LAUTECH Journal of Civil and Environmental Studies
Volume 6, Issue 1; March 2021

DOI: 10.36108/laujoces/1202.60.0120

Microwave Drying of Banana (*Musa acuminata*) Stalk Biomass before Conversion to Value-added Products

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Submitted on: 21/09/2020; *Accepted on: 10/02/2021*

Abstract
Banana stalk biomass can pose disposal, environmental and health challenges. Fortunately, this biomass can be converted to value-added products including biofuels, bioenergy, biosorbents, fibers and animal feeds. However, it is necessary to remove moisture from the fresh biomass by drying before storage and conversion processes. Conventional drying in open sun is slow and weather dependent, but higher heating rates and faster drying rates can be achieved in a microwave dryer. Hence, the microwave drying characteristic of banana stalk biomass was investigated. Banana stalks were sliced into 5 mm thick pieces and dried in a microwave oven at power levels of 400 – 1000 W, the stalk slices were weighed at interval until the mass remained constant. The effective moisture diffusivity, activation energy and energy required for drying were determined. The microwave drying data were also fitted to twelve thin layer drying mathematical models to describe the kinetics of the drying process. The drying time of banana stalk slices decreased with increasing microwave power. The drying occurred mainly in the falling rate period. The effective moisture diffusivities were 4.14×10^{-9} - 2.00×10^{-8} m^2 s^{-1} at 400 – 1000 W. The activation energy was 122 W g^{-1} while the total and specific energies required for the microwave drying were 0.25 – 0.37 kWh and 34.8 – 51 kWh/kg, respectively. The Weibull model suitably described the microwave drying kinetics of banana stalk slices. The moisture present in fresh banana stalk waste biomass can be effectively and rapidly removed by microwave drying before conversion processes.

Keywords: Banana stalk biomass; microwave drying; drying energy; drying kinetics.

Introduction
Banana is a nutritious fruit crop that is consumed as snack or processed into other consumer products globally (Mohapatra *et al.*, 2011; FAO, 2020a). It belongs to the family *Musaceae* (Simmonds, 1962; Mohapatra *et al.*, 2010). Banana is grown in many countries of the world for domestic consumption and as an export produce (FAO, 2020a; FAO, 2020b). A huge amount of residues which include rhizomes, pseudo-stems, stalks, peels and leaves, are generated through the production, processing and consumption of banana (Padam *et al*., 2014; Fernandes *et al*., 2013; Guerrero *et al*., 2016). This large quantity of residues can pose disposal and environmental pollution problems (Guerrero *et al*., 2016).

However, banana stalk biomass can be converted into useful material, biofuels and bioenergy. They can be utilized as adsorbents for the removal of pollutants from wastewater (Shibi *et al*., 2006; Hameed *et al*., 2008; Ogunleye *et al*., 2014; Ogunleye *et al*., 2015a; Ogunleye *et al*., 2015b). Fibers from banana stalk can be used as reinforcement in composite materials as well as in the production of textile and paper (Zuluaga *et al*., 2007; Zuluaga *et al*., 2009; Leao *et al*., 2010; Mohapatra *et al*., 2010; Deumaga *et al*., 2015; Ogunsile and Oladeji, 2016). Banana stalk can also be processed into feeds for animal consumption (Poyyamozhi and Kadirvel, 1986; Viswanathan *et al*., 1989; Ajila *et al*., 2012). In addition, banana stalk biomass can be converted to biofuels and bioenergy through gasification, pyrolysis, hydrothermal carbonization, torrefaction, direct combustion and fermentation processes (Santa-Maria *et al*., 2013; Granados *et al*., 2014; Guerrero *et al*., 2016; Dhyani and Bhaskar, 2017; Gumisiriza, *et al*., 2017; Guerreroa *et al*., 2018; Liao *et al*., 2018; Barskov *et al*., 2019; Islam *et al*., 2019).

Drying is a preservation method employed basically to lessen the moisture content of agricultural produce; it reduces enzyme and microbial activities in the material thus enhancing the shelf-life of the products, it also decreases packaging and transportation cost (Mujumdar and Law, 2010).
The removal of moisture from banana stalk before its storage is necessary for the preservation of fresh banana stalk biomass after harvesting and removal of the banana fruit. It is also essential to remove moisture from banana stalk during the production of adsorbents and animal feeds from the biomass (Viswanathan *et al*., 1989; Ogunleye *et al*., 2014; Ogunleye *et al*., 2015a; Ogunleye *et al*., 2015b). Besides, the high moisture in banana stalk biomass would limit the efficiencies of direct combustion, torrefaction, gasification and pyrolysis, so drying is essential to reduce the moisture content prior to these processes (Hughes and Larson, 1998; McKendry, 2002; Demirbas, 2004; Granados *et al*., 2014).

