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The influence of surface area, temperature and pretreatment on convective hot air oven drying of banana peels biomass

Oluseye Omotoso Agbede1, 2, 3, 4), Gbemileke Raphael Eniola1), Oluwafunmilayo Abiola Aworanti*1, 2),
Funmilayo Nihinlola Osuolale1, 2), Akeem Olatunde Arinkoola1, 4), Solomon Oluyemi Alagbe1, 2, 4),
Samuel Enahoro Agarry1, 3), Oladipupo Olaosebikan Ogunleye1, 4), Kehinde Ayoola Babatunde1, 2),
Ebenezer Olujimi Dada1, 2) and Odunayo Deborah Akinwumi1, 2)

1)Department of Chemical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria
2)Energy and Sustainability Research Group, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria
3)Drying Research Group, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria
4)Process and Product Development Research Group, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria

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Abstract

Untreated banana peels biomass of 15 x 10, 30 x 20 and 60 x 40 mm sizes were dried at 60 °C while untreated and pretreated (hot water and sulphite treated) biomass of 10 x 10 mm size were dried at 80 – 140 °C, to find out the influence of surface area, pretreatment and temperature on convective hot air oven drying of the biomass. The rate of drying of banana peels increased with increasing surface area and temperature while hot water and sulphite pretreatments reduced the time needed for drying. The drying operation occurred primarily in the falling-rate phase. Effective moisture diffusivities for the drying operations were in the range 5.19 x 10^{-10} – 1.55 x 10^{-8} m^2 s^{-1}. The activation energies for drying untreated, sulphite treated and hot water treated peels were 24.7, 21.4 and 21.3 kJ mol^{-1}, respectively. The biomass drying kinetics was well described by the Weibull model. Specific energies needed for drying the 15 x 10, 30 x 20 and 60 x 40 mm banana peels biomass at 60 °C were 157.9 – 335.6 kWh/kg while those required for drying both untreated and pretreated 10 x 10 mm sized banana peels biomass at 80 – 140 °C were 33.5 – 93.9 kWh/kg. The rate of drying banana peels in hot air oven can be considerably improved and the energy needed for drying appreciably reduced by increasing the peel surface area, drying at higher temperatures and pretreating the biomass with hot water or sulphite solution.

Keywords: Drying kinetics, Banana peels, Drying pretreatment, Effective moisture diffusivity, Activation energy, Drying energy

1. Introduction

Agriculture residues are waste biomass for which useful purposes are currently being explored [1-7]. Banana (Musa spp.) is a fruit which is eaten raw or processed into edible snacks globally [8-10]. A very large quantity of wastes biomass (pseudo-stems, rhizomes, leaves, stalks and peels) are produced by the cultivation, processing and utilization of banana which can cause the problems of waste disposal, environmental pollution and health risks [11-15]. For instance, fresh banana consists of 30 – 40% of peels by mass [14, 16]. It is however interesting that banana peel waste can be processed into useful products [14, 17]. Banana peels can be processed into biosorbents (adsorbents) for the adsorption of pollutants including heavy metal ions, organic compounds, dyes, oils and pesticides from wastewater [15, 18-21]. Biofuels (e.g. biogas, bioethanol, bio-oil, biochar, synthesis gas and briquette) and bioenergy can be obtained from banana peels via briquetting, thermochemical (torrefaction, pyrolysis, gasification and direct combustion), fermentation and anaerobic digestion processes [22-32]. Banana peels can also be used as dietary fiber [33-35] and animal feeds [14, 16, 36-39]. They are also good sources of pectin, biofertilizer, antibacterial compounds, antioxidative substance, cellulose nanofibers [12, 14, 40-42].

The production of adsorbents, briquettes, dietary fibers and livestock feeds from banana peels involves the reduction of moisture present in the fresh biomass through drying [14-16, 31, 34, 37, 38, 43]. Also, the moisture present in fresh biomass lowers the product energy and mass yields of torrefaction processes, so drying is essential to the effectiveness of this process [44]. Likewise, it is essential to reduce the moisture in fresh biomass before direct combustion, gasification and pyrolysis processes, because the efficiencies of these processes can be limited by moisture in the fresh material [30, 45-47]. Moreover, moisture removal from banana peels biomass before storage is required to preserve the biomass until its usage. It similarly reduces packaging as well as transportation costs [48]. Therefore, it’s essential to investigate the drying behaviour of banana peels biomass.

Agricultural products are traditionally dried in open sun or direct sunlight. This method is cheap since the energy from the sun is free; however, it depends on the weather conditions so materials might take a very long time to dry. Besides, materials dried in direct sunlight are predisposed to the activities of rodents and insects. Solar dryers of various types, which are a huge improvement over open sun drying, have been developed and evaluated for the drying of agro-products [49-54]; however, their performances are still limited by prevailing weather condition [49]. On the other hand, convective hot air oven drying employs a device that offers a hygienic drying

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*Corresponding author.
Email address: oaaworanti@lautech.edu.ng
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environment as well as higher drying temperatures, better temperature control and uniform drying conditions compared to open sun drying [55-57].

Drying air velocity, relative humidity and temperature, as well as material shape and size, can affect the convective hot air drying rates of agro-products [58-61]. Besides, drying pretreatments such as thermal (e.g. hot water blanching) and chemical solution (e.g. sulphite) treatments can be applied to the material before drying to soften the material tissue and change the membrane permeability, leading to enhanced drying rate [53, 62].

Several researchers have reported the hot air oven drying of banana fruits [63-72]. On the contrary, very few studies on the drying of banana peels have been reported [73, 74]; the influences of surface area (or material size) and pretreatments on the hot air drying of the peels of banana have not been previously reported.

Drying involves both heat and mass transfer processes, so the heat and mass transfer characteristics of the peels of banana such as activation energy, energy consumption and effective moisture diffusivity are necessary for design of convective hot air oven dryers. Also, drying is a process that is energy-intensive; high energy requirement implies huge processing cost, so, energy minimization would cut down the overall biomass processing expenses and increase viability of utilization of banana peels biomass. Hence, the influence of surface area, pretreatment and temperature on drying behaviour, specific energy requirement, effective moisture diffusivity of the convective hot air oven drying of banana peels biomass were investigated.

Moreover, drying processes require models for design, operation, optimization, control and energy integration. Thin layer drying mathematical models are suitable for describing the kinetics of drying processes and estimating drying times; these models have been previously used to describe the drying kinetics of several agricultural materials [58, 75-78]. Therefore, the mathematical modelling of the thin layer drying kinetics of banana peels in a convective hot air oven dryer was also investigated.

2. Materials and methods

2.1 Materials

Fresh banana fruits were purchased from a local market in Ogbomoso, Nigeria. The potassium metabisulphite ($K_2S_2O_5$) used for pretreating the banana peels was also obtained from a local chemical store.

2.2 Sample preparation

The edible parts of the fruits were removed while the fresh peels were cut into four different sizes of 10 x 10 mm, 15 x 10 mm, 30 x 20 mm and 60 x 40 mm, using a kitchen knife. The 15 x 10 mm, 30 x 20 mm and 60 x 40 mm sized banana peels samples were utilized to investigate the influence of peel surface area on the drying characteristics, effective moisture diffusivity and energy requirement of convective hot air drying of banana peels. Some of the 10 x 10 mm size peel slices were dried at 80 – 140 ^{o}C without any pretreatment while the rest were pretreated using either hot water or sulphite solution before the drying operations, to investigate the influence of temperature and pretreatment on the drying process. The thickness of the banana peels was 4 mm; this thickness was uniform for all samples of banana peels.

2.2.1 Sulphite pretreatment

Sulphite pretreatment is a chemical liquid phase pretreatment process which enhances the drying kinetics of agricultural produce by altering the permeability of the material cell membrane [62]. A sulphite solution was made by dissolving 2.5 g of potassium metabisulphite ($K_2S_2O_5$) in 1 litre of water. Some of the 10 x 10 mm banana peel slices were dipped in the sulphite solution for 10 min, after which they were removed, drained and spread in drying pans. The sulphite pretreated samples were then dried in hot air according to the procedure discussed in section 2.3.

2.2.2 Hot water pretreatment

This is a physical heat pretreatment process that can improve the drying rate of material by softening its tissue and changing the cell permeability [62]. Banana peel slices of 10 x 10 mm size were soaked in hot water (which had been heated to 100 ^{o}C) for 10 min. The hot water pretreated samples were thereafter removed from the hot water, totally drained and then spread in drying pans. The hot water pretreated banana peels were subsequently dried in convective hot air oven dryer as described in section 2.3.

2.3 Experimental procedure for convective hot air oven drying of banana peels

Drying pans containing banana peel slices of sizes 15 x 10 mm, 30 x 20 mm and 60 x 40 mm, were placed in a laboratory dryer manufactured by Genlab (MINO/75/F/DIG) and dried at 60 ^{o}C, to study the influence of peel size or surface area on the drying characteristics. A schematic of the laboratory convective hot air oven dryer is shown in Figure 1; the dryer has an automatic temperature controller and can operate in the temperature range of 40 – 250 ^{o}C. The initial mass of banana peels in all cases was similar and about 6 g. The samples were weighed at an interval of 30 min until moisture was entirely removed from the banana peels and the mass remained constant. Similarly, drying pans separately containing untreated, sulphite treated and hot water treated 10 x 10 mm size banana peels were dried in the hot air dryer at 80, 100, 120 and 140 ^{o}C, to study the effects of drying air temperature and pretreatment on the drying behaviour of the peels. The initial mass of each sample in this case was 4 g. Each sample of banana peels was weighed at 30, 15, 10 and 5 min interval during the biomass drying at 80, 100, 120 and 140 ^{o}C, respectively, until the mass of the banana peel became constant. A Mettler (model BB3000) digital weighing balance with an accuracy of ±0.1 g was used for weight measurement. The drying air velocity for all hot air oven drying experiments was 1.5 m s^{-1}. The oven was operated in a laboratory where the ambient temperature was 25 – 30 ^{o}C and the relative humidity was 65 – 80% during the drying experiments.

