H_8O_6$	0.8526	0.3613	1.0491		0.9820	0.0136	0.0008	05
Newton								
Page								0.2292
Henderson								3.32E-
&Pabis				-4.68E-				06
Midilli&Kucuk				04				0.0338
								6.00E-
								05

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

Table 10. Statistical results from various thin-layers Models at 70 °C (double cotyledon).

Pre-treatment/Model	K	n	a	B	R^2	P	RMSE	χ^2
Control								
Newton	1.1709				0.7524	1.1186	0.9624	0.1896
Page	0.8859	0.3899			0.9709	-0.0212	0.7622	7.03E-
Henderson	0.2130		0.6550		0.8194	0.3513	0.8990	05
&Pabis	0.6098	0.4468	1.0310	-1.23E-	0.9746	0.0126	0.0092	0.0193
Midilli&Kucuk				03				2.65E-
Fermented	1.1986				0.9821	1.1934	0.7232	05
Newton	0.9234	0.3863			0.9820	-0.0236	0.7303	
Page	0.2175		0.6578		0.8163	0.2078	0.9043	0.1823
Henderson	0.6213	0.4925	1.0311		0.9915	0.0056	0.0094	6.92E-
&Pabis				-6.80E-				05
Midilli&Kucuk	1.2509			04	0.7473	1.1112	0.9674	0.0245
NaCl	0.9126	0.3760			0.9735	-0.0181	0.7687	8.52E-
Newton	0.2143		0.6409		0.8106	0.3758	0.9108	06
Page	0.7124	0.3383	1.0273		0.9765	0.0119	0.0019	
Henderson								0.1992
&Pabis	1.2543			-1.01E-	0.7246	1.1009	0.9637	5.22E-
Midilli&Kucuk	0.6229	0.3727		03	0.9752	-0.0458	0.7958	05
$NaHSO_3$	0.1790		0.6310		0.8243	0.2864	0.8924	0.0234
Newton	0.7276	0.3247	1.0221		0.9810	0.0083	0.0088	2.50E-
Page								05
Henderson	1.2163				0.7045	1.0889	0.9655	
&Pabis	0.9340	0.3679		-1.63E-	0.9735	-0.0700	0.8290	0.1857
Midilli&Kucuk	0.1944		0.6139	03	0.8256	0.2244	0.8844	0.0003
$C_6H_8O_6$	0.8026	0.3061	1.0175		0.9838	0.0062	0.0008	0.0130
Newton								1.15E-
Page								05
Henderson								
&Pabis				-2.06E-				0.1858
Midilli &Kucuk				03				0.0008
								0.0081
								6.68E-
								06

Journal of Agriculture and Food Sciences
Volume 21, Number 2, October 2023, p p 1- 23 .

Table 11. Statistical results from various thin-layers Models at 80 °C (double cotyledon).

Pre-treatment/Model	K	n	A	b	R^2	P	RMSE	$\chi 2$
Control								
Newton	1.0931				0.9076	0.8627	0.8997	0.0589
Page	0.9027	0.5051			0.9798	0.0734	0.7444	0.0005
Henderson	0.8590		0.9087		0.9129	0.8438	0.8982	0.0587
&Pabis	0.9530	0.4850	1.0400	-5.77E-	0.9810		0.0014	0.0001
Midilli&Kucuk				05		0.0339		
Fermented	1.1208				0.9392		0.9056	0.0509
Newton	0.9002	0.5001			0.9803		0.6932	0.0001
Page	0.8601		0.9004		0.9234	0.8981	0.9238	0.0539
Henderson	0.9729	0.4931	1.0448		0.9802		0.0034	0.0003
&Pabis				-4.98E-		0.0638		
Midilli&Kucuk	1.2034			05	0.9140		0.9023	0.0552
NaCl	0.9479	0.5005			0.9787	0.7929	0.7663	0.0007
Newton	1.0168		0.9277		0.9176	0.0367	0.9030	0.0584
Page	0.9994	0.4838	1.0449		0.9799		0.0072	0.0002
Henderson								
&Pabis	1.1612			-3.82E-	0.8832	0.8489	0.9071	0.0728
Midilli&Kucuk	0.9275	0.4687		04	0.9814		0.7039	0.0001
$NaHSO_3$	1.2389		0.8737		0.8929	0.0935	0.9033	0.0681
Newton	0.9637	0.4453	1.0360		0.9824		0.0074	6.82E-
Page						0.8568		05
Henderson	1.0085				0.7990		0.9379	0.1278
&Pabis	0.8602	0.4262		-3.82E-	0.9782	0.0461	0.7015	2.92E-
Midilli & Kucuk	0.9765		0.7082	04	0.8543		0.8818	05
$C_6H_8O_6$	0.9910	0.3850	1.0300		0.9808	0.9542	0.0002	0.0222
Newton				-1.22E-		0.0353		2.64E-
Page				03		0.9038		05
Henderson						0.0274		
&Pabis								
Midilli &Kucuk						1.0460		
						-0.0161		
						0.4279		
						0.0142		