DRYING KINETICS, ENERGY REQUIREMENT, BIOACTIVE COMPOSITION AND MATHEMATICAL MODELING OF ALLIUM CEPA SLICES

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Abstract

The drying kinetics, specific energy consumed (SEC), effective moisture diffusivity (EMD), flavonoid, phenolic and vit. C contents of onion slices dried under convective oven drying (COD) were compared with microwave drying (MD). Drying was performed with onion slice thicknesses of 2, 4, 6 and 8 mm; air drying temperatures of 60, 80, and 100°C for COD and microwave power of 450 W for MD. A decrease in slice thickness and increase in drying air temperature led to a drop in the drying time. As thickness increased from 2 – 8 mm, EMD rose from 1.1 – 4.35 $\times 10^{-8}$ at 60°C, 1.1 – 5.6 $\times 10^{-8}$ at 80°C and 1.25 – 6.12 $\times 10^{-8}$ at 100°C with MD treatments yielding the highest mean value (6.65$\times 10^{-8}$ m^2 s^{-1}) at 8 mm. Maximum SEC for onion slices in COD was 238.27 kWh/kg H_2O (2 mm thickness) and the minimum was 39.4 kWh/kg H_2O (8 mm thickness) whereas maximum during MD was 25.33 kWh/kg H_2O (8 mm thickness) and minimum, 18.7 kWh/kg H_2O (2 mm thickness). MD treatment gave a significant ($p \leq 0.05$) increase in the flavonoid (39.42 – 64.4%), phenolic (38.0 – 46.84%) and vit. C (3.7 – 4.23 mg 100 g^{-1}) contents while COD treatment at 60°C and 100°C had positive effects on only vit. C and phenolic contents respectively. In comparison, the Weibull model gave the overall best fit (highest R^2=0.999; lowest SSE=0.0002, RSME=0.0123 and χ^2= 0.0004) when drying 2 mm onion slices at 100°C.

Keywords: Allium cepa, drying kinetics, specific energy consumption, flavonoid, vitamin C, microwave oven drying.

1. Introduction

Allium cepa L (onion) is one very profound perishable and largely consumed biennial horticultural crops that are grown across the entire globe (Sagar et al., 2020), which is used for it nutritional and health values. Drying process has long been regarded as an efficient means to increase the shelf-life of crops and createvalue-added added products as well as the reduction in the cost of postharvest handling (Sagar et al., 2020). Drying brings about moisture removal from agricultural products to a certain extent, under controlled conditions, leading to a drop in weight and volume, which is a very vital parameter for storage and transportation (Sakare et al. 2020). Drying also reduces enzymatic activities, diminishes the rate of microbial growth and undesirable chemical changes and enhances the concentration of nutrients and phytochemicals.

All through the decades, convective oven drying (COD) has been generally regarded as one of the most inexpensive, dominant and long-utilized drying methods in the culinary and food industries. This involves concurrent mass exchange prompting the expulsion of moisture from the intercellular spaces of the agricultural products to the ambient environment by means of evapo-diffusion (Castro et al. 2018).

Microwave drying (MD) has attracted a lot of global attention in recent times. During MD short frequency electromagnetic waves are released. As the waves penetrate the cells of the biomaterial, polar molecules, like salts and water, vibrate and cause the transportation of ions, thereby leading to the quick conversion of microwave energy to heat within the sample. Improved product quality, reduced drying time, improved energy consumption, enhanced volumetric heating and lower operating cost are some of the advantages of MD.

Dried onions as powder, granules and flakes are used as culinary ingredient in most processed foods e.g snacks sauces, onion flavored meat, soups products, and salad dressings (Süfer et al., 2018), as a substitute to the fresh form, because of the concentrated nutrients, flavor, aroma and phytochemicals as well as increased storage capacity.

Simulation and modeling of drying processes under varying process conditions is very vital in gaining efficient control over drying processes and an overall best enhancement of the quality of the resultant end product. Models are usually employed to investigate the process parameters needed to predict drying kinetics of biomaterials and to optimize such operating variables (Kaveh et al. (2021). Drying process involving food and vegetable materials ordinarily happen in the falling rate time frame (Agbede et al. (2020). In predicting mass exchange during drying under the falling rate period, a few numerical models are required.

From the industrial perspective, the need for the drying kinetics of onion slices is extremely important and has gained traction in recent times so as to be able to save energy and optimize drying conditions. Therefore, this study aims to explore the drying of onion slices (2 – 8 mm thickness) by contrasting the drying behaviour of the samples utilizing two diverse drying systems like COD (60 – 100^{o}C) and MD (450 W). In addition, the drying parameters of the equations, EMD, activation energy, and specific energy consumption were equally estimated. Some qualitative properties of the sample such as phenolic, flavonoid and vitamin C contents were also investigated.

