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Fluidized bed drying characteristics of moringa leaves and the effects of drying on macronutrients

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Abstract

Moringa oleifera is an important source of nutrients and phytochemicals with beneficial bioactive properties. However, its availability must be improved through processing to transform it into storage-stable products. One of the most important processing steps is drying. The aims of this study were to investigate drying behaviour of moringa leaves under fluidized bed drying conditions and the effects of fluidized bed drying at 35, 45, 55, and 65 °C on nutritional contents of dried moringa leaves. The parameters measured were moisture contents during drying, crude protein, crude fat, crude fibre, ash, and carbohydrate. Results of chemical analysis revealed that the effects of drying on these nutrients can be significant. Moisture content of moringa leaves decreased linearly with time at the early stage of drying and became non-linear after the moisture content dropped to about 60-70% dry basis. Drying process occurred mostly in the constant rate period at low temperature and in the falling rate period at high temperature and drying behavior of moringa leaves can be best fitted using Page model. The effective moisture diffusivity during falling rate period were 4.86 x 10^{-13} m^2/s at 35 °C, 5.70 x 10^{-13} m^2/s at 45°C, 1.07 x 10^{-12} m^2/s at 55°C, 1.44 x 10^{-12} m^2/s at 65 °C.

Keywords: *Moringa oleifera*; fluidized bed dryer; drying kinetics; nutrient degradation.

Practical Application: This research is relevant to the processing of moringa leaves for use as an ingredient in food, drink, and nutrition supplement products. Moringa is an underutilized agricultural product rich in micro and macronutrients as well as phytochemicals. In this study, we used fluidized bed dryer to study drying characteristics of moringa leaves and the effects of drying on macronutrients in moringa leaves.

1 Introduction

Moringa oleifera is a perennial tree originated from northwest India (Flora & Pachauri, 2011) and it has currently been planted in many tropical and subtropical countries (Mbikay, 2012). The leaves of this plant contain high amounts of macro and micronutrients as well as bioactive compounds (Stohs & Hartman, 2015; Oladeji et al., 2017) such as protein, carbohydrate, fibre, fat, minerals, and amino acids and various phytochemical (Moyo et al., 2013; Mukunzi et al., 2011) such as ascorbic acid, flavonoid, phenolic, and carotenoid (Vongsak et al., 2014). These phytochemicals make the moringa leaves a potential source of antioxidant (Atawodi et al., 2010; Ndhlala et al., 2014; Jothilakshmi et al., 2017). Moringa plant is also rich in vitamin A, vitamin C, calcium, potassium, and iron (Mukunzi et al., 2011). Fuglie (2001) reported that moringa leaf contains more than ninety different nutrients and all of the essential amino acids which makes it suitable for use in daily diets as well as for food fortification (Oyeyinka & Oyeyinka, 2018; Alam et al., 2014; Ajibola et al., 2015; Shiriki et al., 2015). Regular consumptions of flavonoid rich foods can reduce the risk of chronic diseases and maintain health (Davis et al., 2009).

Some of the phytochemicals in moringa leaves have high bioactivities which can function as anticancer (Bharali et al., 2003; Khalafalla et al., 2010; Jung, 2014; Maiyo et al., 2016; Fahey et al., 2018, 2019), antiinflammation (Hsu et al., 2006; Gupta et al., 2013) and antihypertensive (Dangi et al., 2002; Stohs & Hartman, 2015) agents. The study reported by Yang et al. (2006a) indicated that rat model fed with a diet containing 5% moringa powder showed lower blood triglycerides and higher immune response. Comprehensive reviews by Mbikay (2012), Dhakad et al. (2019), and a group of researchers led by Fahey (Fahey, 2005; Thurber & Fahey, 2009; Fahey et al., 2018, 2019) provide summaries of medical evidence, therapeutic effects, and nutritional properties of moringa leaves. The therapeutic effects of moringa leaf have also been reported by other researchers (Fahey, 2005; Mbikay, 2012; Sharifudin et al., 2013; Sadek, 2014) and the use of moringa for medical purposes has been shown (Anwar et al., 2007). The therapeutic effects are mostly associated with antioxidant activities of some of the phytochemicals contained in the moringa leaves (Pari & Kumar, 2002). These phytochemicals include ascorbic acid, flavanols, phenols, and carotenoid (Yang et al., 2006a; Anwar et al., 2007; Kumar et al.,

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2010; Khalafalla et al., 2010; Luqman et al., 2012; Jung, 2014; Gupta et al., 2013).

Moringa can become an important source of macro and micronutrients in our diet (Yang et al., 2006a,b). Several researchers have indicated that this plant can be used as a nutritional supplement (Fahey, 2005; Saini et al., 2014a, 2016; Zaku et al., 2015), especially for kids and lactating mothers (Santos et al., 2005; Iqbal & Bhanger, 2006). An extensive study conducted by several researchers (Yang et al., 2006a) on 120 species of edible plants indicated that moringa was the most potential plant that can be used as a source of nutrition and antioxidant. Another important trait of the moringa leaves is that its antinutritional factors such as tannins, oxalate, and oligosaccharides are relatively low (Yang et al., 2006a,b; Ademiluyi et al., 2018). In spite of this high potential as a source for essential micronutrients, moringa is still underutilized (Zaku et al., 2015; Kannan & Thahaaseen, 2016).