Open sun drying is the traditional technique for drying agricultural produce; it uses free solar energy, so it is cheap. However, it is weather dependent, requires long drying time and the material is adversely exposed to rodents, insects, dust and rainfall. However, microwave drying uses electromagnetic microwaves to internally heat the material causing a quick evaporation of water as a result of the rapid absorption of microwave energy by water molecules (Chandrasekaran *et al*., 2013; Rattanadecho and Makul, 2015; Wray and Ramaswamy, 2015). Faster drying rates and shorter drying times are achieved in microwave dryer compared to open sun (Agbede *et al*., 2020). The microwave drying of banana stalk biomass has not been previously reported.

Mass and heat transfer properties of banana stalk biomass including effective moisture diffusivity, activation energy and energy required for drying are essential for the design and operation of efficient dryers because drying is a coupled mass and heat transfer process. Thin layer drying mathematical models are useful for the design, operation, optimization and control of drying processes; they have been used to describe the drying behavior of agricultural products (Erbay and Icier, 2010; Kucuk *et al*., 2014). They can be used to estimate drying times (Akpinar and Bicer, 2008).

Hence, this study aimed at determine the microwave drying characteristics of banana stalk, including the drying rates, effective moisture diffusivities, activation energy, drying energy requirement as well as the thin layer drying mathematical model that best describe the drying process.

Materials and Methods

Sample Collection and Preparation

Banana stalks were obtained from freshly harvested banana bunches sold in a local market in Ogbomoso, Nigeria. The stalks were cleaned and then cut into slices of 5 mm thickness using a knife. The equivalent diameter of the banana stalk was about 33 mm. A banana stalk is shown in Figure 1.

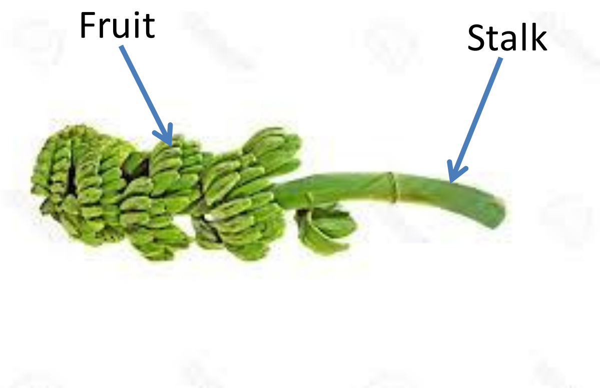

Figure 1: A bunch of bananas

Microwave Drying Procedure

A banana stalk slice was weighed and then placed on the rotating disc of a Hisense H36MOMMMI microwave oven. The microwave power level was set to 400 W and the material was heated for 5 min after which the sample was removed from the microwave oven and weighed. The microwave heating and subsequent weighing of the material continued until its mass remained constant. The microwave drying experiments were repeated using power levels of 600, 800 and 1000 W and heating times of 5, 3 and 3 min, respectively. The experiments were carried out in triplicates at each power level.

Analysis of Microwave Drying Data

The moisture content of the banana stalk slice at time, t, X_t (g water. g dry matter^{-1}) was defined as:

$$X_t = \frac{m_t - m_d}{m_d} \quad (1)$$

where m_t and m_d are mass (g) of the banana stalk slice at any time (min) t and mass (g) of absolutely dried slice, respectively. The moisture content was further transformed to a dimensionless moisture ratio (M_R) defined as:

$$M_R = \frac{X_t - X_e}{X_i - X_e} \quad (2)$$

where X_i and X_e are initial and equilibrium moisture contents, respectively. For a long drying time, the values of X_e are small compared with X_t and X_i, so the moisture ratio can be simplified to equation 3 (Perea-Flores *et al*., 2012):

$$M_R = \frac{X_t}{X_i} \quad (3)$$

The drying rate of the banana stalk slice was expressed as:

$$D_R = \frac{X_{t+dt} - X_t}{dt} \quad (4)$$

where D_R is drying rate (g water/g dry matter. min), X_{t+dt} is moisture content at time $t+dt$ (g water. g dry matter^{-1}) and dt is time increment (min).