2. Materials and method

2.1 Sample preparation of onion

Matured and ripe onion (*Allium cepa*) was procured from a known onion farmer in Ogige Main Market, Nsukka City, Enugu State, Nigeria. Uniform onion sizes were selected and stored in a refrigerator (6^{o}C). Using a digital weight balance (A-200DS Digital Analytical Balance, Denver Instruments, Germany), 120 kg of onion was measured and the average initial moisture content (MC) of the samples was estimated at 89.35 ± 0.5% (wet basis) by dehydration at 72 ± 1°C for 24 hr according to oven drying method (AOAC, 1990). The onion was neatly cut into slices of various thicknesses (2, 4, 6 and 8 mm) using a stainless-steel knife.

2.2 Drying experiments

2.2.1 COD

A laboratory oven (CD21, Gallekamp) was used for the drying. An anemometer (Lutron AM-4202; Electronic Enterprise Co., Taipei, Taiwan) was used to measure the inside air velocity of the oven as 1.0 ms^{-1}.

2.2.2 MD

The drying experiment was performed with a Haier thermocool laboratory microwave oven (HTMO-Trendy slv D90D25EL-QF) with maximum output power of 900 W.

2.3 Analysis of drying characteristics

Equations (1 & 2), (3), (4 - 6) were used to evaluate the moisture content (MC) (w.b & db), drying rate (DR) and moisture ratio (MR) respectively for the onion slices (Agbede et al., 2020):

$$MC = \frac{W_w - W_d}{W_w} \quad (1)$$

$$MC = \frac{W_w - W_d}{W_d} \quad (2)$$

$$DR = \frac{M_{t1} - M_{t2}}{t_2 - t_1} \quad (3)$$

$$MR = \exp\left(-\left(\frac{t}{\alpha} \right)^{\beta} \right) \quad (4)$$

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (5)$$

$$MR = \frac{M_t}{M_o} \quad (6)$$

Where, MC is moisture content (%, wb) or (%, db); W_w is Total mass of wet sample (g);W_d is Mass of sample after drying (g); DR is drying rate (% hr^{-1}); M_{t1} and M_{t2} are moisture contents (% w.b) at t_1 and t_2; t_1 and t_2 are different drying times (hour) during drying; MR is moisture ratio, α is the scale parameter (min), which represents drying rate constant, β is the shape parameter, which relates to the drying rate and moisture transfer mechanism in the drying process; M_t is moisture content at any time (% wet basis); M_e is equilibrium moisture content (% wet basis); M_o is initial moisture content (% wet basis)

Equation (4) was used in calculating the MR of the onion slices during thin-layer drying. Oftentimes, values for the equilibrium moisture content (M_e) is relatively small compared with M_o or M_t. Then, Equ. (5) can be simplified as Equ. (6) (Süfer and Palazoğlu, 2019).

2.4 Determination of effective moisture diffusivity (EMD), total energy consumed, specific energy consumption (SEC) and activation energy (AE)

Numerous complex processes are involved in mass and heat transfer during the drying of agricultural and food items. Capillary tube movement, molecular penetration and hydrodynamic flow, or surface propagation are difficult to analyze. Fick's second law is normally employed to measure such processes (Agbede et al. 2020). As a result, effective moisture diffusion is described by Equation (7) (Kaveh et al., 2021) which is further expressed as Equation (8).

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \quad (7)$$

$$\frac{dM}{dt} = D_{eff} \frac{d^2 M}{dr^2} \quad (8)$$

For long drying measure (MR < 0.6) and assuming rectangular geometry for the onion, negligible surface resistance to heat and mass exchange flow within the onion, uniform mass exchange and distribution of initial moisture for the onion and approximating the coefficient to a uniform value all through the experiment, Equ. (8) can be expressed as shown in Equ. (9) (Süfer and Palazoğlu, 2019)

$$D_{eff} = \frac{-4L^2}{\pi^2 t} In\left(\frac{MR\pi^2}{8}\right) \quad (9)$$

Where D_{eff} is effective moisture diffusivity (m^2s^{-1}), L is half the thickness of the slices (m), MR is moisture ratio and t is the drying time (Secs).