Moringa is generally used as cooked vegetable in the form of stew or soup. In order to increase its availability and consumption, moringa leaves must be processed into dry powder which can be used in product formulations for production of functional foods and drinks. Moringa powder can also be used directly as a nutrition supplement. Processing of moringa leaves must be done immediately after harvest since its physical and nutritional quality can degrade rapidly due to its high moisture content and high respiration and transpiration rates. On the other hand, inappropriate processing method and condition can destroy its nutritional content and the functionality of the phytochemicals in the moringa leaves. Some forms of degradation that have been reported during drying of agricultural products include colour (Ali et al., 2014; Guiné & Barroca, 2012; Managa et al., 2020; Schmalko et al., 2005; Stanley et al., 2017), nutritional contents (Managa et al., 2020; Emelike & Akusu, 2020; Mutuli & Mbuge, 2018; Piyarach et al., 2020), and sensorial properties (Ali et al., 2014; Guiné & Barroca, 2012; Mutuli & Mbuge, 2018; Stanley et al., 2017).

Drying is probably one of the most frequent processing procedures used to extend shelf life and to prepare moringa leaves for use as an ingredient for food, beverage, or pharmaceutical industries. Drying of plant materials such as leaves is essential since their moisture at harvest is generally high. At high moisture content, plant materials are susceptible to rapid deterioration due to microbial, enzymatic, and physiological activities. Studies on drying of moringa leaves have been reported by many researchers. These studies include traditional drying methods through sun drying or shade drying (Ademiluyi et al., 2018; Gyamfi et al., 2011; Foline et al., 2011; Mishra et al., 2012; Satwase et al., 2013; Adeyemi et al., 2014; Adenike, 2014; Anuja & Ramkumar, 2017; Babiker et al., 2018) and artificial drying using tray dryer, oven, microwave, and freeze dryer (Ademiluyi et al., 2018; Gyamfi et al., 2011; Saini et al., 2014b; Suzauddula et al., 2019; Olalusi & Odiase, 2015; Potisate et al., 2014). Some of these studies focused on drying kinetics and the effects of drying on nutritional contents of dried moringa leaves. More recent studies on microwave, oven, and freeze drying of valuable agricultural products have also been reported (Aydar, 2020, 2021; Xu et al., 2021).

Kannan & Thahaaseen (2016) indicated that the quality of moringa powder obtained from shade drying was better than those obtained from sun drying and oven drying. Clement et al. (2017) compared the retention of vitamins A and C during room temperature drying (in room drying), sun drying, and oven drying at 60 °C and 105 °C. These researchers reported that highest vitamin A retention was obtained at 60 °C while sun drying gave highest vitamin C retention. The retention of vitamin A at shade drying was slightly lower than that at 60 °C which indicates that the longer drying at room temperature (up to 96 hours in their study) caused vitamin A degradation. It was also reported that protein content in samples dried at room temperature were slightly lower compared to those dried at 60 °C but vitamin C retention was slightly higher in samples dried at room temperature.

Degradation of quality attributes and nutrient contents of agricultural products are affected by drying temperature and drying duration. The effects of temperature can be modelled using the Arrhenius equation while those of drying duration were generally modelled using first order kinetics. In drying operation, however, these two parameters cannot be isolated from one another since the end point of the drying process was determined by the desired final moisture content. Drying at high temperature will results in short drying duration while drying at low temperature will require longer drying duration. None of the aforementioned drying studies considered these two factors together and all of them only addressed the effects of drying method and drying temperature. In addition, study on drying of moringa leaves using fluidized bed dryer is still lacking. Therefore, the aims of this study were to investigate fluidized bed drying characteristics of moringa leaves and the effects of fluidized bed drying on the nutritional contents of dried moringa leave.

2 Materials and methods

The moringa leaves used in this study were harvested early in the morning at a local farm by cutting leaves stems at the fifth to the ninth nodes from the apex of each branch. The freshly harvested moringa leaves were first washed with running water, dried using paper towel, and detached from their stems. The moringa samples used in each experimental run was 300 grams. Drying experiments were performed using fluidized bed dryer equipped with a blower, 1000-Watt air heater, and a drying chamber made of PVC pipe (50 cm length and 12.5 cm diameter). Air velocity used was controlled by controlling the speed of the blower using a Variable Frequency Drive (VFD) and drying temperature was controlled using a PID temperature controller. The drying temperatures used in this study were 35, 45, 55, and 65 °C. Sample weight was measured every 30 min and drying were terminated after the desired final weight were reached (moisture contents were estimated below 10% wet basis).