The internal mass transfer is the rate controlling mechanism during the falling rate period, so the Fick's second law of diffusion can be used to describe the diffusion of moisture from the internal part of the stalk slice to its surface (Doymaz, 2008; Agbede *et al*., 2020). The Fick's law in terms of the moisture ratio was expressed as (Vega-Galvez *et al*, 2010):

$$\frac{dM_R}{dt} = D_{eff}\,\frac{d^2M_R}{dx^2} \tag{5}$$

where D_{eff} is the effective moisture diffusivity (m^2 s^{-1}) and x is spatial dimension (m). The solution of this equation proposed by Crank (1975) is:

$$M_R = \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left[\frac{-(2i+1)^2 D_{eff}\pi^2 t}{4L^2}\right] \tag{6}$$

This is based on the assumption of a one-dimensional transport of moisture in an infinite banana stalk slab, negligible shrinkage, uniform initial moisture distribution, constant diffusivity and negligible external resistant. A good estimate of the solution is given by the first term in the series expansion of equation (6), for sufficiently long drying time (Di Scala and Crapiste, 2008):

$$M_R = \frac{8}{\pi^2}\exp\left[\frac{-D_{eff}\pi^2 t}{4L^2}\right] \tag{7}$$

where L is half of the thickness of the slab (m) and t the drying time (min). A linear form of equation (7) is:

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

A plot of $In(M_R)$ versus t results in a straight line with slope (S_D) from which D_{eff} was calculated:

$$S_D = \frac{D_{eff}\pi^2}{4L^2} \tag{9}$$

The microwave power dependence of the effective moisture diffusivity can be described by an Arrhenius-type relationship (Olanipekun *et al*., 2015):

$$D_{eff} = D_o \exp\left[\frac{-E_a m}{P}\right] \tag{10}$$

where D_o is the Arrhenius or pre-exponential factor (m^2 s^{-1}), E_a the activation energy (W g^{-1}), P the microwave power (W) level and m the mass (g) of fresh banana stalk slice. A linear form of equation (10) is:

$$In\ D_{eff} = In\ D_o - \frac{E_a m}{P} \tag{11}$$

The activation energy E_a can be determined from the slope (S_E) of the straight line obtained from the plot of $In\ D_{eff}$ versus m/P :

$$S_E = E_a \tag{12}$$

The total energy E_t (kWh) and specific energy E_{sp} (kWh/kg banana stalk) required for microwave drying of fresh banana stalk were computed from equations 13 and 14, respectively:

$$E_t = P \times D_t \tag{13}$$

$$E_{sp} = \frac{E_t}{m_i - m_d} \tag{14}$$

where P is microwave power (kW) and D_t is the total drying time (h), m_i is initial mass of the banana stalk slice (kg) and m_d is mass of the absolutely dried banana stalk slice (kg).

Thin Layer Mathematical Modelling of Microwave Drying Kinetics

The twelve thin layer models presented in Table 1 are those that have most frequently well described the drying kinetics of agricultural products (Kucuk *et al*., 2014), so they were fitted to the drying data to identify the model that most suitably describe the microwave drying kinetics of banana stalk. The data were fitted to the models by nonlinear regression analysis using the Statistical Package for the Social Sciences (SPSS) version 20 software. The statistical parameters used as criteria to determine the model that best describe the microwave drying data were the coefficient of determination (R^2), sum of square error (*SSE*), root mean square error (*RMSE*) and Chi-square (χ^2). The model that best describes the experimental data is one that has the highest value of R^2 and lowest values of *SSE*, *RMSE* and χ^2 (Kucuk et al., 2014). The values of *SSE*, *RMSE* and χ^2 were calculated from equations 15, 16 and 17, respectively, using Microsoft Excel, but R^2 values were obtained from the SPSS software.