Total energy consumed (TEC) for MD could be computed by the expression in Equ. 10 (Agbede et al., 2020)

$$E_{tMD} = P_{MD} \times t_{MD} \quad (10)$$

The specific energy consumed (SEC) of the onion during the MD treatment, which is defined as the amount of energy utilized to evaporate one kilogram of H_2O from the material, was determined using Equ. (11) (Taghinezhad et al., 2020).

$$SEC_{MD} = \frac{P_{MD} \times t_{MD}}{M_w} \quad (11)$$

Where E_{tMD} is total energy consumed (kWhr), SEC_{MD} is the specific energy consumed (kWh $kg^{-1}H_2O$ removed), P_{MD} is microwave oven power (kW), t_{MD} is the entire drying duration (hr) and M_w is the weight of water evaporated (kg).

The activation energy (AE) for the MD (E_{aMD}) (W g^{-1}) was computed by the Arrhenius type model relating D_{eff}, mass (kg) and microwave power (W) as shown in Equ. (12) (Agbede et al. 2020).

$$D_{eff} = D_o \exp\left(\frac{E_{aMD} \times M}{P}\right) \quad (12)$$

Equ. (13) is obtained when (12) is expressed in a logarithmic form.

$$In(D_{eff}) = In(D_o) - \left(\frac{E_{aMD}}{P}\right)(M) \quad (13)$$

By plotting ln(D_{eff}) versus (m/P), the slope (K_2) (Equ. 14) is computed for the MD and needed for computing the AE for the MD system (Equ. 15).

$$K_2 = Slope = E_{aMD} \quad (14)$$

$$E_{aMD} = K_2 \quad (15)$$

TEC and SEC submitted for COD were determined by the expressions in Equs. (16) and (17) respectively (Agbede et al., 2020)

$$E_{tCOD} = AV\ell_a C_a (T_{in} - T_{amb}) \times D_t \quad (16)$$

$$E_{sCOD} = \frac{E_{tCOD}}{M_w} \quad (17)$$

Where, A is the area of the tray (m^2), the velocity of air ($m\ s^{-1}$), ℓ_a is the density of air ($kg\ m^{-3}$), C_a is the specific heat capacity of air (1828.8 $kJ\ kg^{-1}\ {}^oC^{-1}$), T_{amb} is the ambient temperature (^oC), T_{in} is inlet temperature (^oC), D_t is the entire drying duration (s) and M_{wthe} is the weight of water evaporated from the sample (kg)

The relationship between diffusion coefficient and the temperature was also expressed by an Arrhenius-type model (Equ. 18)

$$D_{eff} = D_o \exp\left(\frac{E_{a\,COD}}{R_g T_a}\right) \quad (18)$$

Activation energy (AE) for the COD (E_{aCOD}) was evaluated by plotting the D_{eff} curve against the corresponding reciprocal of absolute air temperature (T_a) (Jebri et al. 2019).

Where D_o and R_g are constant and universal gas (8.3143 $kJ\ mol^{-1}$) constant respectively

Applying the logarithms, Equ. (18) could be expressed in linear form as shown in Equ. (19).

$$In(D_{eff}) = In(D_o) - \left(\frac{E_{aCOD}}{R_g}\right)\left(\frac{1}{T_a}\right) \quad (19)$$

By plotting the graph of In(D_{eff}) against ($1/T_a$), the slope K_1 can be obtained as shown in Equ. (20) which will enable the computation of the activation energy for the COD using Equ. (21).

$$K_1 = \frac{E_{aCOD}}{R_g} \quad (20)$$

$$E_{aCOD} \times R_g \quad (21)$$

2.5 Mathematical modeling of drying curves and fitting of models to drying data

The SPSS software (version 21) was utilized to fit the mathematical models in Table 1. Statistical parameters such as of SSE, RMSE, χ^2 and R^2 calculated from equations 22, 23, 24 and 25 respectively using Microsoft Excel and SPSS software (version 21) were utilized to select appropriate drying descriptors. Drying models with the greatest R^2 and least SSE, RMSE and χ^2 was chosen as the most suitable model for portraying the drying kinetics.

$$SSE = \frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2 \quad (22)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2\right]^{1/2} \quad (23)$$

$$\chi^2 = \frac{\sum_{i-1}^{N}(MR_{\exp,i} - MR_{pred,i})^2}{N - z} \quad (24)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pred,i} - MR_{\exp,i})^2}{\sum_{i=1}^{N}(MR_{pred,i} - \overline{MR}_{\exp,i})^2} \quad (25)$$

Where $MR_{pred,i}$ is the i^{th} predicted values of the moisture ratio calculated using the models, $MR_{\exp,i}$ is the i^{th} experimental moisture ratio calculated using the models, N is the number of observations and z is the number of constants in each model.