In addition to the experiments using fluidized bed dryer, control samples were also prepared by drying detached moringa leaves at room temperature. The dry samples were ground to particle size of about 120 mesh using a blade grinder. The final moisture contents of the samples were later determined using oven method at 105 °C. All treatments were done in triplicate.

Nutritional analyses were done to determine protein, carbohydrate, fat, mineral, and fibre contents of the dried samples.

2.1 Drying kinetics

Drying kinetics of moringa leaves during fluidized bed drying was studied based on weight degradation during drying, from which moisture contents were calculated using Equation 1.

$$M_{db} = \frac{m_w}{m_{ds}} x100\% \quad (1)$$

In Equation 1, M_{db} is dry basis moisture content, m_w and m_{ds} are the weight of water and dry solid in the sample, and m_s is total sample weight. It is important to note that in this study, drying process was terminated when sample weight reached a predetermined weight which corresponds to moisture content of about 10% (before equilibrium moisture content was reached). This is done to avoid excessive degradation of nutrients in the samples. Therefore, the formula used to calculate moisture ratio (Equation 2) was modified from the commonly used formula as previously done by many researchers (Salengke & Sastry, 2005; Menges & Ertekin, 2006; Wang et al., 2007a; Ali et al., 2014; Akoy, 2014; Vijayan et al., 2016). Drying characteristics of moringa leaves during fluidized bed drying was assessed using dimensionless moisture ratio shown in Equation 2 and drying rate was calculated using Equation 3.

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

$$D_R = \frac{m_{s,t-dt} - m_{s,t}}{dt} \quad (3)$$

In the above equations, M_R is dimensionless moisture ratio, M_0 and M_t are initial moisture content and moisture content at time t (dry basis), D_R is drying rate, $m_{s,t}$ is sample weight at time t, $m_{s,t-dt}$ is sample weight at time t-dt, and dt is time interval of weight measurement. The simplified equation for moisture ratio calculation (Equation 2) essentially assumes that equilibrium moisture content (M_e) under drying conditions is equal to zero. Many authors have indicated that the error associated with this simplification is negligible since the value of M_e is much smaller compared to the initial moisture content (M_0) and the moisture of the material during drying (M_t) (Akgun & Doymaz, 2005; Mahdhaoui et al., 2014).

Drying behaviour of agricultural materials is characterized by a short constant rate period and a long falling rate period. In some cases, the absence of constant rate period has been reported (Mohapatra & Rao, 2005; Doymaz, 2007). During the falling rate period, the rate of drying depends on the rate of moisture diffusion from within the material and this process is controlled by moisture diffusivity of the material being dried. To assess the effective moisture diffusivity during drying, the Fick's second law can be used. For infinite slabs, the general form of Fick's law can be written as shown in Equation 4 (Wang et al., 2007a; Premi et al., 2010; Potisate et al., 2014; Doymaz, 2014),

$$M_R = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left(-\frac{(2n+1)^2 . \pi^2}{(2L)^2} . D_{eff} . t \right) \quad (4)$$

where D_{eff} is effective moisture diffusivity, L is half of the leaf thickness (moisture evaporation from both sides of the leaves), and n is non-negative integers (0, 1, 2, …). Expansion of the above equation to the first three terms will give the following equation (Equation 5).

$$M_R = \frac{8}{\pi^2} \left\{ exp\left(-\frac{\pi^2}{4L^2} . D_{eff} . t \right) + \frac{1}{9} exp\left(-\frac{9\pi^2}{4L^2} . D_{eff} . t \right) + \frac{1}{25} exp\left(-\frac{25\pi^2}{4L^2} . D_{eff} . t \right) \right\} \quad (5)$$

It is clear from Equation 5 that for long drying time (large t value), the value of the first term in the series will be much larger than those of the subsequent terms. Therefore, the second and the third terms in the series can be neglected with very small error and Equation 5 can be reduced to Equation 6. Equation 6 can be modified into a linear equation by taking natural logarithm at both sides of the equation (Wang et al., 2007b; Sacilik, 2007; Özbek & Dadali, 2007) as shown in Equation 7. The effective moisture diffusivity in Equation 7 can then be determined from the slope of the plot or from linear regression between $ln\, M_R$ vs. t as shown in Equation 8.

$$M_R = \frac{8}{\pi^2} \left\{ exp\left(-\frac{\pi^2 . D_{eff}}{4 . L^2} . t \right) \right\} \quad (6)$$

$$ln(M_R) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 . D_{eff}}{4 . L^2} . t \right) \quad (7)$$

$$D_{eff} = \frac{-slope . 4L^2}{\pi^2} \quad (8)$$

To describe the drying behaviour of agricultural and food materials, the dimensionless moisture ratios can also be fitted using some of the well-known semi-theoretical drying models (Fernando & Amarasinghe, 2016; Inyang et al., 2018). Drying of moringa leaves under fluidized bed drying conditions can be regarded as a thin layer drying since the leaves are very thin and they stack very loosely in the fluidized bed dryer. Therefore, drying kinetics under these conditions can be modelled using semi-theoretical thin layer drying models. In this study, the drying behaviour of moringa leaves under fluidized bed drying conditions were described using Newton model (Equation 9) (Lewis, 1921 in Akoy, 2014), Page model (Equation 10) (Page, 1949 in Wang et al., 2007a; Akoy, 2014), Henderson-Pabis model (Equation 11) (Henderson & Pabis, 1961 in Wang et al., 2007a; Akoy, 2014), and two-term model (Equation 12) (Henderson, 1974 in Wang et al., 2007a; Mohapatra & Rao, 2005). The goodness of fit of these models were determined using the correlation coefficient (R^2) and the reduced Chi-square (χ^2) values (Equation 13).