Table 1: Thin layer drying models fitted to drying data

No	Model Name	Model Equation	References
1	Midilli-Kucuk	$M_R = a\exp\left(-kt^n\right) + bt$	Midilli *et al.* (2002)
2	Page	$M_R = \exp\left(-kt^n\right)$	Page (1949)
3	Logarithmic	$M_R = a\exp\left(-kt\right) + c$	Chandra and Singh (1995)
4	Two-term	$M_R = a\exp\left(-k_0t\right) + b\exp\left(-k_1t\right)$	Henderson (1974), Glenn (1978)
5	Wang and Singh	$M_R = 1 + at + bt^2$	Wang and Singh (1978)
6	Approximation of diffusion	$M_R = a\exp\left(-kt\right) + \left(1-a\right)\exp\left(-kbt\right)$	Kaseem (1998)
7	Modified Henderson and Pabis	$M_R = a\exp\left(-kt\right) + b\exp\left(-gt\right) + c\exp\left(-ht\right)$	Karathanos (1999)
8	Modified Page	$M_R = \exp\left(-(kt)^n\right)$	White *et al*. (1978)
9	Henderson and Pabis	$M_R = a\exp\left(-kt\right)$	Henderson and Pabis (1961)
10	Two-term exponential	$M_R = a\exp\left(-kt\right) + \left(1-a\right)\exp\left(-kat\right)$	Sharaf-Eldeen *et al*. (1980)
11	Verma	$M_R = a\exp\left(-kt\right) + \left(1-a\right)\exp\left(-gt\right)$	Verma *et al.* (1985)
12	Weibull	$M_R = a - b\exp\left(-kt^n\right)$	Weibull (1951)

$$SSE = \frac{1}{N}\sum_{i=1}^{N}\left(M_{R_{\exp,i}} - M_{R_{pred,i}}\right)^2 \quad (15)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(M_{R_{pred,i}} - M_{R_{\exp,i}}\right)^2\right]^{\frac{1}{2}} \quad (16)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(M_{R_{\exp,i}} - M_{R_{pred,i}}\right)^2}{N - z} \quad (17)$$

where $M_{R_{\exp,i}}$, $M_{R_{pred,i}}$, N and z are experimental moisture ratio, predicted moisture ratio, number of observations and number of constants, respectively.

Results and Discussion

Drying Curves

The plots of moisture ratio versus drying time for the microwave drying of banana stalk slices at 400 – 1000 W are shown in Figure 2. The moisture ratio decreased as the microwave drying progressed, indicating that moisture was effectively removed from the banana stalk slices by microwave heating. The drying times decreased with increasing microwave power level; drying times of 55, 35, 27 and 15 min, were observed at 400, 600, 800 and 1000 W, respectively. Higher drying rates and shorter drying times were achieved at higher microwave power levels because the larger thermal energy generated by higher microwave energy available at elevated microwave power levels resulted in a more rapid evaporation of moisture from the banana stalk slices (Chandrasekaran, *et al*., 2013). Shorter drying times at higher microwave power levels have been reported for the microwave drying of spinach (Alibas Ozkan *et al*., 2007), mint leaves (Özbek and Dadali, 2007), basil (Demirhan and Özbek, 2009), coriander (Sarimeseli, 2011), turmeric slices (Surendhar *et al*., 2019) and green microalgae paste biomass (Agbede *et al*., 2020).

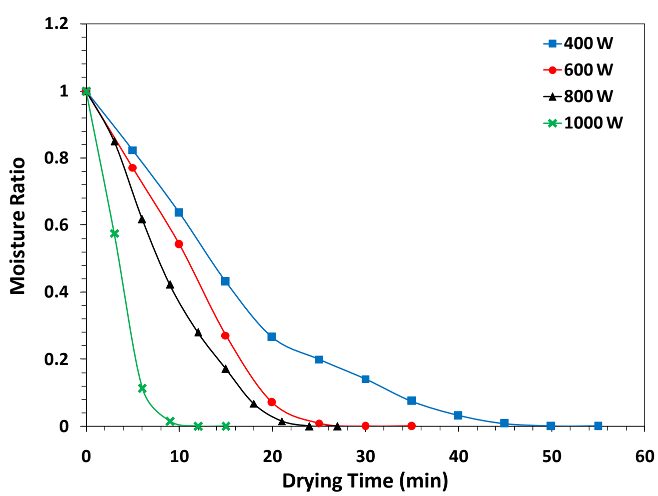

Figure 2: Plot of moisture ratio versus drying time for microwave drying of banana stalk slices

Drying Rates

The plots of drying rates versus drying times for the microwave drying of banana stalk slices at 400 – 1000 W are shown in Figure 3. At each of the power levels studied, the drying rate initially increased briefly during the warming up stage then decreased with drying time. The highest drying rates were 0.52, 0.62, 0.99 and 1.79 g water / g dry matter.min at 400, 600, 800 and 1000 W, respectively. Higher initial drying rates were observed at higher microwave powers. The drying took place mainly in the falling rate period and was controlled by diffusion of moisture from the inner part of the banana stalk slice to its surface (Doymaz, 2008; Ruiz Celma *et al*., 2008). A brief initial warming up period followed by a main falling rate period has been similarly reported for the microwave drying of *Gundelia tournefortii* (Ervin, 2012) and green microalgae paste biomass (Agbede *et al*., 2020).