Table 1. Some empirical models used for the onion drying kinetics

S/N	Model Name	Model Equation	Constants/Coefficient
1	Linear	$MR = 1 + bt$	Karacabey (2016)
2	Newton	$MR = \exp(-kt)$	Doymaz (2012)
3	Page	$MR = \exp(-kt^n)$	Omari et al. (2018)
4	Henderson and Pabis	$MR = a\exp(-kt)$	Srikanth et al. (2019)
5	Two Term	$MR = a\exp(-k_o t) + b\exp(-k_1 t)$	Liter et al. (2018)
6	Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Abbaszadeh et al. (2011)
7	Midilli Kucuk	$MR = a\exp(-kt^n) + bt$	Doymaz (2018)
8	Wang and Singh	$MR = 1 + at + bt^2$	Agbede et al.(2020)
9	The linear-plus-exponential	$MR = a\exp(-kt^n) + bt + c$	Thanimkarn et al. (2020)
10	Modified Page	$MR = \exp(-(kt)^n)$	Ertekin and Firat (2017)
11	Logarithmic	$MR = a\exp(-kt) + c$	Jebri et al. (2019)
12	Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	Ertekin and Firat (2017)
13	Two Term Exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	Ertekin and Firat (2017)
14	Cavalcanti-Mata	$MR = a_1\exp(-k_1 t^{n1}) + a_2\exp(-k_1 t^{n2}) + a_3$	Silva et al. (2014)
15	Verma	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	Makokha et al. (2021)

2.6 Determination of bioactive compounds and vit. C content

2.6.1 Determination of phenolic content and flavonoid contents

The total phenol content was assessed with the Folin- Ciocalteu's measure utilizing gallic acid as standard (Sasongko et al., 2020).

Total flavonoid content was assesed by Aluminium chloride ($AlCl_3$) technique utilizing quercetin as a standard for the calibration curve (Azeez et al., 2012).

2.6.2 Determination of vitamin C content

Vit. C content (ascorbic acid) was assessed by utilizing 2,6 dichlorophenol–indo-phenol (Merck KGaA, Darmstadt, Germany) tritimetric technique according to AOAC method No. 967.21 (AOAC, 2000).

2.7 **Statistical analysis of data**

The outcomes acquired for the various properties of the dried *Allium cepa* were subjected to descriptive inferential statistical analysis using SPSS, version 21; Excel software, Windows 10; Multiple comparisons test with the mean values in ANOVA were performed utilizing the least significant difference (LSD) and Fisher ratio (F), and statistical significance was set at 5% ($p < 0.05$). The outcomes were expressed as mean values ± standard deviation.

3. Results and Discussion

3.1 Results

Table 1 presents the calculated values for all the MD (450W) and COD experiments (60, 80, and 100°C air drying temperature and air velocity of 1 m s^{-1}), the calculated values for the coefficient of regression (R^2), SSE, RMSE and χ^2 ranged between 0.516 - 0.999, 0.0002 – 0.1431, 0.0015 - 0.3783, and 0.0004 - 1.0017, respectively.

From the summary of the examined models (Table 2), the Weibull, Midilli Kucuk, Two Term, Wang and Singh and Modified Page were considered to be the best models that satisfactorily described the drying behaviour of onion slices (2, 4, 6, and 8 mm thickness) for both the COD (60, 80 and 100^{o}C) and MD (450 W). The other different models showed no solid fit.

From Table 2, the Weibull model was seen to best depict the drying conduct of 2, 4, and 6 mm thick onion slices at 60^{o}C; 2, 4, 6, and 8 mm thick onion slices at 80^{o}C; 8 mm thick onion slices at 100^{o}C during COD treatment; and 2 and 6 mm onion thickness during MD (450 W) treatment with highest R^2 (0.999) and least SSE (0.0002), RMSE (0.0123) and χ^2 (0.0004) values accomplished was during 2 mm thick COD treatment at 100^{o}C drying temperature. Wang and Singh, Modified Page and Midilli Kucuk models were seen to perfectly describe the drying curve of 2, 4 and 6 mm thick onion slices respectively at 100^{o}C. During COD treatment (450 W), the Wang and Singh model most appropriately fitted the 4 and 8 mm thick onion slices, with R^2 values of 0.982 and 0.979 respectively.