$$M_R = \exp(-k.t) \quad (9)$$

$$M_R = \exp(-k.t^n) \quad (10)$$

$$M_R = a . \exp(-k.t) \quad (11)$$

$$M_R = a . \exp(-k_1.t) + b . \exp(-k_2.t) \quad (12)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(M_{R_{exp,\,i}} - M_{R_{pred,\,i}}\right)^2}{N-m} \quad (13)$$

In the above equations, a, b, k, k_1, k_2, and n are model parameters, $M_{Rexp,i}$ and $M_{Rpred,i}$ are measured and predicted moisture ratios, N is the number of M_R data, and m is the number of parameters in each model.

2.2 Crude protein determination

Crude protein contents were determined using the standard AOAC 984.13 (Kjeldahl Method) which determines crude protein based on Total Kjeldahl Nitrogen. Powdered moringa samples (0.5 ± 0.0001 g) were placed into 250 mL digestion tubes and added with Kjeldahl catalyst (Selenium reagent mixture; Sigma-Aldrich) and 6 mL of concentrated H_2SO_4. The solutions were then homogenized and the tubes were placed into a digestion block and digestion was run at 420 °C for about 1.5 hours or until the samples were yellow and clear. After the digestion, the samples were analysed using Kjeltec™ 8400 Analyser (FOSS Analytical, Denmark) for protein content determination.

2.3 Crude fat determination

Crude fat contents were determined using the standard AOAC 920.39 method. Two grams of moringa samples were placed in cellulose thimbles capped with cotton fibres and the thimbles were then placed in Soxtec apparatus (Soxtec™ 2050, FOSS Analytical, Denmark) in the rinsing position. Aluminium extraction caps were filled with 80 mL organic solvent (petroleum benzene) and then secured in the Soxtec apparatus under the thimbles. The thimbles were then lowered into the extraction cap by raising the knob to boiling position and extraction was conducted at 135 °C. Fat content was determined using Equation 14.

$$\%\,fat = \frac{Fat\ \ weight}{Sample\,weight}\ x\ 100 \quad (14)$$

2.4 Mineral content determination

Mineral contents of the moringa samples were determined based on total ash content. Measurements were conducted using the standard AOAC 942.05 method. Two grams of moringa samples were weighed into porcelain crucibles. The crucibles were then placed into a furnace (Nabetherm, Germany) and ignited at 600 °C for 3 hours. Total ash contents were determined using the following equation (Equation 15).

$$\%\ ash = \frac{Ash\,weight}{Sample\,weight}\ x100 \quad (15)$$

2.5 Crude fibre determination

Crude fibre determination was performed using AOAC 962.09 method. One gram of each sample was placed in crucibles and then 25 mL of acetone was added and left at room temperature for 10 min to allow for fat extraction. The liquid part was separated and 25 mL of acetone was added to the residue and left for 10 min. This procedure was repeated twice to insure maximum extraction of fat from the sample. After the fat extraction, the defatted samples were rinsed twice with deionized water and the crucibles were transferred to fibertec apparatus (Fibertec™ 2010, FOSS Analytical, Denmark) for hydrolysis with hot H2SO4 (to remove sugars and starch) and then with hot NaOH (to remove protein and some carbohydrates). After the hydrolysis process, the crucibles containing the samples were dried in an oven at 130 °C for 2 hours and then transferred to a furnace for ashing at 525 °C for 3 hours. Crude fibre contents of the samples were determined using Equation 16.

$$\%\,fibre = \frac{W_2 - W_3}{W_1}\ x100 \quad (16)$$

Where W_1, W_2, and W_3 are sample weight, weight after drying, and weight after ashing respectively.

2.6 Moisture content determination

Moisture contents were determined using oven method following the standard AOAC 930.15 method. One gram sample from each experimental run was weighed in a porcelain cup and then dried in an oven at 135 °C for 8 hours. Moisture content was calculated using Equation 17.

$$\%water = \frac{M_1 - M_2}{M_1}\ x\ 100 \quad (17)$$

Where M_1 and M_2 are sample weight before drying and after drying respectively.

2.7 Carbohydrate determination

Carbohydrates in the samples can be considered to consist of crude fibres and nitrogen-free extract such as sugars and starch. The nitrogen-free extract (*NFE*) is usually determined by difference using the following equation (Equation 18).

$$\%NFE = 100 - \left(\%Water + \%Fat + \%Protein + \%Ash + \%Fibre\right) \quad (18)$$

Total carbohydrate was determined as the sum of the NFE and the crude fibre in the sample.