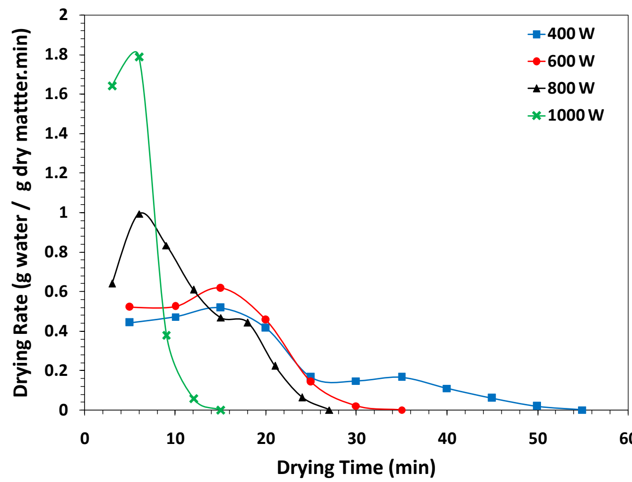

Figure 3: Plot of drying rate versus drying time for microwave drying of banana stalk slices

Effective Moisture Diffusivities

The measured effective moisture diffusivities for the microwave drying of banana stalk slices at 400, 600, 800 and 1000 W were 4.14 x 10^{-9}, 7.56 x 10^{-9} , 7.73 x 10^{-9} and 2.00 x 10^{-8} m^2 s^{-1}, respectively. They are within the range of 10^{-12} – 10^{-6} m^2 s^{-1} previously reported for agro-products (Erbay and Icier, 2010). The effective moisture diffusivity increased with increasing microwave power because the activity of moisture in the banana stalk increased due to the higher heating rate at higher microwave power resulting in larger moisture diffusivities. The effective moisture diffusivities for the microwave drying of banana stalk slices of 4.14 x 10^{-9} - 2.00 x 10^{-8} m^2 s^{-1} at 400 – 1000 W obtained in this study are larger than those of 2.168 x 10^{-10} - 7.899 x 10^{-10}, 3.982 x 10^{-11} - 2.073 x 10^{-10} and 6.3 x 10^{-11} - 2.19 x $10^{-10}$$m^2$ s^{-1} previously reported for the microwave drying of basil leaves (Demirhan and Özbek, 2009), mint leaves (Özbek and Dadali, 2007) and coriander leaves (Sarimeseli, 2011), respectively. However, they are lower than 8.315 x 10^{-8} - 2.363 x 10^{-7} and 5.5 × 10^{-8} - 3.5 × $10^{-7}$$m^2$ s^{-1} reported for the microwave drying of green pepper (Darvishi *et al*., 2014) and *Gundelia tournefortii* (Ervin, 2012), respectively.

Activation Energy

The effective moisture diffusivity was well described by the Arrhenius-type equation 10, the activation energy for microwave drying of the banana stalk slices was 122 W g^{-1}. This energy is a measure of the energy required to initiate diffusion of moisture from the inner part of the stalk slice to its surface. It is far larger than those of 10.43, 12.28, 14.19, 21.40 and 39.32 W/g reported for the microwave drying of basil leaves (Demirhan and Özbek, 2009), mint leaves (Özbek and Dadali, 2007), green pepper (Darvishi *et al*., 2014), microalgae paste (Agbede *et al*., 2020) and turmeric slices (Surendhar *et al*., 2019), respectively.

Microwave Drying Energy

The total and specific energies required for microwave drying of banana stalk slices at 400 – 1000 W are shown in Figure 4 and Figure 5, respectively. Both the total and specific energies required for microwave drying of the banana stalk slices did not change significantly at power levels lower than 1000 W, but decreased significantly at 1000 W due to higher drying rate and shorter drying time achieved at this power level. The total and specific energies for the microwave drying of banana stalk slices were 0.25 – 0.37 kWh and 34.8 – 51 kWh/kg, respectively. The specific energies required for microwave drying of banana stalk slices at 400 – 1000 W are much higher than those of 2.72 – 6.84 kWh/kg required for microwave drying of turmeric slices at 270 – 900 W (Surendhar *et al*., 2019).