In model comparison among COD and MD, the Weibull model gave the overall general best fit (highest R^2=0.999; lowest SSE=0.0002, RSME=0.0123 and χ^2= 0.0004) when drying 2 mm onion slice at 100^{o}C. For the drying characteristics and modeling of apple slices during microwave intermittent drying, Dai *et al*. (2019) reported Weibull as the best fit with R^2 = 0.999, RMSE = 0.0091, χ^2 = 0.0011. However, Agbede *et al*. (2020) reported Wang and Singh model as best fitted for both the thin layer open sun and solar drying of the green microalgae (Chlorella sp.) biomass paste while the logarithmic and two-term models were identified to best describe the drying kinetics of scent and lemon basil leave at 70 ^{o}C and 60 ^{o}C respectively (Mbegbu et al., 2021). Similarly, Kaveh et al. (2021) reported that the Page Model with the maximum values of R^2 (0.9997–0.9999), and the least RMSE (0.0159–0.0754) and $\chi 2$ (0.0003–0.0011) best described the drying kinetics of pomegranate arils under COD (50 – 70^o) at 1 m s^{-1} air velocity and MD (270 – 630 W). Differences may be due to the drying system employed and type/nature of the biomass.

Table 2. Summary of statistical parameters of thin layer mathematical models for convective oven drying (60, 80 and 100°C) and microwave drying (450 W) of onion slices

Drying Type	Slice Thickness (mm)	Model Name(s)	Highest R^2	Lowest SSE	Lowest RMSE	Lowest χ^2
	2	Weibull	0.955	0.0062	0.0790	0.0137
COD 60°C	4	Weibull	0.971	0.0038	0.0015	0.0083
	6	Midilli Kucuk and Weibull	0.988	0.0013	0.0362	0.0021
	8	Two-Term	0.978	0.0025	0.0497	0.0039
	2	Midilli Kucuk and Weibull	0.985	0.0021	0.0462	0.0043
COD 80°C	4	Midilli Kucuk and Weibull	0.990	0.0012	0.0341	0.0023
	6	Midilli Kucuk and Weibull	0.993	0.0012	0.0345	0.0024
	8	Midilli Kucuk and Weibull	0.996	0.0005	0.0227	0.0010
	2	Wang and Singh	0.991	0.0011	0.0335	0.0016
COD 100°C	4	Modified Page	0.998	0.0014	0.0370	0.0019
	6	Midilli Kukuk	0.998	0.0004	0.0187	0.0008
	8	Midilli Kucuk and Weibull	0.994	0.0008	0.0279	0.0018
	2	Weibull	0.999	0.0002	0.0123	0.0004
MD	4	Wang and Singh	0.982	0.0023	0.0481	0.0008
	6	Weibull	0.982	0.0024	0.0493	0.0030
	8	Wang and Singh	0.979	0.0026	0.0510	0.0030

3.2 Discussion

3.2.1 Drying characteristics

During COD treatment, increased air-drying temperature from 60 to 100°C resulted in increased water activity and mass exchange ratio because of ascend in heat energy occasioned by the rise in air temperature, prompting the decrease in the drying time and energy consumption. MD significantly shortened the drying duration for all the slices. The shortest drying time of 120 min was achieved with the MD at 450 W (1 d), compared to COD method at 60°C (270 min) (1 a), 80°C (180 min) (1 b) and 100°C (150 min) (1 c) (Figure 1). Reduction in slice thickness also resulted in reduction in the drying times. MR decreased significantly during drying operations until complete dehydration of the onion slices was achieved, showing that by employing the two drying methods, moisture was effectively removed from the un-dried samples

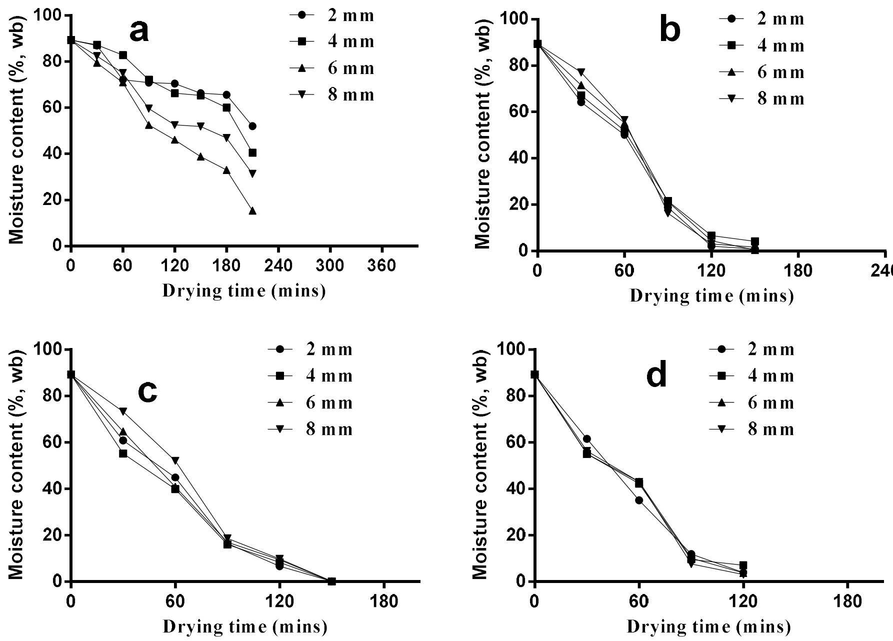

Figure 1. Curves of moisture content against drying time for various slice thicknesses submitted to convective oven drying, COD(a, 60ºC; b, 80ºC; c, 100ºC and microwave drying, MD (d, 450 W)