2.8 Statistical analysis

The effects of drying condition on the nutritional contents of moringa leaves were analysed using One-way analysis of variance in Minitab 19 (Minitab LLC, Pennsylvania, USA). Comparisons among the means were done using Fisher Pairwise comparisons (LSD method) and the means were considered differed significantly when the P value was less than 0.05.

3 Results and discussion

3.1 Drying characteristics

Drying of moringa leaves using fluidized bed dryer required significantly different drying time at different drying temperature to reduce moisture content from initial moisture of about 73-75% to the targeted moisture content below 10% wet basis (below

11% dry basis). In this study, drying time varied from 2.5 hours at 65 °C, 3.5 hours at 55 °C, 6.5 hours at 45 °C, and 9.5 hours at 35 °C (Figure 1). In addition, the time required for moringa leaves to dry by shade drying was about 96-120 hours. Therefore, the effects of drying on the nutritional contents as reported later were due to the coupled effects of temperature and drying time.

Drying curves at various temperatures (Figure 1) show that dry basis moisture content of moringa leaves decreased linearly at the early stage of drying (R^2 > 0.99) and became non-linear only after the moisture content dropped to about 60-70% dry basis. Drying rate curves shown in Figure 2 also indicate that the changes in drying rates were relatively small at lower drying temperature and became significant only at 65 °C. These trends indicate that the drying pattern of moringa leaves under the fluidized bed drying conditions applied in this study occurred mostly close to the constant rate period at low drying temperature and in the falling rate period at high temperature. Closer inspections on the drying curves revealed that the lengths of the constant rate period were about 60-70% of total drying time at low drying temperature (35 and 45 °C) and about 40-50% of the drying time at 55 °C.

Moisture ratio curves presented in Figure 3 show that the curves became steeper as drying temperature increases due to the increase in drying rate. The increase in the drying rate as drying temperature was increased is attributable to the increase in the rate of moisture evaporation from the surface at the start of the drying and the increase in the moisture diffusivity from the internal to the surface of the leaf. To estimate the effective moisture diffusivity during drying, it is important to first estimate the start of the falling rate period. Based on the drying data, the start of the falling rate period for the respective drying temperature was estimated to occur after 5.5 hours of drying at 35 °C, 2.5 hours of drying at 45 °C, 1.5 hours of drying at 55 °C, and 1 hour of drying at 65 °C. Based on these estimates, regression of $ln\ M_R$ versus t (Equation 7) provided good fits with R^2 values were in the range of 0.970-0.996. By using the regression coefficients obtained, the effective moisture diffusivity for each drying temperature was calculated using Equation 8 and revealed that moisture diffusivity increased from 4.86 x 10^{-13} m^2/s at 35 °C, 5.70 x 10^{-13} m^2/s at 45 °C, 1.07 x 10^{-12} m^2/s at 55 °C, 1.44 x 10^{-12} m^2/s at 65 °C. These results are much lower than the results reported by Premi et al. (2010) which showed effective diffusivity in the range of 2.4 x 10^{-9} to 3.89 x 10^{-9} m^2/s for tray drying at 50 to 80 °C and Díaz et al. (2018) which showed moisture diffusivity in the range of 1.547 x 10^{-7} to 4.868 x 10^{-8} for drying at 40-60 °C. However, the effective moisture diffusivities found in this study were in the same order of magnitude as the results reported by Potisate et al. (2014) which were in the range of 3.14 x 10^{-13} to 4.44 x 10^{-12} m^2/s for tray drying at 40-60 °C. The lower effective moisture diffusivity obtained in the current study might be due to the much higher mass of the material (300 g) dried in the fluidized bed chamber compared to the mass of samples used in the studies reported by Premi et al. (2010), Potisate et al. (2014), and Díaz et al. (2018).

Results of model fittings for moisture ratio data using the four models used in this study are presented in Table 1. The results shown in Table 1 indicate that the four drying models used to fit the moisture ratio data can adequately predict the measured data (R^2 > 0.95 and χ^2 <= 0.001). However, Page Model (Equation 10) seems to provide the best prediction at the four drying temperatures as indicated by the correlation coefficient R^2 (highest) and the reduced Chi-square χ^2 (lowest). The comparisons between the predicted moisture ratio obtained from the Page model and the measured values are shown in Figure 3.

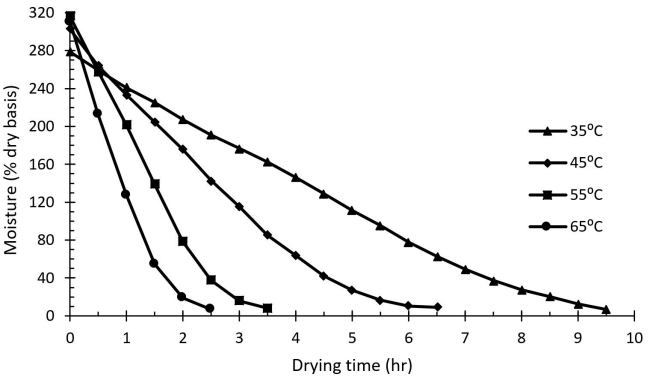

Figure 1. The change in moisture content during fluidized bed drying of moringa leaves.