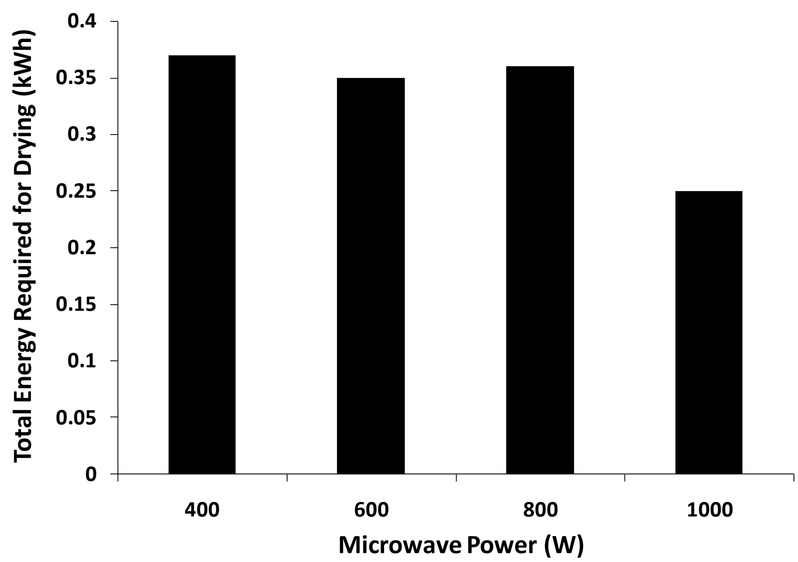

Figure 4: Total energy required for microwave drying of banana stalk slices at 400 – 1000 W

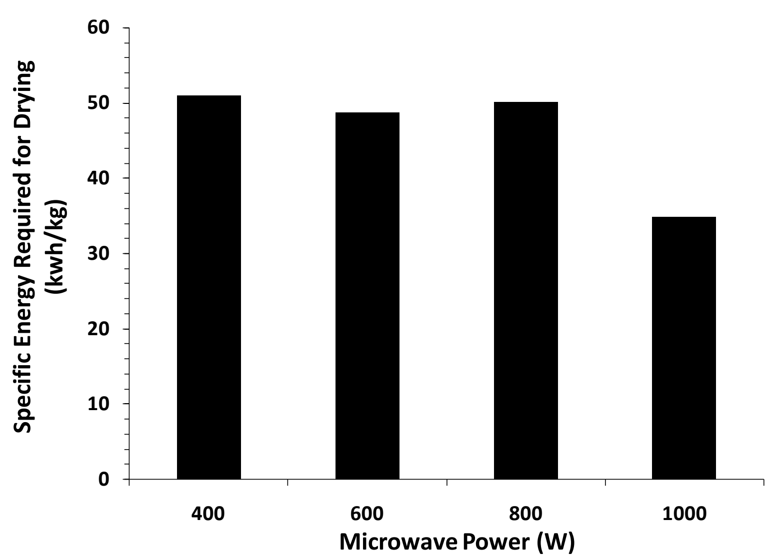

Figure 5: Specific energy required for microwave drying of banana stalk slices at 400 – 1000 W

Microwave Drying Kinetics

The constants and statistical parameters obtained when the thin layer drying models were fitted to the microwave drying data are presented in Tables 2 - 5. The Midilli-Kucuk, Page, modified page, Verma and Weibull models had the highest R^2 value of 0.998 compared to the other seven models, these five models also had the lowest *SSE* (0.0002), *RMSE* (<0.0153) and χ^2 (<0.0004) values at the microwave power 400 W compared to the other seven models as shown in Table 2. The Midilli-Kucuk and Weibull models had the highest R^2 value of 0.996 compared to the other ten models, both models also have the lowest value of *SSE* (0.0006), but the Weibull model had lower *RMSE* (0.0248) and χ^2 (0.0012) values at the microwave power 600 W as shown in Table 3.