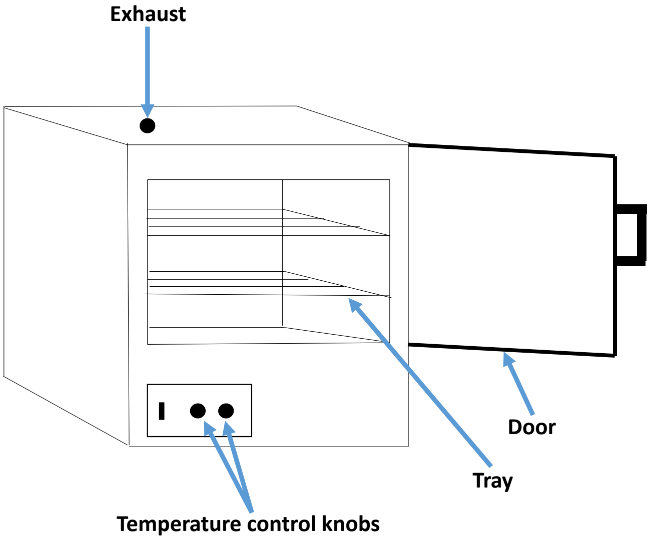

Figure 1 Schematic of a convective hot air oven dryer

2.4 Experimental procedure for open sun drying of banana peels

To compare the open sun drying characteristics of banana peels with the hot air oven drying, untreated samples of 4 mm thick, 15 x 10 mm size banana peels were dried in the open sun. The untreated banana peels samples were spread in drying pans and then placed in the open sun. The banana peel samples were weighed at 30 min interval until the mass was constant. The open sun drying experiments were performed between 9 am and 5 pm in the city of Ogbomoso, Nigeria. The temperature, relative humidity and air velocity of the ambient were measured using a PCE Instruments Kestrel 4000 NV weather tracker, which has accuracies of ±1 ^{o}C, ±3.0% RH and 3% of the air velocity reading, respectively. The measured air velocity was in the range 0.9 to 4.9 m s^{-1} while the relative humidity was 45 – 60 % during the open sun drying.

2.5 Drying data analysis

The moisture in the peel at time *t*, is:

$$X_t = \frac{m_t - m_d}{m_d} \tag{1}$$

where m_t is mass of peel at time t, m_d is mass (g) of peel when it is completely dry while X_t is the moisture content (g water. g dry matter^{-1}). The moisture content can be defined in terms of moisture ratio (M_R):

$$M_R = \frac{X_t - X_e}{X_i - X_e} \tag{2}$$

where X_e is equilibrium moisture content and X_i is initial moisture content. The values of X_e are small compared with X_t and X_i for a long drying period, so the moisture ratio is expressed as [57]:

$$M_R = \frac{X_t}{X_i} \tag{3}$$

The banana peels were dried at a drying rate:

$$D_R = \frac{X_t - X_{t+dt}}{dt} \tag{4}$$

where D_R is the rate of drying (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). When drying occurs in the falling-rate phase, mass transfer of moisture within the banana peels controls the drying rate; hence, the diffusion of moisture in the peels can be explained by the Fick’s second law of diffusion [76]. This law can be expressed in terms of the moisture ratio as:

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

Where X is spatial dimension (m) and D_{eff} is the effective moisture diffusivity (m^2 s^{-1}).

Banana peel slices have the geometry of a slab, so if uniform initial distribution of moisture in a slab that is infinite, moisture transfer in one-dimension, constant moisture diffusivity, insignificant shrinkage and negligible external resistant are assumed, equation (5) can be solved [79] to obtain:

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

The first term of a series expansion of this equation provides a suitable estimate to the solution for a drying time that is long [80]:

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

where L is half of the thickness of the slab (m) when drying occurs from both sides of the slab but L is the thickness of the slab (m) when drying occurs from only one side [76], while t is the drying time. A linear form of Equation (7) is:

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

The graph of $In(M_R)$ against t is a straight line. The effective moisture diffusivity is estimated from the slope (S_1):

$$S_1 = -\frac{D_{eff} \pi^2}{4L^2} \tag{9}$$

An Arrhenius relationship can describe the dependence of the effective moisture diffusivity on temperature [57, 81, 82]:

$$D_{eff} = D_o \exp\left(\frac{-E_a}{RT}\right) \tag{10}$$

where D_o is the Arrhenius factor ($m^2 s^{-1}$), R the universal gas constant (8.314 J mol^{-1} K^{-1}), $E_a$the activation energy (kJ mol^{-1}) and T the absolute temperature (K). Equation (10) can be written in a linear form:

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

The activation energy E_a is then calculated from the slope, S_2:

$$S_2 = -\frac{E_a}{R} \tag{12}$$

Total energy E_t (kWh) needed for hot air drying was calculated by Equation (13) [81, 83-87] while the specific energy E_{sp} (kWh/kg banana peels) was estimated by Equation (14) [81, 83-87]:

$$E_t = A\upsilon\rho_a c_a \Delta T D_t \tag{13}$$

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

where υ is air velocity (m s^{-1}), A is tray area (m^2), C_a is specific heat of air (kJ/kg °K), ΔT is temperature difference (°K), ρ_a is air density (kg/m^3), m_i is initial mass of peel (kg) and D_t is total drying time (s).

2.6 Thermophysical parameters of the drying air

The specific heat of air (kJ/kg °K) was estimated from equation (15) [88, 89]:

$$c_a = 1.04841 - \frac{3.83719T}{10^4} + \frac{9.45378T^2}{10^7} - \frac{5.49031T^3}{10^{10}} + \frac{7.92981T^4}{10^{14}} \quad (15)$$

The air density ρ_a (kg/m^3) at each operating temperature, T (°K) was computed from equation (16) [83, 88-90]:

$$\rho_a = \frac{101.325}{0.287T} \quad (16)$$

2.7 Mathematical modeling of thin layer drying kinetics

Nonlinear regression analysis, using the Excel Software of Microsoft Office, was employed to fit drying data to the models shown in Table 1, to find the model that best describe the kinetics of the convective hot air oven drying of banana peels. It has been reported that these models suitably describe the drying data of biological materials [77]. The model that best describe the drying data was identified using the Chi-square (χ^2), sum of square error (SSE), coefficient of determination (R^2) and root mean square error (RMSE) as statistical parameter. The drying kinetics is best described by the model which has the highest R^2 and lowest RMSE, SSE and χ^2 values [77]. The statistical parameters (RMSE, SSE and χ^2) were obtained from equations 17-19 using the Microsoft Excel Spreadsheet while the value of R^2 was obtained using the Excel "RSQ" function.

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

$$RMSE = \left[\frac{1}{N} \Sigma_{i=1}^{N} \left(M_{R_{pred,i}} - M_{R_{\exp,i}} \right)^2 \right]^{\frac{1}{2}} \quad (18)$$

$$\chi^2 = \frac{\Sigma_{i=1}^{N} \left(M_{R_{\exp,i}} - M_{R_{pred,i}} \right)^2}{N - z} \quad (19)$$

where $M_{R_{pred,i}}$, $M_{R_{exp,i}}$, z and $N$are predicted moisture ratio, experimental moisture ratio, number of constants and number of observations, respectively. The drying kinetics of the peels were investigated using data obtained during the convective hot air drying of untreated, hot water treated and sulphite treated banana peels.

Table 1 Mathematical models fitted to drying data

No	Model Name	Model Equation	References
1	Weibull	$M_R = a - b\exp\left(-kt^n\right)$	[91]
2	Two-term exponential	$M_R = a\exp\left(-kt\right) + \left(1-a\right)\exp\left(-kat\right)$	[92]
3	Midilli-Kucuk	$M_R = a\exp\left(-kt^n\right) + bt$	[93]
4	Modified Page	$M_R = \exp\left(-(kt)^n\right)$	[94]
5	Logarithmic	$M_R = a\exp\left(-kt\right) + c$	[95]
6	Page	$M_R = \exp\left(-kt^n\right)$	[96]
7	Wang and Singh	$M_R = 1 + at + bt^2$	[97]
8	Modified Henderson and Pabis	$M_R = a\exp\left(-kt\right) + b\exp\left(-gt\right) + c\exp(-ht)$	[98]
9	Two-term	$M_R = a\exp\left(-k_0 t\right) + b\exp\left(-k_1 t\right)$	[99, 100]
10	Verma	$M_R = a\exp\left(-kt\right) + \left(1-a\right)\exp\left(-gt\right)$	[101]
11	Henderson and Pabis	$M_R = a\exp\left(-kt\right)$	[102]
12	Approximation of diffusion	$M_R = a\exp\left(-kt\right) + \left(1-a\right)\exp\left(-kbt\right)$	[103]

2.8 Experimental uncertainty

Uncertainty and errors in experiments can occur from test planning, environment, operating condition, data recording as well as instrument selection, calibration, condition and reading [104]. Hence, the method described by [105] was employed to carry out an uncertainty analysis. The details of the calculation procedure of the uncertainty analysis have been previously reported in several studies [75, 104, 106]. The uncertainties in time, mass loss, air temperature, relative humidity and velocity measurements were ±0.1 min, ±0.51 g, ±1.07 °C, ±3.00 % and ±0.18 m s^{-1}, respectively.