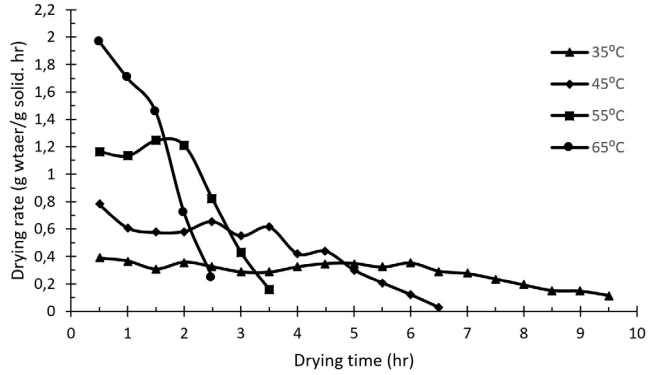

Figure 2. Drying rates of moringa leaves during fluidized bed drying.

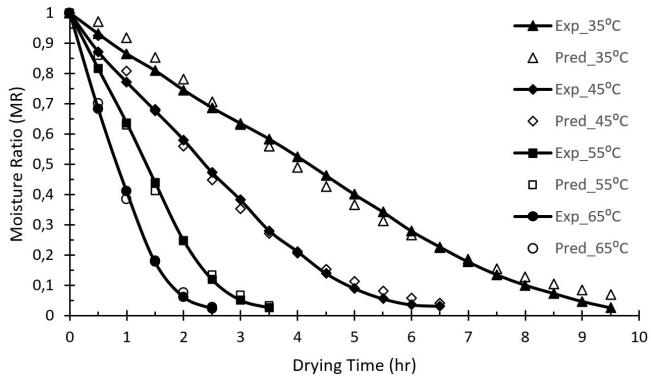

Figure 3. Comparisons between predicted (Pred) and measured (Exp) moisture ratio during drying.

Table 1. Results of curve fittings for moisture ratio using thin-layer drying models.

Model	Temperature, °C	Model constants				R^2	χ^2
Newton	35	k=0.2026				0.967	0.0059
	45	k=0.3559				0.977	0.0030
	55	k=0.6445				0.969	0.0025
	65	k=0.0178				0.983	0.00099
Page	35	k=0.0859	n=1.5278			0.991	0.00106
	45	k=0.2135	n=1.4462			0.995	0.00046
	55	k=0.4657	n=1.5930			0.997	0.00018
	65	k=0.9558	n=1.4321			0.998	0.00007
Henderson-Pabis	35	k=0.2227	a=1.0925			0.958	0.00486
	45	k=0.3922	a=1.0755			0.972	0.00260
	55	k=0.6880	a=1.0726			0.964	0.00219
	65	k=1.0515	a=1.0382			0.980	0.00095
Two-term	35	k_1=0.2227	k_2=0.2227	a_1=0.90528	a_2=0.18726	0.958	0.00546
	45	k_1=0.3822	k_2=0.3822	a_1=0.54808	a_2=0.52739	0.972	0.00292
	55	k_1=0.6880	k_2=0.6880	a_1=0.54991	a_2=0.52271	0.964	0.00247
	65	k_1=1.0515	k_2=1.0515	a_1=0.53363	a_2=0.50460	0.980	0.00107

3.2 Crude protein content

Results of proximate analysis of moringa leaf powder obtained from different drying conditions is presented in Table 2. The crude protein content of moringa powder produced from the experiments ranged from 35.67% to 41.66% dry basis. The values obtained from this study were significantly higher than those reported by Adeyemi et al. (2014), Emelike & Akusu (2020), Emelike & Ebere (2016), and Alakali et al. (2015) but comparable to those reported by Foline et al. (2011), Castillo-Lopez et al. (2017), Kane et al. (2017), Kshirsagar et al., (2017) and Olabode et al. (2015). Protein contents of the samples dried using fluidized bed dryer were slightly lower than the value reported by Wickramasinghe et al. (2020).

Adeyemi et al. (2014) reported that drying method significantly affected protein content with sun dry resulted in highest protein content (22.52 mg/g) while shade drying gave lowest protein content (11.75 mg/g). On the other hand, results of a study by Alakali et al. (2015) and Foline et al. (2011) indicated that shade drying resulted in highest protein content while hot air drying resulted in lower protein content. The results reported by Alakali et al. (2015) also showed that drying in oven significantly decreased protein content as drying temperatures were increased from 40 °C to 50, 60, and 70 °C. However, a study by Ali et al. (2014) showed that shade drying, oven drying at 40-60 °C, microwave drying, and freeze drying had no effect on protein content of dried moringa leaves.