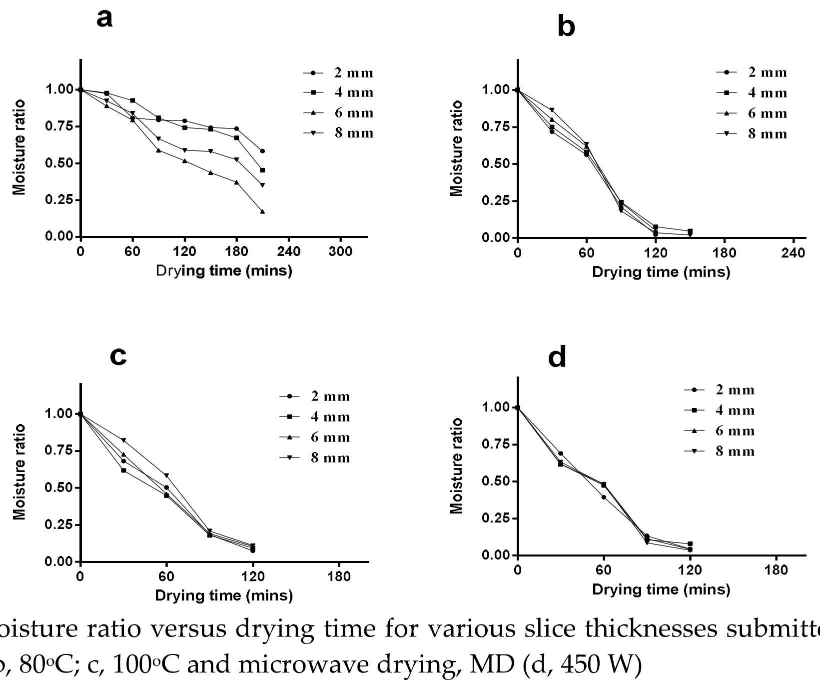

Figure 2. Curves of moisture ratio versus drying time for various slice thicknesses submitted to convective oven drying, COD(a, 60ºC; b, 80ºC; c, 100ºC and microwave drying, MD (d, 450 W)

3.2.2 Effective moisture diffusivity, total energy consumed, specific energy consumption and activation energy

From Table 3, effective moisture diffusivity (EMD) is positively correlated to both drying temperature and slice thickness for COD treatment. This report affirms the direct relationships between EMD and drying air temperature, showing that increase in the drying air temperature results in an increment in EMD and a decrease in the drying time (Kaveh et al., 2021). The increase in drying air temperature could lead to the activation of water molecules within the samples, accelerating the transfer of water molecules thereby causing increased water diffusion (Liu et al., 2015). In the present study, values ranged between 1.1 – 6.12$\times10^{-8}$ $m^2\ s^{-1}$ for COD and 1.49 – 6.65 $\times10^{-8}$ $m^2\ s^{-1}$ for MD treatment. As slice thickness increased from 2 – 8 mm, EMD rose from 1.1 – 4.35 $\times10^{-8}$ at 60°C, 1.1 – 5.6 $\times10^{-8}$ at 80°C and 1.25 – 6.12 $\times10^{-8}$ at 100°C.

Table 3. Effective moisture diffusivity of onion slices in different drying air temperatures

Slice thickness (mm)	Effective moisture diffusivity ($\times10^{-8}$ $m^2\ s^{-1}$)			
	60°C	80°C	100°C	MD (450 W)
2	1.1	1.1	1.25	1.49
4	2	2.28	3.31	4.25
6	3.32	2.59	3.37	4.31
8	4.35	5.6	6.12	6.65

SEC values in drying 2, 4, 6, and 8 mm onion slices under COD with temperatures of 60, 80 and 100°C and under MD with the power of 450 W are presented in Figure 3. It is obvious that SEC is negatively correlated to both drying temperature and slice thicknesses of onion slices. Increasing drying temperature resultedan an increase in the SEC. Similarly, as slice thickness increased SEC also increased (Kaveh et al., 2021). For the COD experiments, the SEC value obtained was in the range of 39.4 - 238.27 kWh/kg H_2O. The highest (238.27 kWh/kg H_2O, at 2 mm thickness) and lowest (39.4 kWh/kg H_2O, at 8 mm thickness) SEC values were utilized at drying temperatures of 60 and 100°C, respectively.