3. Results and discussion

3.1 Comparison of hot air oven and open sun drying of untreated banana peels

Figure 2a shows the variation of ambient temperature during the open sun drying of banana peels; the ambient temperature varied between 34 and 44 °C due to the fluctuation in weather condition during the drying operation. Figure 2b is a graph of moisture ratio against drying time for both open sun drying and hot air oven drying (at 60 °C) of banana peels. Drying time of 570 min was required to completely dry banana peels of an initial mass of 3.5 g by the open sun drying method compared to 390 min required by the hot air oven dryer. Drying in direct sunlight took a longer time than the hot air oven drying because the drying temperature was limited by the weather conditions to the highest value of 44 °C, compared to 60 °C that could be applied in the hot air oven dryer. Besides, the oven drying environment (e.g. temperature) could be better controlled to achieve uniform drying conditions compared to the direct sunlight drying process where the environment and drying operation were influenced by the weather conditions, as evident in the data variation shown by the error bars of Figure 2b. Besides, a more hygienic drying environment was available in the hot air oven dryer compared to drying in the open sun where the material was exposed to dust, insects, etc.

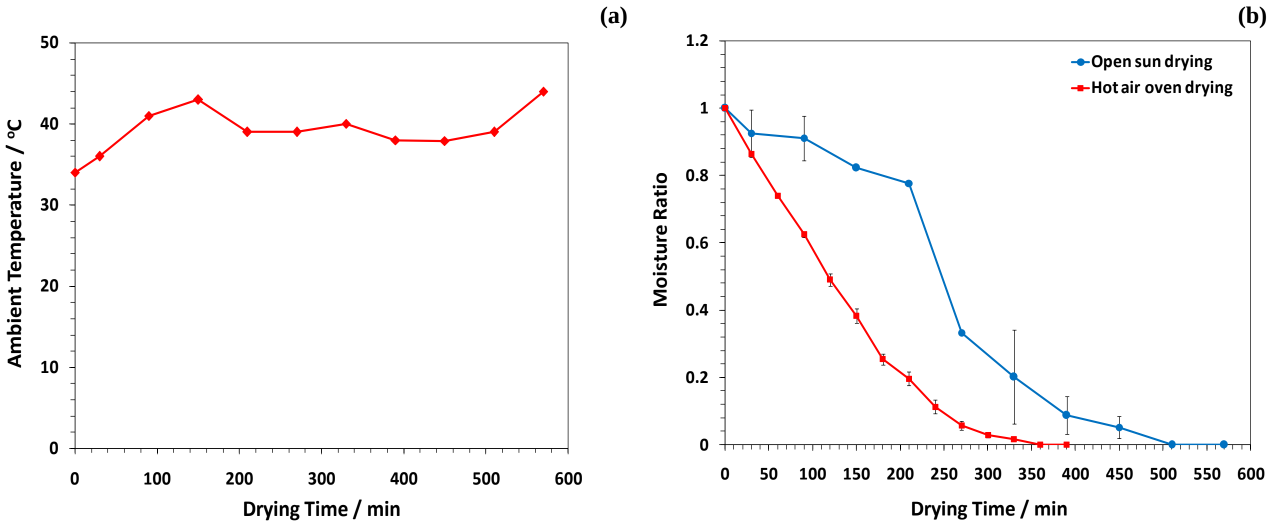

Figure 2 (a) Variation of ambient temperature during drying of banana peels in direct sunlight (b) Graph of moisture ratio against drying time for open sun drying and hot air oven drying (at 60 °C) of banana peels of 15 x 10 mm size

3.2 Convective hot air oven drying characteristics of banana peels

3.2.1 Effect of surface area

Figure 3a is the graph of moisture ratio against time for convective hot air drying of banana peel slices of 15 x 10, 30 x 20 and 60 x 40 mm sizes at 60 °C. The moisture ratio of each size of the banana peel decreased with increasing drying time, which implies that moisture was progressively evaporated from the peel by hot air. Drying times required for drying the 15 x 10, 30 x 20 and 60 x 40 mm sized banana peels at 60 °C were 480, 690 and 1020 min, respectively. Larger drying surface areas were obtained when the banana peels were cut into smaller sizes. This implies that the drying rate of the peels increased due to the increase in the surface area associated with smaller peel sizes. Hence, the drying rate of banana peel slices can be considerably improved and the drying time effectively reduced by increasing the surface area of the banana peels before the drying operation. An improved drying rate with an increase in the surface area of the material has been observed during the drying of several agro-products [82, 107, 108].

Figure 3b is the graph of drying rate against time for convective hot air drying of banana peel slices of 15 x 10, 30 x 20 and 60 x 40 mm sizes at 60 °C. The drying rate initially increased slightly but then decreased as the drying proceeded; drying rate initially increased to about 0.06, 0.05 and 0.04 g water / g dry matter. min for the 15 x 10, 30 x 20 and 60 x 40 mm sized peels, respectively, before falling and decreasing progressively to a value of zero at the end of the drying process. Drying occurred mainly in the falling-rate phase signifying that the movement of moisture from inside the banana peel to its surface controlled the drying rate [76]. A falling-rate phase has been equally observed during the convective hot air drying of several agricultural produce [57, 81, 82, 108, 109,].

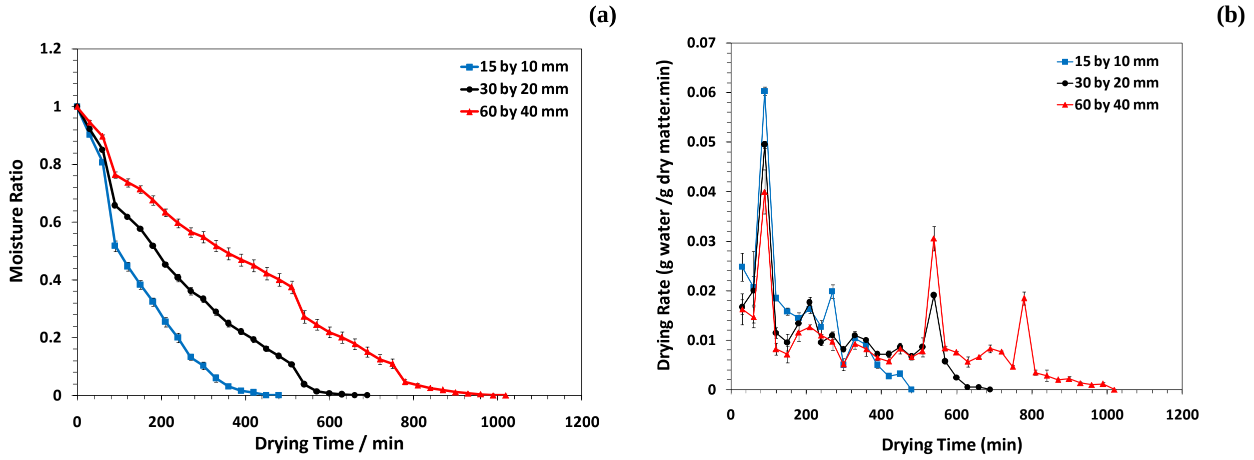

Figure 3 Effect of surface area on convective hot air drying characteristics of banana peel slices of 15 x 10, 30 x 20 and 60 x 40 mm sizes at 60 °C (a) graph of moisture ratio against drying time (b) graph of drying rate against drying time

3.2.2 Effect of drying air temperature

The graphs of moisture ratio against time for convective hot air drying of peels of 10 x 10 mm size at 80, 100, 120 and 140 °C are shown in Figure 4a. Moisture ratio of the peels diminished gradually with increasing drying time at each temperature considered signifying that moisture was essentially vapourised from the peels by hot air blown through the convective dryer. Increase in drying air temperature resulted in a decrease in drying time; the time needed for drying the banana peels were 210, 120, 80 and 55 min at 80, 100, 120 and 140 °C, respectively. This result signifies that the time needed for drying the peels can be substantially shortened by drying the peels at higher temperatures. The drying time decreased because the drying rate increased with increase in air temperature as a result of the rise in thermal energy and consequent increase in water activity associated with increasing temperature [56, 110]. Reductions in drying times of biological materials with increase in air temperature have also been previously reported [57, 58, 82, 111, 112].

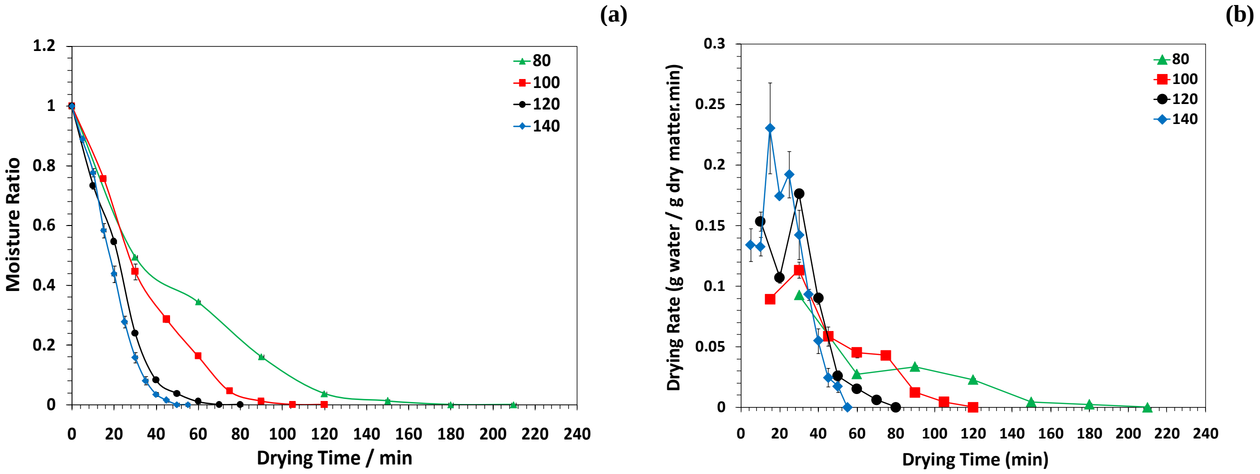

Figure 4 Effect of temperature on convective hot air drying characteristics of banana peel slices of 10 x 10 mm size (a) graph of moisture ratio against drying time (b) graph of drying rate against drying time

Figure 4b shows the plot of drying rate versus drying time for the convective hot air drying of banana peels at 80 - 140 °C. Peak drying rates of 0.093, 0.113, 0.177 and 0.230 g water / g dry matter.min were achieved at 80, 100, 120 and 140 °C drying air temperatures, respectively, implying that higher air temperature enhanced the drying rate of the biomass. The drying process occurred primarily in the falling-rate phase and was controlled by moisture movement within the peels [57, 76].