The results of analysis of variance on the proximate compositions of the dried moringa leaves as shown in Table 2 indicate that samples dried by shade drying provided significantly higher protein content compared to those dried using fluidized bed dryer. Protein contents of samples dried at 35 to 65 °C were relatively the same which indicate that the coupled effects of temperature and drying time on protein content was insignificant. However, it is worthy of note that moringa leaves dried at 65 °C tended to have the lowest protein content. The reductions of protein content due to hot air drying as observed in this study was similar to those observed by Alakali et al. (2015) and Tamang & Tashi (2020) attributed this reduction to protein denaturation during drying.

The results obtained from this study may indicate that the higher rate of protein degradation at high temperature was compensated by shorter drying time and the advantage of low rate of degradation at low drying temperature was negated by longer drying time required to reach the desired moisture content. This is in accordance with the findings reported by Tamang & Tashi (2020) which showed that drying time and temperature significantly affect protein contents of dried moringa leaves. Therefore, we can expect that there is an optimum drying condition where the coupled effects of drying temperature and drying time provide the lowest degradation of protein and other valuable constituents in moringa leaves.

3.3 Crude fat content

Crude fat contents of moringa leave powder obtained from the experiments (Table 2) show that the crude fat contents ranged from 7.68% dry basis for samples dried at room temperature (shade drying) to about 10.76% for samples dried using fluidized bed dryer. These values are significantly higher compared to the values reported by Adeyemi et al. (2014), Alakali et al. (2015), Foline et al. (2011) and slightly higher than the values reported by Castillo-Lopez et al. (2017), Wickramasinghe et al. (2020), and Kane et al. (2017).

Table 2. Results of proximate analysis (% dry basis) of moringa leave powder obtained from different drying condition.

Parameter	Shade drying	Fluidized bed drying				*p*-Value
	30 ± 2 °C	35 °C	45 °C	55 °C	65 °C	
Crude protein	41.663[a]	36.50[b]	36.26[b]	36.83[b]	35.67[b]	0.007
Crude fat	7.68[b]	9.99[a]	9.56[ab]	10.76[a]	10.36[a]	0.041
Crude fibre	6.33[a]	5.58[ab]	4.68[b]	4.61[b]	4.45[b]	0.033
Ash	12.52[a]	10.34[b]	10.31[b]	10.74[b]	10.20[b]	0.003
Nitrogen-free-extract	21.47[b]	25.88[ab]	28.46[a]	29.37[a]	30.02[a]	0.004
Total carbohydrate	27.80[b]	31.46[ab]	33.14[ab]	33.98[a]	34.47[a]	0.113

Values are means of 3 readings. Means with different indices in each row are significantly different (P ≤ 0.05).

However, the fat contents obtained in this study were comparable to those reported by Emelike & Ebere (2016), Emelike & Akusu (2020), Kane et al. (2017), Kshirsagar et al., (2017), and right in the range listed by Ali et al. (2014). In addition, the fat contents obtained in this study was slightly lower than those reported by Tamang & Tashi (2020)

The result of analysis of variance on the fat content indicates that the effect of drying temperature on fat content is not significant but shade drying gave significantly lower fat content. This trend is similar to the trend reported by Adeyemi et al. (2014) which showed lowest fat content from moringa sample dried under shade, even though the difference was insignificant compared to the fat contents of samples obtained from oven drying and sun drying. Experimental results reported by Alakali et al. (2015) and Ali et al. (2017) also showed that fat contents of oven dried samples and those of samples dried at room temperature (shade drying) were not significantly different.

3.4 Crude fiber contents

Crude fiber contents of dried moringa powder obtained from this study ranged from 4.45% to 6.33% dry basis which are comparable to the findings reported by Emelike & Ebere (2016). These values are lower than the values reported by Adeyemi et al. (2014), Foline et al. (2011), Tamang & Tashi (2020), and Kane et al. (2017), Wickramasinghe et al. (2020) but slightly higher than the values reported by Castillo-Lopez et al. (2017). However, the crude fibre contents found in this study were significantly lower than those found by Alakali et al. (2015), Emelike & Akusu (2020), and Kshirsagar et al., (2017) who reported crude fiber contents in the range of 16.33-17.66%, 19.98-24.55%, and 12.16-28.02% respectively. Experimental results reported by Olabode et al. (2015) and Mensah et al. (2012) also indicate fiber contents which are much higher than the results obtained in this study.

The results of analysis of variance presented in Table 2 indicate that samples dried at room temperature (shade drying) gave higher fiber content than those dried at elevated temperatures (35-65°C). In this study, fiber content of the samples dried at room temperature (shade drying) was significantly higher than those dried at 45, 55, and 65 °C. The results in Table 2 also show that fiber content tended to decrease as drying temperature was increased. This trend was contrary to the findings reported by Emelike & Ebere (2016) and Satwase et al. (2013) which showed relatively higher fiber content in samples dried at elevated temperature (oven dried) compared to the fibre content of samples dried at room temperature (shade dried). Findings reported by Tamang & Tashi (2020) also showed that fiber contents tended to increase as drying duration and temperature increased.