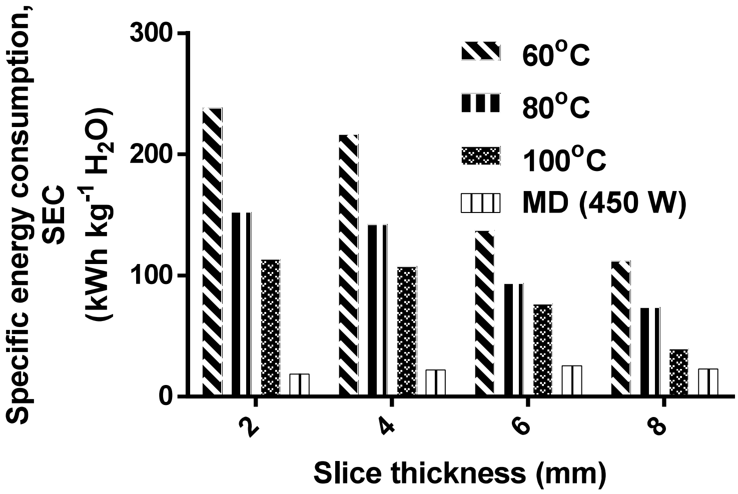

Figure 3. Effects of drying air temperature and onion slice thickness on the specific energy consumption

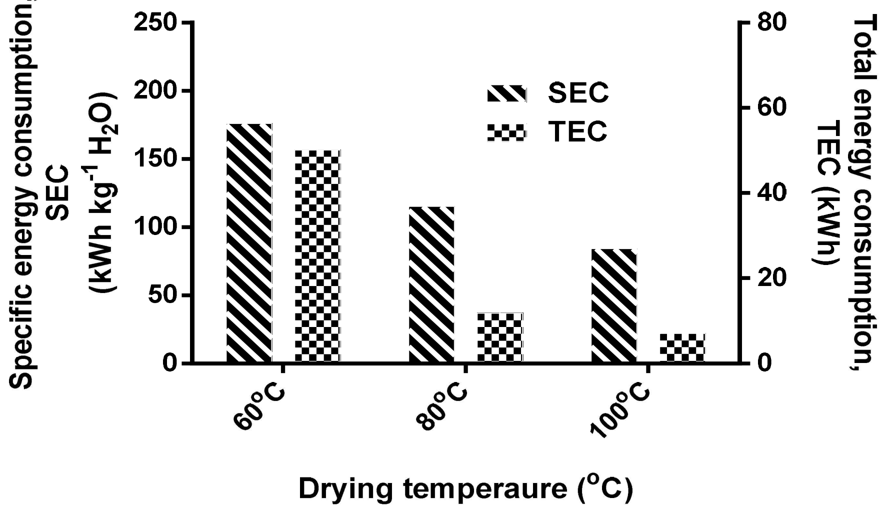

Figure 4. Graph of specific energy consumption (SEC) and total energy consumption (TEC) versus drying temperature

From Table 4, the highest values of activation energy (AE) obtained during onion drying under COD and MD systems were 71.42 kJ mol^{-1} (2 mm slices) and 34.52 W g^{-1} (6 mm slices) respectively (Table 5). MD treatments commanded the lowest AE values. Drying systems, air temperature and slice thicknesses were vital parameters influencing the AE. It is established that increasing temperature reduces the AE as a result of increased moisture loss and higher mass transfer from onions slices (Kaveh et al., 2021). In the present study, the mean AE values under MD (450 W), COD (60°C), (80°C) and (100°C) were 29.96 W g^{-1}, 66.80 kJ mol^{-1}, 56.51 kJ mol^{-1} and 59.32 kJ mol^{-1} respectively.