Table 2: Constants and statistical parameters of the thin layer drying models for microwave drying of banana stalk at 400 W

Model	Model Constants	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	a = 1.001, b = 0, k = 0.022, n = 1.337	0.998	0.0002	0.0152	0.0003
Page	k = 0.02, n = 1.373	0.998	0.0002	0.0141	0.0002
Logarithmic	a = 1.142, c = -0.101, k = 0.051	0.992	0.0008	0.0290	0.0011
Two-term	a = 0.533 b = 0.533, k_0 = 0.065, k_1 = 0.065	0.982	0.0020	0.0446	0.0030
Wang and Singh	a = -0.043, b = 0	0.995	0.4387	0.6623	0.5264
Approximation of diffusion	a = 1, b = 1, k = 0.061	0.997	0.0025	0.0504	0.0033
Modified Henderson and Pabis	a = 0.356, b = 0.356, c = 0.356, g = 0.065, h = 0.065, k = 0.065	0.982	0.0020	0.0446	0.0040
Modified Page	k = 0.058, n = 1.373	0.998	0.0002	0.0140	0.0002
Henderson and Pabis	a = 1.067, k = 0.065	0.982	0.0020	0.0446	0.0024
Two-term exponential	a = 1, k = 0.061	0.977	0.0025	0.0504	0.0030
Verma	a = 4.259, g = 0.134, k = 0.106	0.998	0.0002	0.0148	0.0003
Weibull	a = -0.014, b = -1.016, k = 0.022, n = 1.33	0.998	0.0002	0.0131	0.0003

Table 3: Constants and statistical parameters of the thin layer drying models for microwave drying of banana stalk at 600 W

Model	Model Constants	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	a = 0.983, b = -0.001, k = 0.011, n = 1.766	0.996	0.0006	0.0253	0.0013
Page	k = 0.012, n = 1.757	0.995	0.0007	0.0259	0.0009
Logarithmic	a = 1.259, c = -0.214, k = 0.016	0.977	0.2181	0.4671	0.3490
Two-term	a = 0.537, b = 0.537, k_0 = 0.092, k_1 = 0.092	0.951	0.0067	0.0816	0.0133
Wang and Singh	a = -0.062, b = 0.001	0.987	0.0031	0.0553	0.0041
Approximation of diffusion	a = 1, b = 1, k = 0.087	0.944	0.0075	0.0866	0.0120
Modified Henderson and Pabis	a = 0.358, b = 0.358, c = 0.358, g = 0.092, h = 0.092, k = 0.092	0.951	0.0067	0.0816	0.0266
Modified Page	k = 0.08, n = 1.757	0.995	0.0007	0.0258	0.0009
Henderson and Pabis	a = 1.073, k = 0.092	0.944	0.0067	0.0816	0.0089
Two-term exponential	a = 1, k = 0.087	0.944	0.0075	0.0866	0.0100
Verma	a = 9.395, g = 0.201, k = 0.117	0.989	0.0015	0.0382	0.0023
Weibull	a = -0.02, b = -1.004, k = 0.011, n = 1.742	0.996	0.0006	0.0248	0.0012

Also, for the microwave drying data obtained at 800 W, the Midilli-Kucuk and Weibull models had the highest R^2 value of 0.999 compared to the other ten models, both models also have the lowest values of *SSE* (0.0001) and χ^2 (0.0002), but the Weibull model had an *RMSE* value of 0.0108 which was lower than that of 0.0110 obtained for the Midilli-Kucuk model as shown in Table 4. The Midilli-Kucuk, Page, modified Henderson and Pabis, modified Page, Verma and Weibull models had the highest R^2 value of 1.000 compared to the other models for microwave drying of banana stalk slices at 1000 W, these models also have lower *SSE* (<0.0054), *RMSE* (<0.0732) and χ^2 (<0.0375) values. Notably, the Weibull model had *SSE*, *RMSE* and χ^2 values of 0.0039, 0.0628 and 0.0092, respectively, as shown in Table 5. Hence, the Weibull model was deemed to best fit the microwave drying data.

Table 4: Constants and statistical parameters of the thin layer drying models for microwave drying of banana stalk at 800 W

Model	Model Constants	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	a =1, b = -0.001, k = 0.033, n = 1.47	0.999	0.0001	0.0110	0.0002
Page	k = 0.029, n =1.542	0.998	0.0002	0.0153	0.0003
Logarithmic	a = 1.259, c = -0.212, k = 0.076	0.990	0.0012	0.0353	0.0018
Two-term	a = 0.542 b = 0.542, k_0 = 0.115, k_1 = 0.115	0.967	0.0040	0.0631	0.0066
Wang and Singh	a = -0.077, b = 0.001	0.995	0.0272	0.1649	0.0340
Approximation of diffusion	a = 1, b = 1, k = 0.107	0.959	0.0050	0.0706	0.0071
Modified Henderson and Pabis	a = 0.361, b = 0.361, c = 0.361, g = 0.115, h = 0.115, k = 0.115	0.967	0.0034	0.0631	0.0100
Modified Page	k = 0.132, n = 3.81 x 10^{-17}	0.321	0.0830	0.2881	0.1037
Henderson and Pabis	a = 1.084, k = 0.115	0.967	0.0040	0.0631	0.0050
Two-term exponential	a = 1, k = 0.107	0.959	0.0050	0.0706	0.0062
Verma et al	a = 6.374, g = 0.245, k = 0.205	0.996	0.0005	0.0216	0.0007
Weibull et al	a= -0.034, b = -1.034, k = 0.033, n = 1.451	0.999	0.0001	0.0108	0.0002