3.2.3 Effect of pretreatment

The graph of moisture ratio against drying time for the hot air oven drying of untreated and pretreated 10 x 10 mm sized banana peels at 80, 100, 120 and 140 °C are shown in Figure 5a, Figure 5c, Figure 5e and Figure 5g, respectively. Drying times of 210, 120, 80 and 55 min were needed for the hot air drying of untreated samples at 80, 100, 120 and 140°C, respectively. However, shorter drying times of 180, 105, 50 and 40 min were required for drying the hot water treated samples while 180, 105, 50 and 45 min were needed for drying the sulphite treated samples at 80, 100, 120 and 140 °C, respectively. The hot water and sulphite pretreatments softened the banana peel tissues and altered the permeability of the membrane of the cell leading to a reduction in the resistance to the migration of moisture and increase in drying rates of pretreated banana peels [62, 82]. The drying times of eggplant [107], peach [109] and tomato [82] have also been reduced by the application of pretreatments before the convective hot air drying operations.

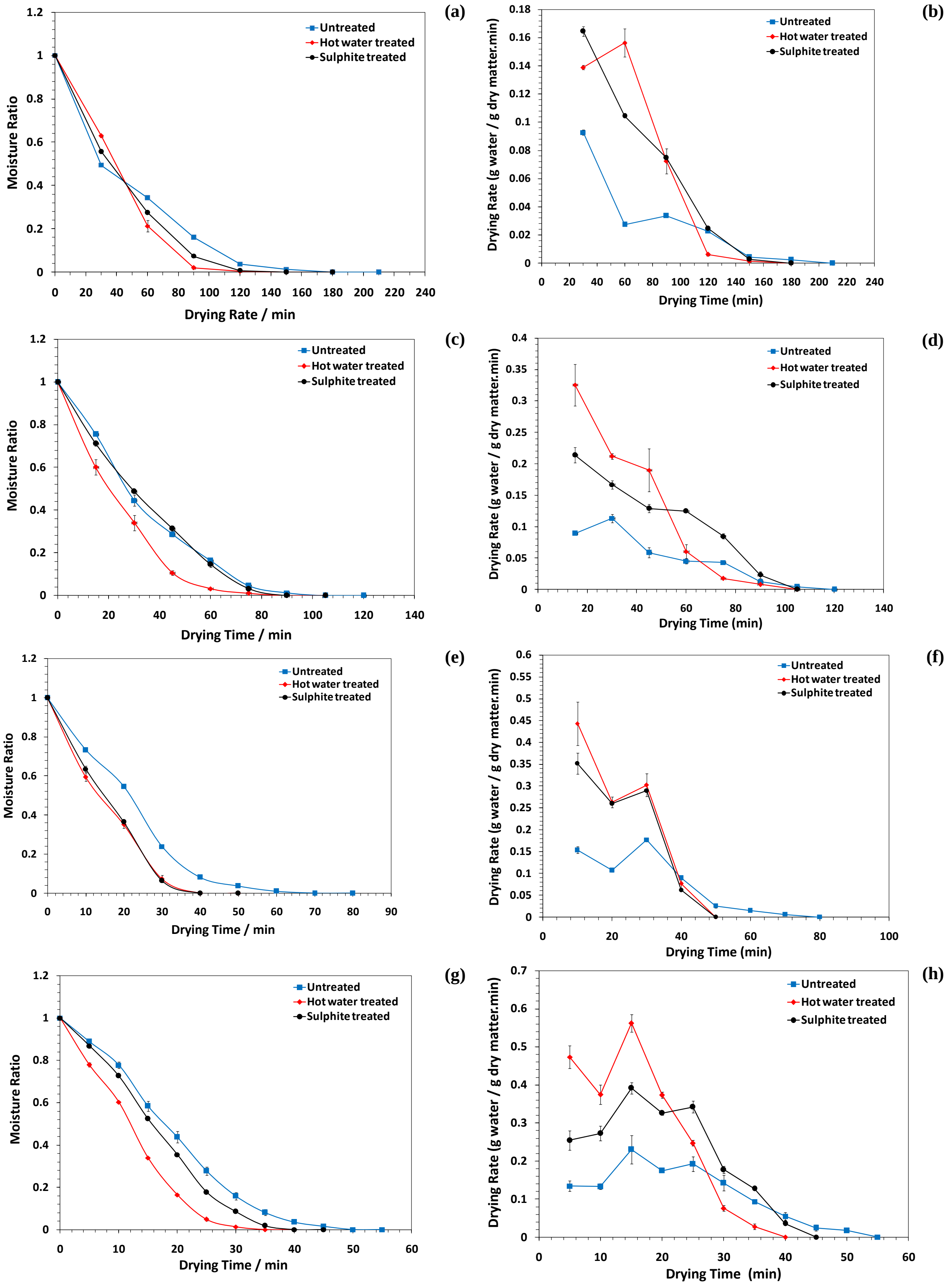

Figure 5 Effect of pretreatment on convective hot air drying characteristics of banana peel slices of 10 x 10 mm size (a) graph of moisture ratio against drying time for data obtained at 80 ºC (b) graph of drying rate against drying time for data obtained at 80 ºC (c) graph of moisture ratio against drying time for data obtained at 100 ºC (d) graph of drying rate against drying time for data obtained at 100 ºC (e) graph of moisture ratio against drying time for data obtained at 120 ºC (f) graph of drying rate against drying time for data obtained at 120 ºC (g) graph of moisture ratio against drying time for data obtained at 140 ºC (g) graph of drying rate against drying time for data obtained at 140 ºC

The graph of drying rates against drying times for convective hot air drying of untreated and pretreated peels at 80, 100, 120 and 140 °C are shown in Figure 5b, Figure 5d, Figure 5f and Figure 5h, respectively. The highest drying rates achieved during the drying of untreated, sulphite treated and hot water treated banana peels biomass at 80 – 140 °C were 0.093 – 0.230, 0.164 – 0.391 and 0.156 – 0.562 g water / g dry matter.min, respectively. The initial drying rates of the hot water treated and sulphite treated banana peels biomass were higher than those of the untreated peels at all temperatures considered, indicating that the hot water and sulphite pretreatments improved the rate of peel drying.

3.3 Effective moisture diffusivities

The moisture diffusivities for the convective hot air drying of the 15 x 10, 30 x 20 and 60 x 40 mm sized banana peels at 60 °C are shown in Figure 6a. The effective moisture diffusivity increased from 5.19 x 10^{-10} m^2 s^{-1} observed for drying of 60 x 40 mm sized peels to 1.17 x 10^{-9} m^2 s^{-1} measured for drying of 15 x 10 mm sized peels, confirming that moisture diffusion within the banana peels was enhanced by the rise in surface area. The improvement in moisture diffusion within the banana peels due to increased surface area resulted in the observed increase in drying rate with decreasing size of banana peels biomass discussed in section 3.2.1.

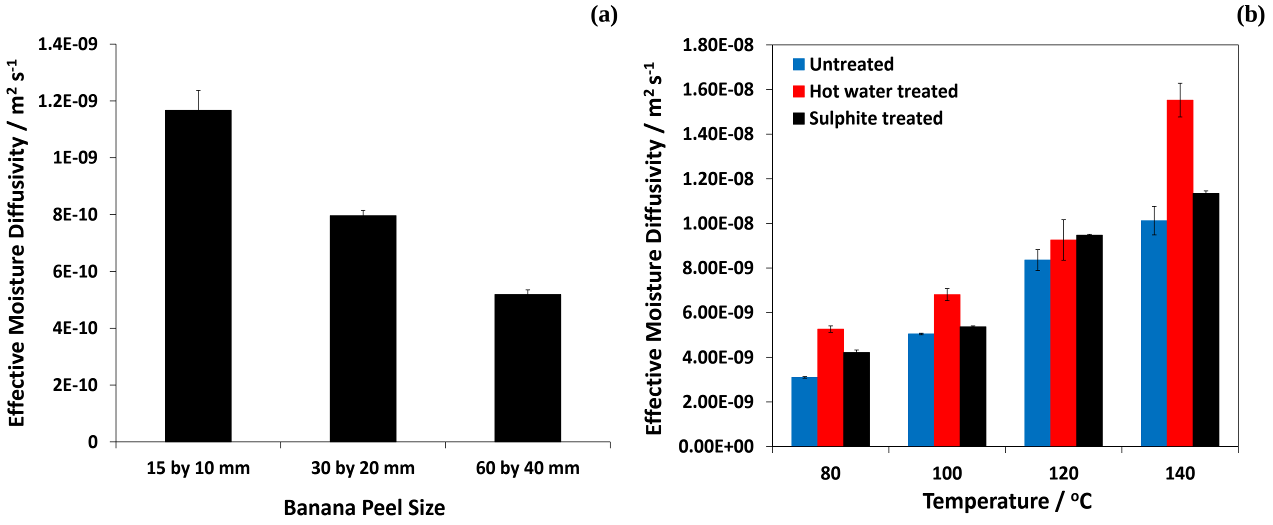

Figure 6 Effective moisture diffusivities for the convective hot air drying of banana peels biomass (a) Graph of effective moisture diffusivity against peel size, for peels dried at 60 °C (b) Graph of effective moisture diffusivity against drying air temperature, for untreated, hot water treated and sulphite treated 10 x 10 mm sized banana peels

Figure 6b shows the influence of temperature and pretreatment on the moisture diffusivities for convective hot air drying of banana peels biomass. The effective moisture diffusivity increased with increasing temperature indicating that higher drying air temperature increased the drying rate of the peels by improving moisture migration within the banana peels. The diffusivities for the drying of hot water treated and sulphite treated 10 x 10 mm sized banana peels at 80 – 140 °C were 5.26 x 10^{-9} – 1.55 x 10^{-8} and 4.21 x 10^{-9} – 1.13 x 10^{-8} m^2 s^{-1}, respectively. The moisture diffusivities for the drying of the hot water and sulphite treated banana peels biomass also increased with increasing temperature as depicted in Figure 6b. However, they were larger than those of 3.10 x 10^{-9} – 1.01 x 10^{-8} m^2 s^{-1} measured for the drying of the untreated samples. This implies that the pretreatments reduced the resistance to migration of moisture in the peels leading to shorter drying times. The moisture diffusivities for convective hot air drying of banana peels are within 10^{-12} – 10^{-6} m^2 s^{-1} earlier reported for the drying of agricultural materials [76].