3.5 Ash content

Ash represents inorganic matters, mainly minerals, present in the food. Therefore, ash content can be used as a rough estimate of the mineral contents of food materials. The ash contents of the dried moringa leaves obtained from this study ranged from 10.2 to 12.52% dry basis. These values are higher than those reported by Adeyemi et al. (2014), Alakali et al. (2015), Ali et al. (2017), Emelike & Ebere (2016), Foline et al. (2011) and Castillo-Lopez et al. (2017) but comparable to the findings reported by Emelike & Akusu (2020), Wickramasinghe et al. (2020), and Tamang & Tashi (2020).

The results of the analysis of variance given in Table 2 show that ash content of moringa leaves dried at room temperature (shade dried) was significantly higher than the ash content of moringa leaves dried at elevated temperature using fluidized bed dryer. Similar trend was reported by Emelike & Ebere (2016). The results also show that drying temperature in the range used in this study did not affect ash content. The trend observed in this study was contrary to the trend reported by Adeyemi et al. (2014) which showed higher ash content in samples dried at elevated temperature (oven drying) compared to those dried at room temperature (shade drying). Experimental results reported by Alakali et al. (2015) also showed that samples dried at higher temperature (60 and 70 °C) had significantly higher ash content compared to those dried at lower temperatures (shade, 40, and 50°C). However, research findings reported by Ali et al. (2017), Satwase et al. (2013), Tamang & Tashi (2020), and Foline et al. (2011) showed no significant difference in ash contents among the samples dried at elevated temperature and those dried at room temperature (shade dried).

3.6 Carbohydrate content

Total carbohydrate contents were computed as the sum of crude fibre and nitrogen free extract (NFE), where the NFE was determined by difference. Total carbohydrate content of dry moringa powder obtained from this study ranged from 27.8% for shade dried samples to 34.47% dry basis for sample dried at 65 °C. These values are comparable to those reported

by Foline et al. (2011), Kshirsagar et al. (2017), and Tamang & Tashi (2020) but higher than the results reported by Emelike & Ebere (2016). However, carbohydrate contents found in this study significantly lower than those reported by Adeyemi et al. (2014) who reported carbohydrate contents in the range of 54.18% for sun dried samples to 72.98% for shade dried samples. The results obtained were also lower than the experimental results reported by Alakali et al. (2015), Ali et al. (2017), Castillo-Lopez et al. (2017), Satwase et al. (2013), and Emelike & Akusu (2020).

The results of analysis of variance (Table 2) show that carbohydrate contents of shade dried samples were lower than those dried at elevated temperatures. The results also show that samples dried at 55 and 65 °C gave significantly higher carbohydrate content than that the samples dried at room temperature (shade dried). However, carbohydrate contents of samples dried at 35 and 45 °C did not differ significantly to those dried at 55 °C and 65 °C. The trend of increasing carbohydrate content as drying temperature and duration increase has been reported by Tamang & Tashi (2020). Alakali et al. (2015) also reported significant increase in carbohydrate content as drying temperature increased. This trend is contrary to the trend reported by Adeyemi et al. (2014) which showed significantly lower carbohydrate content in samples dried by sun drying or oven drying compared to those dried at room temperature. Ali et al. (2017) also reported the decrease in carbohydrate contents as drying temperature increased from 40 °C to 50 °C and to 60 °C.

4 Conclusion

Moisture content of moringa leaves decreased linearly with time at the early stage of drying and became non-linear only after the moisture content dropped to about 60-70% dry basis. The changes in drying rates were relatively small at lower drying temperature and the absence of constant rate drying period was only observed at 65 °C. The trends observed indicate that the drying pattern of moringa leaves under the fluidized bed drying conditions applied in this study occurred mostly in the constant rate period at low drying temperature and in the falling rate period at high temperature. The lengths of the constant rate period were about 60-70% of total drying time at low drying temperature (35 °C and 45 °C) and about 40-50% of the drying time at 55 °C. The effective moisture diffusivities during the falling rate period were in the range of 4.86×10^{-13} m^2/s at 35 °C to 1.44×10^{-12} m^2/s at 65 °C. Drying behaviour of moringa leaves under fluidized bed drying can be adequately modelled using Newton, Page, Henderson-Pabis, and Two Term models ($R^2 > 0.95$ and $\chi^2 \leq 0.001$). However, Page Model seems to provide the best prediction at the four drying temperatures as indicated by the correlation coefficient R^2 (highest) and the reduced Chi-square χ^2 (lowest).

The overall results of proximate analysis indicate that *Moringa oleifera* leave contain macronutrients such as protein, carbohydrate, fat, and fibers in high amounts which makes it suitable to be used in food products formulation. The effects of drying on these nutrients can be significant. Therefore, processing conditions such as drying temperature and duration must be optimized to preserve these nutrients during drying. The possible benefits of drying at low temperature can be negated by the long drying time required to reach the desired moisture content. On the other hand, the possible negative effects of drying at high temperature can be lessen by a much shorter drying time.

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