A comparison of moisture ratios predicted by the Weibull model with experimental moisture ratios is shown in Figure 6. The predicted moisture ratios are in good agreement with the experimental moisture ratios (R^2 values of 0.996 – 1.000), indicating that the Weibull model suitably described the microwave drying kinetics of banana stalk slices.

Table 5: Constants and statistical parameters of the thin layer drying models for microwave drying of banana stalk at 1000 W

Model	Model Constants	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	a =1, b = 0, k = 0.064, n = 1.971	1.000	0.0042	0.0647	0.0098
Page	k = 0.064, n =1.967	1.000	0.0041	0.0639	0.0057
Logarithmic	a = 1.106, c = -0.081, k = 0.229	0.974	0.0047	0.0687	0.0083
Two-term	a = 0.516 b = 0.516, k_0 = 0.277, k_1 = 0.277	0.965	0.0053	0.0731	0.0125
Wang and Singh	a = -0.18, b = 0.008	0.985	0.0211	0.1453	0.0296
Approximation of diffusion	a = 1, b = 1, k = 0.271	0.964	0.0055	0.0743	0.0097
Modified Henderson and Pabis	a = 0.344, b = 0.344, c = 0.344, g = 0.277, h = 0.277, k = 0.277	1.000	0.0053	0.0731	0.0374
Modified Page	k = 0.247, n = 1.967	1.000	0.0041	0.0637	0.0057
Henderson and Pabis	a = 1.032, k = 0.277	0.965	0.0053	0.0731	0.0075
Two-term exponential	a = 1, k = 0.271	0.964	0.0055	0.0743	0.0077
Verma	a = 5.528, g = 0.947, k = 0.628	1.000	0.0039	0.0627	0.0069
Weibull	a= -0.002, b = -0.998, k = 0.063, n = 1.976	1.000	0.0039	0.0628	0.0092

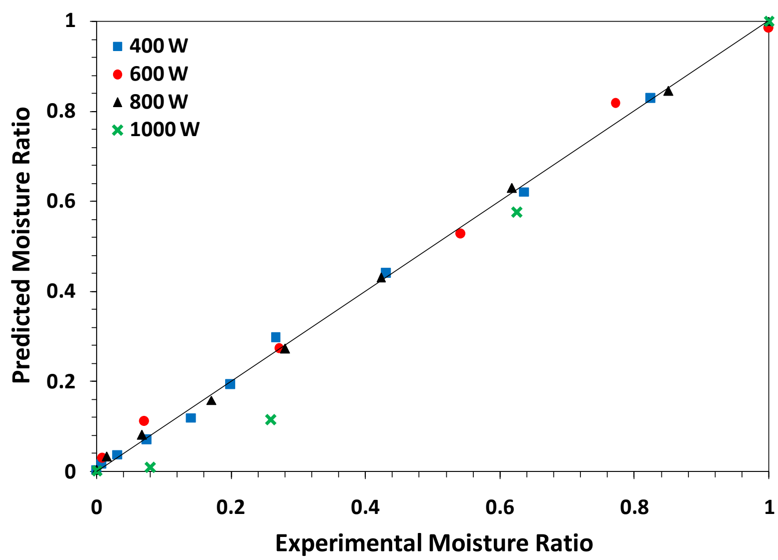

Figure 6: Comparison of Weibull model predicted moisture ratio and experimental moisture ratio for microwave drying of banana stalk slices

Conclusion

The microwave drying of banana stalk biomass was controlled by moisture migration within the biomass. The drying rate of the biomass can be appreciably enhanced by drying at higher microwave powers. An Arrhenius-type equation suitably described the microwave power dependence of the effective moisture diffusivity, with activation energy of 122 W g^{-1}. The specific energy required for drying banana stalk slices can be significantly reduced by drying at microwave power levels higher than 800 W. The Weibull thin layer drying mathematical model well described the microwave drying kinetics of banana stalk slices.

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