The dependence of diffusivity on temperature was suitably explained by the Arrhenius relationship for moisture diffusivity. The activation energy of 24.7 kJ mol^{-1} was required for drying the untreated biomass; this is the barrier of energy that must be surmounted for convective hot air drying of banana peels to take place. This value is within the range of 18 – 49.5 kJ mol^{-1} previously reported in the literature for the drying of agricultural materials [76]. It is slightly lower than that of 25.4 - 29.2, 32.65, 27.7 and 28.7 kJ mol^{-1} for the hot air drying of olive pomace [113], banana fruit [67], plantain [84] and microalgae [57], respectively. The activation energies for drying the hot water treated and sulphite treated samples were 21.3 and 21.4 kJ mol^{-1}, respectively. These values are slightly lower than the activation energy of 24.7 kJ mol^{-1} measured for the drying of the untreated peels, indicating that the pretreatments reduced the activation energy required for drying the biomass, thereby enhancing the drying rate.

3.4 Drying energy requirement

The specific energies required for drying the 15 x 10, 30 x 20 and 60 x 40 mm sized banana peels biomass at 60 °C are shown in Figure 7a. The specific energy increased from 157.9 kWh/kg required for drying the 15 x 10 mm sized peel slices to 335.6 kWh/kg needed for drying the 60 x 40 mm sized peel slices. This observation suggests that the energy requirement for drying the peels can be considerably decreased by using smaller peel slices or a larger surface area.

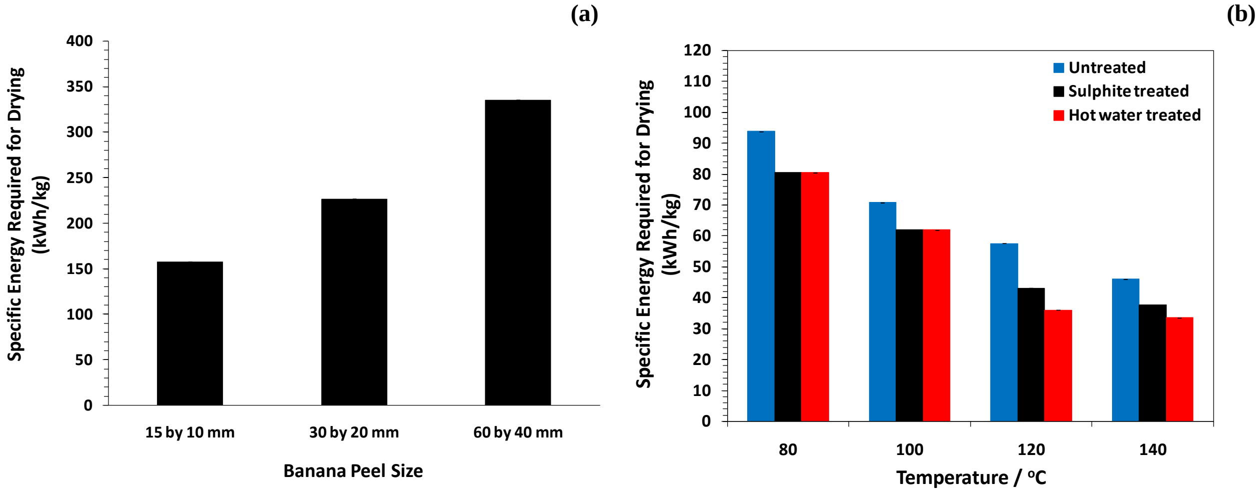

Figure 7 Drying energy requirement for convective hot air oven drying of banana peels (a) graph of specific energy required for drying banana peels at 60 °C versus peel size (b) graph of specific energy required for drying untreated, hot water treated and sulphite treated banana peels of 10 x 10 mm size versus drying air temperature

Figure 7b shows the graph of specific energy required for drying untreated and pretreated banana peel slices of 10 x 10 mm size at 80 - 140 °C using air velocity of 1.5 m s^{-1}. Specific energies of 46.1 – 93.9 kWh/kg were required for drying the untreated banana peels biomass at 80 – 140 °C. The specific energy requirement for hot air drying of banana peels are within the range of specific energies previously reported by other studies. Aghbashlo et al. [85] reported specific energies of 20.9 - 1110.1 kWh/kg for the convective hot air drying of berberis fruit at 50 – 70 °C with air velocities of 0.5 - 2 m s^{-1} while Motevali et al. [86] reported energies of 50.8 – 252.3 kWh/kg for hot air drying of pomegranate arils at 45 – 70 °C with air velocities of 0.5 - 1.5 m s^{-1}. Specific energies of 47.88 – 93.45, 11.87 - 21.57 and 48.37 – 184.29 kWh/kg were also consumed during the hot air drying of mushroom [87], dog rose medicinal plant [114] and Pistacia Atlantica [115] at 40 – 60 °C (with air velocities of 0.5 - 1 m s^{-1}), 40 – 60 °C (with air velocities of 0.4 – 1 m s^{-1}) and 40 – 70 °C (with air velocities of 0.5 - 1.5 m s^{-1}), respectively.

The specific energies required for both untreated and pretreated banana peels decreased with increasing air temperature, suggesting that the energy requirement for drying the biomass can be considerably lowered by drying at elevated temperatures. A reduction in drying energy requirement with increasing drying temperature has also been reported for the convective hot air drying of nettle leaves [116], berberis fruit [85], pomegranate arils [86], mushroom [87], dog rose medicinal plant [114] and Pistacia Atlantica [115].

The specific energies of 33.5 – 80.5 and 37.7 – 80.5 kWh/kg required for drying the hot water and sulphite treated banana peels, respectively, were lower than those of 46.1 – 93.9 kWh/kg required for drying the untreated samples of banana peels. This indicates that hot water and sulphite pretreatments can be used to substantially reduce the energy requirement for drying banana peels biomass. Hence, the operating energy cost for the hot air drying of banana peels can be significantly lowered by drying the biomass at higher temperatures using smaller sizes of the peels and applying hot water or sulphite pretreatment prior to the drying operation.

3.5 Drying kinetics

Table 2 – Table 6 show the constants and statistical parameters obtained when the twelve thin layer drying mathematical models described in Table 1 were fitted to the drying data for the convective hot air oven drying of untreated, hot water treated and sulphite treated banana peels. Table 2 indicates that the Weibull model had the highest values of R^2 ($\geq$0.99) and the least SSE ($\leq$0.00095), RMSE ($\leq$0.0309) and χ^2 ($\leq$0.00125) values when the experimental drying data obtained for hot air drying of untreated banana peels of sizes 15 x 10, 30 x 20 and 60 x 40 mm at 60 °C were fitted to the models in Table 1.

Similarly, it was observed, as shown on Table 3, that the Weibull model best fitted the drying data obtained at 80 °C. This model had the highest value of R^2 (0.9930) and least values of SSE (0.00076), RSME (0.0276) and χ^2 (0.00152) when it was fitted to the drying data for the untreated peels at 80 °C. Though the Weibull, Page, Midilli-Kucuk and modified Page models had the highest value of R^2 (0.9996) for the drying of the hot water treated peels at 80 °C compared to the other models, it was Weibull model that still possessed the least values of RSME (0.0071) and SSE (5.050 x 10^{-5}). In the case of the sulphite treated samples, the Weibull model had the highest value of R^2 (0.9983) and least values of SSE (0.00021), RSME (0.0145) and χ^2 (0.00049).
Both Weibull and Midilli-Kucuk models had the highest value of R^2 (0.9980) for the drying of untreated banana peels at 100 °C, but the Weibull model possessed the least values of χ^2 (0.00042), RMSE (0.0153) and SSE (0.00023) as shown in Table 4. For the hot water and sulphite treated banana peels dried at 100 °C, the Weibull model had the highest values of R^2 (>0.99) and least values of SSE (<0.00041), RMSE (<0.0200) and χ^2 (<0.00081).

The data of Table 5 on the hot air drying of banana peels at 120 °C show that the Weibull model also had the highest values of R^2 (>0.9920) and least values of SSE (<0.00100), RMSE (<0.0316) and χ^2 (<0.00299). Likewise, Table 6 shows that Weibull model possessed the highest values of R^2 that were >0.9960 with corresponding least values of RMSE (<0.0225), χ^2 (<0.00095) and SSE (<0.00055) compared to the other models, when the data obtained during the drying operations at 140 °C were fitted to the models. Therefore, the Weibull model was considered to best describe the convective hot air drying kinetics of untreated, hot water treated and sulphite treated banana peels biomass.

Figures 8a-e show the plots of predicted moisture ratio (by the Weibull model) against experimental moisture ratio for the convective hot air oven drying of untreated, hot water treated and sulphite treated banana peels at 60 – 140 °C. The moisture ratios predicted by the Weibull model and those measured by experiments show a good agreement which implies that this model well defined the kinetics of the convective hot air oven drying of banana peels biomass. The Weibull model has been similarly reported to most suitably define the rates of hot air oven drying of garlic [117], blueberries [118], persimmon slices [119] and microalgae [57].