Table 4. Effects of slice thickness and temperature on total energy (E_t), specific energy (E_s) consumed and activation energy (E_a) submitted to microwave drying (MD) and convective oven drying (COD)

Slice thickness (mm)	**Energy for microwave drying (450 W)**			**Activation energy for convective oven drying E_{aCOD} (kJ mol^{-1})**		
	E_{tMD}(kWh)	**E_{sMD}(kWh/kg H_2O)**	**E_{aMD} (W g^{-1})**	**60°C**	**80°C**	**100°C**
2	1.35	18.70	27.82	71.42	65.18	68.48
4	1.13	22.02	25.79	68.22	63.31	66.87
6	1.35	25.33	34.52	64.03	50.52	53.16
8	1.35	22.88	31.69	63.52	47.04	48.76
MEAN	**1.295**	**22.23**	**29.96**	**66.80**	**56.21**	**59.32**

3.2.3 Bioactive compounds and vitamin C. content

Effects of convective oven drying (COD) (60°C, 80°C and 100°C) and microwave drying (MD) (450 W) on the flavonoid, phenolic and vit. C contents of onion slices is presented in Figure 5. MD (450 W) and COD (60, 80, and 100°C) treatments had significant effects on the flavonoid, phenolic and vit. C contents of onion. Significant ($p \leq 0.05$) increase in the flavonoid, phenolic and vit. C contents from 39.42 – 64.4%, 38.0 – 46.84%, and 3.7 – 4.23 mg 100 g^{-1} respectively were obtained for onion slices that were treated with MD at 450 W powers compared to the fresh un-dried (FUD) samples. This finding is consistent with the report of Ozcan-Sinir et al. (2018) that microwave drying and vacuum drying were able to yield higher quantity of bioactive compounds from kumquat (Citrus japonica) slices. A significant increase in the phenolic content was noticed in onion samples subjected to COD treatments at drying air temperatures of 80°C (40.19%) and 100°C (46.32%) except for 60°C (37.72%).

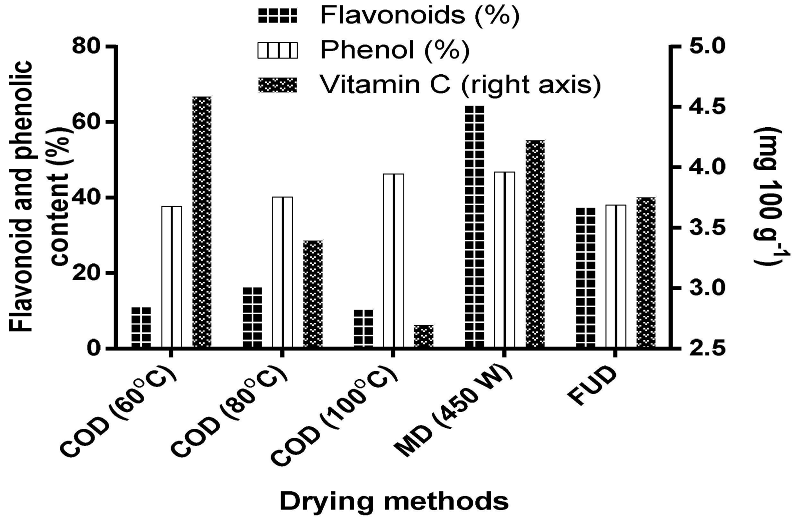

Figure 5. Effects of convective oven drying and microwave drying on the flavonoid, phenolic and vit. C contents of onion

Conclusion

The results revealed that drying air temperatures and slice thickness had significant effects ($p \leq 0.05$) on the drying kinetics, specific energy consumed (SEC), effective moisture diffusivity (EMD), flavonoid, phenolic and vit. C contents of onion slices dried under convective oven drying (COD) and microwave drying (MD). An increase in drying air temperature and reduction in slice thickness brought about decrease in the drying duration. Drying time of onion slices was shorter under MD than COD. Weibull model was the most appropriate in predicting the drying behaviour of 2 mm thick onion slices at 100°C (highest R^2=0.999; lowest SSE=0.0002, RSME=0.0123 and χ^2= 0.0004). As thickness increased from 2 – 8 mm, EMD rose from 1.1 – 4.35 $\times 10^{-8}$ at 60°C, 1.1 – 5.6 $\times 10^{-8}$ at 80°C and 1.25 – 6.12 $\times 10^{-8}$ at 100°C with MD treatments yielding the highest mean value (6.65 $\times 10^{-8}$ $m^2 s^{-1}$) at 8 mm. Maximum SEC for onion slices in COD was 238.27 kWh/kg H_2O (2 mm thickness) and the minimum was 39.4 kWh/kg H_2O (8 mm thickness) whereas maximum during MD was 25.33 kWh/kg H_2O (8 mm thickness) and minimum, 18.7 kWh/kg H_2O (2 mm thickness). MD treatment gave a significant ($p \leq 0.05$) increase in the flavonoid (39.42 – 64.4%), phenolic (38.0 – 46.84%) and vit. C (3.7 – 4.23 mg 100 g^{-1}) contents while COD treatment at 60°C and 100°C had positive effects on only vit. C and phenolic contents respectively.

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Conflict of interest

The authors state no conflict of interest

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