Table 2 Statistical parameters and constants obtained after models were fitted to the drying data for convective hot air drying of untreated 15 x 10, 30 x 20 and 60 x 40 mm sized banana peels at 60 °C

Peel Size (mm)	Model	R^2	χ^2	RMSE	SSE	Model Constants
15 x 10	Weibull	**0.9907**	**0.00125**	**0.0309**	**0.00095**	a = -0.036, b = -1.055, k = 0.003, n = 1.175
	Two-term exponential	0.9608	0.00993	0.0936	0.00876	a = 1.000, k = 0.009
	Midilli-Kucuk	0.9906	0.00127	0.0312	0.00097	a = 1.028, b = -8.188×10^{-5}, k = 0.0032, n = 1.137
	Modified Page	0.9664	0.00898	0.0890	0.00793	k = 0.009, n = 0.009
	Logarithmic	0.9689	0.00985	0.0901	0.00811	a = 1.033, c = -0.027, k = 0.009
	Page	0.9664	0.00898	0.0890	0.00793	k = 0.005, n = 1.119
	Wang and Singh	0.9755	0.00694	0.0782	0.00612	a = -0.006, b = 7.621×10^{-6}
	Modified Henderson and Pabis	0.9586	0.01325	0.0926	0.00857	a = 0.433, b = 0.433, c = 0.151, g = 0.009, h = 0.009, k = 0.009
	Two-term	0.9586	0.01121	0.0926	0.00857	a = 0.933, b = 0.085, k_0 = 0.009, k_1 = 0.009
	Verma	0.9630	0.01002	0.0908	0.00825	a = 1.052, g = 1.000, k = 0.010
	Henderson and Pabis	0.9586	0.00972	0.0926	0.00857	a = 1.000, k = 0.009
	Approximation of diffusion	0.9608	0.01064	0.0936	0.00876	a = 1, b = 1, k = 0.009
30 x 20	Weibull	**0.9945**	**0.00060**	**0.0224**	**0.00050**	a = -0.276, b = -1.290, k = 0.004, n = 0.909
	Two-term exponential	0.9849	0.00227	0.0457	0.00208	a = 1.000, k = 0.004
	Midilli-Kucuk	0.9944	0.00060	0.0224	0.00050	a = 1.017, b = 2.320×10^{-4}, k = 0.005, n = 0.919
	Modified Page	0.9864	0.00141	0.0359	0.00129	k = 0.004, n = 1.183
	Logarithmic	0.9940	0.00062	0.0232	0.00054	a = 1.181, c = -0.185, k = 0.003
	Page	0.9864	0.00141	0.0359	0.00129	k = 0.001, n =1.183
	Wang and Singh	0.9911	0.00108	0.0315	0.00099	a = -0.003, b = 2.112×10^{-6}
	Modified Henderson and Pabis	0.9821	0.00247	0.0430	0.00185	a = 0.453, b = 0.453, c = 0.141, g = 0.004, h = 0.004, k = 0.004
	Two-term	0.9821	0.00222	0.0430	0.00185	a = 0.979, b = 0.067, k_0 = 0.042, k_1 = 0.004
	Verma	0.9832	0.00194	0.0412	0.00170	a = 1.077, g = 1.000, k = 0.004
	Henderson and Pabis	0.9821	0.00202	0.0430	0.00185	a = 1.047, k = 0.004
	Approximation of diffusion	0.9849	0.00238	0.0457	0.00208	a = 1, b = 1, k = 0.004
60 x 40	Weibull	**0.9900**	**0.00103**	**0.0302**	**0.00091**	a = -0.901, b = -1.892, k = 0.002, n = 0.881
	Two-term exponential	0.9638	0.00472	0.0667	0.00445	a = 1.000, k = 0.002
	Midilli-Kucuk	0.9841	0.00164	0.0381	0.00145	a = 0.906, b = -7.399×10^{-5}, k = 1.102×10^{-4}, n = 1.457
	Modified Page	0.9719	0.00290	0.0523	0.00273	k = 0.002, n = 1.288
	Logarithmic	0.9897	0.00103	0.0306	0.00094	a = 1.488, c = -0.520, k = 0.001
	Page	0.9719	0.00290	0.0523	0.00273	k = 4.078×10^{-4}, n = 1.288
	Wang and Singh	0.9782	0.00316	0.0546	0.00298	a = -0.002, b = 9.781×10^{-7}
	Modified Henderson and Pabis	0.9591	0.00501	0.0645	0.00415	a = 0.490, b = 0.490, c = 0.070, g = 0.003, h = 0.003, k = 0.003
	Two-term	0.9896	0.00107	0.0308	0.00095	a = 1.269, b = -0.299, k_0 = 0.001, k_1 = -2.697×10^{-4}
	Verma	0.9599	0.00443	0.0637	0.00405	a = 1.069, g = 1.000, k = 0.003
	Henderson and Pabis	0.9591	0.00441	0.0645	0.00415	a = 1.051, k = 0.003
	Approximation of diffusion	0.9638	0.00487	0.0667	0.00445	a = 1, b = 1, k = 0.002

Table 3 Statistical parameters and constants obtained after models were fitted to the drying data for convective hot air drying of untreated, hot water treated and sulphite treated banana peels at 80 °C

	Model	**R^2**	**χ^2**	**RMSE**	**SSE**	**Model Constants**
Untreated	Weibull	**0.9930**	**0.00152**	**0.0276**	**0.00076**	a = -0.062, b= -1.059, k = 0.030, n = 0.881
	Two-term exponential	0.9912	0.00142	0.0327	0.00107	a = 0.039, k = 0.532
	Midilli-Kucuk	0.9925	0.00162	0.0285	0.00081	a = 0.997, b = -2.222 x 10^{-4}, k = 0.028, n = 0.913
	Modified Page	0.9906	0.00144	0.0329	0.00108	k = 0.021, n = 1.018
	Logarithmic	0.9920	0.00138	0.0293	0.00086	a = 1.021, c = -0.032, k = 0.019
	Page	0.9906	0.00144	0.0329	0.00108	k = 0.020, n = 1.018
	Wang and Singh	0.9737	0.00508	0.0617	0.00381	a = -0.013, b = 4.096 x 10^{-5}
	Modified Henderson and Pabis	0.9908	0.00434	0.0329	0.00108	a = 0.335, b = 0.335, c = 0.327, g = 0.021, h = 0.021, k = 0.021
	Two-term	0.9908	0.00217	0.0329	0.00108	a = 0.514, b = 0.483, k$_0$ = 0.021, k$_1$ = 0.021
	Verma	0.9907	0.00174	0.0330	0.00109	a = 0.5, g = 0.021, k = 0.021
	Henderson and Pabis	0.9908	0.00145	0.0329	0.00108	a = 0.996, k = 0.021
	Approximation of diffusion	0.9907	0.00174	0.0330	0.00109	a = 0.149, b = 1.000, k = 0.021
Hot water treated	Weibull	**0.9996**	**0.00012**	**0.0071**	**5.050 x 10^{-5}**	a = -0.003, b= -1.002, k = 0.001, n = 1.795
	Two-term exponential	0.9721	0.00674	0.0694	0.00481	a = 1.799 x 10^{-5}, k = 1314
	Midilli-Kucuk	0.9996	0.00012	0.0073	5.284 x 10^{-5}	a = 0.999, b = -1.553 x 10^{-5}, k = 9.929 x 10^{-4}, n = 1.801
	Modified Page	0.9996	7.761 x 10^{-5}	0.0074	5.544 x 10^{-5}	k = 0.022, n = 1.804
	Logarithmic	0.9757	0.00575	0.0573	0.00328	a = 1.106, c = -0.074, k = 0.020
	Page	0.9996	7.761 x 10^{-5}	0.0074	5.544 x 10^{-5}	k = 9.858 x 10^{-4}, n =1.804
	Wang and Singh	0.9848	0.00288	0.0454	0.00206	a = -0.015, b = 5.651 x 10^{-5}
	Modified Henderson and Pabis	0.9706	0.03188	0.0675	0.00455	a = 0.350, b = 0.350, c = 0.341, g = 0.024, h = 0.024, k = 0.024
	Two-term	0.9706	0.01063	0.0675	0.00455	a = 0.539, b = 0.502, k$_0$ = 0.024, k$_1$ = 0.024
	Verma	0.9721	0.00842	0.0694	0.00481	a = 0.5, g = 0.024, k = 0.024
	Henderson and Pabis	0.9706	0.00638	0.0675	0.00455	a = 1.041, k = 0.024
	Approximation of diffusion	0.9721	0.00842	0.0694	0.00481	a = 0.150, b = 1.000, k = 0.024
Sulphite treated	Weibull	**0.9983**	**0.00049**	**0.0145**	**0.00021**	a = -0.017, b = -1.015, k = 0.007, n = 1.280
	Two-term exponential	0.9914	0.00216	0.0393	0.00154	a = 3.049 x 10^{-4}, k = 75.516
	Midilli-Kucuk	0.9982	0.00053	0.0151	0.00023	a = 0.998, b = -8.354 x 10^{-5}, k = 0.007, n = 1.297
	Modified Page	0.9980	0.00039	0.0167	0.00028	k = 0.022, n = 1.332
	Logarithmic	0.9944	0.00122	0.0264	0.00070	a = 1.073, c = -0.061, k = 0.020
	Page	0.9980	0.00039	0.0167	0.00028	k = 0.006, n = 1.332
	Wang and Singh	0.9934	0.00133	0.0309	0.00095	a = -0.015, b = 5.344 x 10^{-5}
	Modified Henderson and Pabis	0.9907	0.01030	0.0384	0.00147	a = 0.343, b = 0.343, c = 0.335, g = 0.023, h = 0.023, k = 0.024
	Two-term	0.9907	0.00343	0.0384	0.00147	a = 0.528, b = 0.493, k$_0$ = 0.023, k$_1$ = 0.023
	Verma	0.9914	0.00269	0.0392	0.00154	a = 0.5, g = 0.023, k = 0.023
	Henderson and Pabis	0.9907	0.00206	0.0384	0.00147	a = 1.021, k = 0.023
	Approximation of diffusion	0.9914	0.00269	0.0392	0.00154	a = 0.150, b = 1.000, k = 0.023

Table 4 Statistical parameters and constants obtained after models were fitted to the drying data for convective hot air drying of untreated, hot water treated and sulphite treated banana peels at 100 °C

	Model	R^2	χ^2	RMSE	SSE	Model Constants
Untreated	Weibull	**0.9980**	**0.00042**	**0.0153**	**0.00023**	a = -0.021, b= -1.023, k = 0.008, n = 1.331
	Two-term exponential	0.9865	0.00351	0.0522	0.00273	a = 5.704 x 10^{-4}, k = 50.552
	Midilli-Kucuk	0.9980	0.00043	0.0155	0.00024	a = 1.002, b = -1.603 x 10^{-4}, k = 0.008, n = 1.345
	Modified Page	0.9976	0.00039	0.0174	0.00030	k = 0.027, n = 1.393
	Logarithmic	0.9916	0.00148	0.0314	0.00099	a = 1.136, c = -0.105, k = 0.024
	Page	0.9976	0.00039	0.0174	0.00030	k = 0.007, n = 1.393
	Wang and Singh	0.9962	0.00057	0.0211	0.00045	a = -0.020, b = 9.944 x 10^{-5}
	Modified Henderson and Pabis	0.9839	0.00704	0.0484	0.00235	a = 0.354, b = 0.354, c = 0.344, g = 0.030, h = 0.030, k = 0.030
	Two-term	0.9839	0.00422	0.0484	0.00235	a = 0.546, b = 0.506, k_0 = 0.030, k_1 = 0.030
	Verma	0.9865	0.00408	0.0522	0.00272	a = 0.5, g = 0.029, k = 0.029
	Henderson and Pabis	0.9839	0.00302	0.0484	0.00235	a = 1.052, k = 0.030
	Approximation of diffusion	0.9865	0.00408	0.0522	0.00272	a = 0.145, b = 1.000, k = 0.029
Hot water treated	Weibull	**0.9974**	**0.00062**	**0.0175**	**0.00031**	a = -0.012, b= -1.008, k = 0.014, n = 1.307
	Two-term exponential	0.9828	0.00434	0.0570	0.00325	a = 7.017 x 10^{-4}, k = 40.761
	Midilli-Kucuk	0.9973	0.00064	0.0179	0.00032	a = 0.996, b = -1.002 x 10^{-4}, k = 0.013, n = 1.321
	Modified Page	0.9972	0.00046	0.0186	0.00035	k = 0.038, n = 1.341
	Logarithmic	0.9922	0.00148	0.0304	0.00092	a = 1.072, c = -0.056, k = 0.036
	Page	0.9972	0.00046	0.0186	0.00035	k = 0.013, n =1.341
	Wang and Singh	0.9893	0.00192	0.0380	0.00144	a = -0.026, b = 1.639 x 10^{-4}
	Modified Henderson and Pabis	0.9889	0.00644	0.0401	0.00161	a = 0.346, b = 0.346, c = 0.334, g = 0.042, h = 0.042, k = 0.042
	Two-term	0.9889	0.00322	0.0401	0.00161	a = 0.538, b = 0.488, k_0 = 0.042, k_1 = 0.042
	Verma	0.9897	0.00273	0.0413	0.00171	a = 0.5, g = 0.041, k = 0.041
	Henderson and Pabis	0.9889	0.00215	0.0401	0.00161	a = 1.026, k = 0.042
	Approximation of diffusion	0.9897	0.00273	0.0413	0.00171	a = 0.123, b = 1.000, k = 0.041
Sulphite treated	Weibull	**0.9967**	**0.00080**	**0.0200**	**0.00040**	a = -0.074, b= -1.068, k = 0.010, n = 1.232
	Two-term exponential	0.9828	0.00434	0.0570	0.00325	a = 7.017 x 10^{-4}, k = 40.761
	Midilli-Kucuk	0.9964	0.00087	0.0208	0.00043	a = 0.993, b = -0.001, k = 0.010, n = 1.261
	Modified Page	0.9940	0.00107	0.0283	0.00080	k = 0.027, n = 1.379
	Logarithmic	0.9941	0.00112	0.0265	0.00070	a = 1.198, c = -0.184, k = 0.020
	Page	0.9940	0.00107	0.0283	0.00080	k = 0.007, n = 1.379
	Wang and Singh	0.9927	0.00155	0.0342	0.00117	a = -0.018, b = 7.808 x 10^{-5}
	Modified Henderson and Pabis	0.9800	0.01184	0.0544	0.00296	a = 0.351, b = 0.351, c = 0.341, g = 0.030, h = 0.030, k = 0.030
	Two-term	0.9800	0.00592	0.0544	0.00296	a = 0.541, b = 0.502, k_0 = 0.030, k_1 = 0.030
	Verma	0.9828	0.00519	0.0569	0.00324	a = 0.5, g = 0.029, k = 0.029
	Henderson and Pabis	0.9800	0.00395	0.0544	0.00296	a = 1.042, k = 0.030
	Approximation of diffusion	0.9828	0.00519	0.0569	0.00324	a = 0.146, b = 1.000, k = 0.029

Table 5 Statistical parameters and constants obtained after models were fitted to the drying data for the convective hot air oven drying of untreated, hot water treated and sulphite treated banana peels at 120 °C

	Model	**R^2**	**χ^2**	**RMSE**	**SSE**	**Model Constants**
Untreated	Weibull	**0.9936**	**0.00144**	**0.0283**	**0.00080**	a = -0.009, b = -0.992, k = 0.005, n = 1.621
	Two-term exponential	0.9715	0.00661	0.0717	0.00514	a = 0.001, k =33.283
	Midilli-Kucuk	0.9935	0.00155	0.0284	0.00081	a = 0.982, b = -1.024 x 10^{-4}, k = 0.005, n = 1.635
	Modified Page	0.9933	0.00111	0.0294	0.00087	k = 0.041, n = 1.606
	Logarithmic	0.9777	0.00416	0.0527	0.00278	a = 1.156, c = -0.117, k = 0.036
	Page	0.9933	0.00111	0.0294	0.00087	k = 0.006, n =1.606
	Wang and Singh	0.9899	0.00168	0.0361	0.00131	a = -0.031, b = 2.336 x 10^{-4}
	Modified Henderson and Pabis	0.9682	0.01385	0.0679	0.00462	a = 0.357, b = 0.357, c = 0.345, g = 0.046, h = 0.046, k = 0.046
	Two-term	0.9682	0.00831	0.0679	0.00462	a = 0.556, b = 0.503, k_0 = 0.046, k_1 = 0.046
	Verma	0.9714	0.00768	0.0715	0.00512	a = 0.5, g = 0.044, k = 0.044
	Henderson and Pabis	0.9682	0.00594	0.0679	0.00462	a = 1.060, k = 0.046
	Approximation of diffusion	0.9714	0.00768	0.0715	0.00512	a = 0.110, b = 1.000, k = 0.044
Hot water treated	Weibull	**0.9928**	**0.00291**	**0.0311**	**0.00097**	a = -0.055, b=-1.050, k = 0.023, n = 1.290
	Two-term exponential	0.9789	0.00574	0.0618	0.00382	a = 0.004, k = 14.630
	Midilli-Kucuk	0.9924	0.00304	0.0318	0.00101	a = 0.995, b = -0.001, k = 0.022, n = 1.319
	Modified Page	0.9910	0.00195	0.0360	0.00130	k = 0.058, n = 1.421
	Logarithmic	0.9893	0.00285	0.0378	0.00142	a = 1.172, c = -0.162, k = 0.046
	Page	0.9910	0.00195	0.0360	0.00130	k = 0.018, n =1.421
	Wang and Singh	0.9906	0.00306	0.0451	0.00204	a = -0.039, b = 3.761 x 10^{-4}
	Modified Henderson and Pabis	0.9774	-	0.0603	0.00363	a = 0.347, b = 0.347, c = 0.333, g = 0.064, h = 0.064, k = 0.064
	Two-term	0.9774	0.01089	0.0603	0.00363	a = 0.514, b = 0.514, k_0 = 0.064, k_1 = 0.064
	Verma	0.9790	0.00756	0.0615	0.00378	a = 0.5, g = 0.063, k = 0.063
	Henderson and Pabis	0.9774	0.00545	0.0603	0.00363	a = 1.028, k = 0.064
	Approximation of diffusion	0.9790	0.00756	0.0615	0.00378	a = 0.009, b = 1.023, k = 0.061
Sulphite treated	Weibull	**0.9928**	**0.00298**	**0.0315**	**0.00099**	a = -0.040, b=-1.034, k = 0.013, n = 1.471
	Two-term exponential	0.9708	0.00819	0.0739	0.00546	a = 0.003, k = 18.633
	Midilli-Kucuk	0.9926	0.00309	0.0321	0.00103	a = 0.993, b = -0.001, k = 0.013, n = 1.499
	Modified Page	0.9916	0.00187	0.0353	0.00124	k = 0.556, n = 1.568
	Logarithmic	0.9843	0.00434	0.0466	0.00217	a = 1.219, c = -0.201, k = 0.042
	Page	0.9916	0.00187	0.0353	0.00124	k = 0.011, n = 1.568
	Wang and Singh	0.9915	0.00208	0.0373	0.00139	a = -0.040, b = 3.956 x 10^{-4}
	Modified Henderson and Pabis	0.9687	-	0.0716	0.00513	a = 0.351, b = 0.351, c = 0.337, g = 0.063, h = 0.063, k = 0.063
	Two-term	0.9687	0.01540	0.0716	0.00513	a = 0.549, b = 0.489, k_0 = 0.063, k_1 = 0.063
	Verma	0.9711	0.01083	0.0736	0.00542	a = 0.5, g = 0.061, k = 0.061
	Henderson and Pabis	0.9687	0.00770	0.0716	0.00513	a = 1.039, k = 0.063
	Approximation of diffusion	0.9711	0.01083	0.0736	0.00542	a = 0.019, b = 0.999, k = 0.061

Table 6 Statistical parameters and constants obtained after models were fitted to the drying data for convective hot air drying of untreated, hot water treated and sulphite treated banana peels at 140 °C

	Model	**R^2**	**χ^2**	**RMSE**	**SSE**	**Model Constants**
Untreated	Weibull	**0.9989**	**0.00022**	**0.0121**	**0.00015**	a = -0.015, b=-0.998, k = 0.004, n = 1.786
	Two-term exponential	0.9652	0.01007	0.0916	0.00839	a = 8.385 x 10^{-4}, k = 59.204
	Midilli-Kucuk	0.9988	0.00022	0.0122	0.00015	a = 0.982, b = - 2.765 x 10^{-4}, k = 0.004, n = 1.799
	Modified Page	0.9984	0.00028	0.0153	0.00023	k = 0.047, n = 1.781
	Logarithmic	0.9801	0.00338	0.0504	0.00254	a = 1.360, c = -0.291, k = 0.033
	Page	0.9984	0.00028	0.0153	0.00023	k = 0.004, n =1.781
	Wang and Singh	0.9880	0.00246	0.0452	0.00205	a = -0.035, b = 3.030 x 10^{-4}
	Modified Henderson and Pabis	0.9563	0.01303	0.0807	0.00651	a = 0.377, b = 0.377, c = 0.363, g = 0.055, h = 0.055, k = 0.055
	Two-term	0.9563	0.00977	0.0807	0.00651	a = 0.588, b = 0.528, k_0 = 0.055, k_1 = 0.055
	Verma	0.9654	0.01115	0.0914	0.00836	a = 0.5, g = 0.050, k = 0.050
	Henderson and Pabis	0.9563	0.00782	0.0807	0.00651	a = 1.116, k = 0.055
	Approximation of diffusion	0.9655	0.01115	0.0914	0.00836	a = 0.088, b = 1.000, k = 0.050
Hot water treated	Weibull	**0.9961**	**0.00090**	**0.0223**	**0.00050**	a = -0.02, b = -1.001, k = 0.012, n = 1.645
	Two-term exponential	0.9690	0.00805	0.0792	0.00626	a = 0.003, k = 29.209
	Midilli-Kucuk	0.9960	0.00094	0.0229	0.00052	a = 0.978, b = - 2.404 x 10^{-4}, k = 0.011, n = 1.697
	Modified Page	0.9954	0.00082	0.0252	0.00064	k = 0.071, n = 1.656
	Logarithmic	0.9808	0.00367	0.0495	0.00245	a = 1.237, c = -0.195, k = 0.055
	Page	0.9954	0.00082	0.0252	0.00064	k = 0.013, n =1.656
	Wang and Singh	0.9923	0.00150	0.0342	0.00117	a = -0.055, b = 7.415 x 10^{-4}
	Modified Henderson and Pabis	0.9641	0.01627	0.0736	0.00542	a = 0.363, b = 0.363, c = 0.346, g = 0.081, h = 0.081, k = 0.081
	Two-term	0.9641	0.00976	0.0736	0.00542	a = 0.571, b = 0.502, k_0 = 0.081, k_1 = 0.081
	Verma	0.9692	0.00931	0.0788	0.00621	a = 0.5, g = 0.077, k = 0.077
	Henderson and Pabis	0.9641	0.00697	0.0736	0.00542	a = 1.073, k = 0.081
	Approximation of diffusion	0.9691	0.00930	0.0787	0.00620	a = - 0.035, b =1.145, k = 0.067
Sulphite treated	Weibull	**0.9981**	**0.00041**	**0.0156**	**0.00024**	a = -0.028, b=-1.008, k = 0.005, n = 1.803
	Two-term exponential	0.9592	0.01181	0.0972	0.00945	a = 0.002, k = 36.692
	Midilli-Kucuk	0.9980	0.00045	0.0165	0.00027	a = 0.976, b = -3.088 x 10^{-4}, k = 0.004, n = 1.877
	Modified Page	0.9972	0.00053	0.0207	0.00043	k = 0.053, n = 1.827
	Logarithmic	0.9805	0.00365	0.0506	0.00256	a = 1.465, c = -0.407, k = 0.033
	Page	0.9972	0.00053	0.0014	0.00043	k = 0.005, n =1.827
	Wang and Singh	0.9864	0.00280	0.0473	0.00224	a = -0.040, b = 3.697 x 10^{-4}
	Modified Henderson and Pabis	0.9499	0.01913	0.0875	0.00765	a = 0.374, b = 0.374, c = 0.359, g = 0.062, h = 0.062, k = 0.062
	Two-term	0.9499	0.01275	0.0875	0.00765	a = 0.584, b = 0.523, k_0 = 0.062, k_1 = 0.062
	Verma	0.9592	0.01342	0.0969	0.00939	a = 0.5, g = 0.057, k = 0.057
	Henderson and Pabis	0.9499	0.00956	0.0875	0.00765	a = 1.107, k = 0.062
	Approximation of diffusion	0.9592	0.01342	0.0969	0.00939	a = 0.047, b = 1-000, k = 0.057

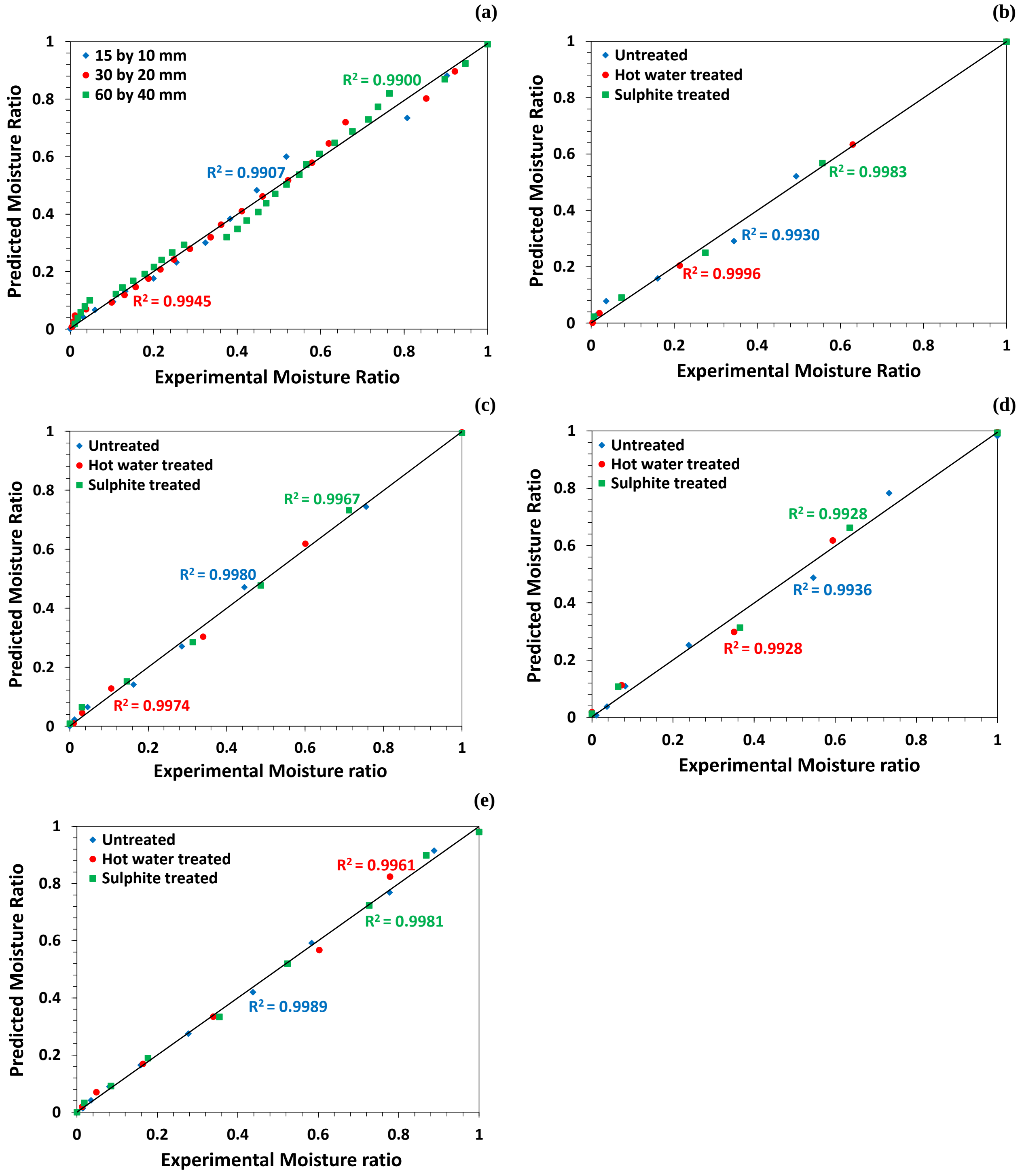

Figure 8 Comparison of moisture ratio predicted by the Weibull model and experimental moisture ratio for convective hot air drying of banana peels biomass at (a) 60 °C (b) 80 °C (c) 100 °C (d) 120 °C (e) 140 °C

4. Conclusions

The drying rate of banana peels biomass was considerably increased while the drying time and specific energy requirement were consequently reduced by drying the biomass at higher temperatures using smaller peel sizes (or larger peel surface areas) and applying hot water or sulphite pretreatments. The drying of the peels was controlled by the diffusion of moisture inside the banana peels. The dependence of the effective moisture diffusivities on temperature was suitably defined by an Arrhenius-type relationship with activation energies of 24.7, 21.4 and 21.3 kJ mol^{-1} required for drying untreated, sulphite treated and hot water treated banana peels, respectively. The Weibull model well explained the convective hot air drying of banana peels biomass.

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