

Modelling the Water Absorption Characteristics of Different Maize (*Zea Mays L.*) Types during Soaking

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Abstract
Water absorption characteristic of six different types of maize namely; dent corn (white and yellow), corn flour (white and yellow), popcorn and sweet corn during water soaking were studied at four different temperatures of 30, 40, 50 and 60 ^{o}C.The water absorption data fitted very well into both Peleg's and Becker's models as to correspondingly determine the saturation moisture content (hydration equilibrium moisture content) and moisture diffusivity. The water absorption capacity and saturation moisture contents of each maize type increased as the water soaking temperature increased. The absorption kinetics followed the Fick's law of diffusion during the first hours of soaking. The determined diffusion coefficients values varied from 10.6 to 13.5 $\times 10^{-11}$ m^2/s for sweet corn, 6.74 to 8.88 $\times 10^{-11}$ m^2/s for white flour, 5.27 to 7.09 $\times 10^{-11}$ m^2/s for yellow flour, 4.44 to 5.79$\times 10^{-11}$ m^2/s for popcorn, 4.25 to 5.69 $\times 10^{-11}$ m^2/s for dent white corn and 3.28 to 4.68 $\times 10^{-11}$ m^2/s for dent yellow corn, respectively. An Arrhenius–type equation was used to relate the moisture diffusivity (diffusion coefficient) of dent corn (white and yellow), corn flour (white and yellow), popcorn and sweet corn to temperature, and the energy of activation for dent corn (white and yellow), corn flour (white and yellow), popcorn and sweet corn was estimated. The values determined were 8.17, 9.59, 7.83, 8.45, 6.61 and 8.01 kJ/mol for dent white corn, dent yellow corn, white corn flour, yellow corn flour, sweet corn and popcorn, respectively.
Keywords: Maize varieties; Water absorption; Peleg's model; Becker's model; Arrhenius-type equation

1. Introduction

In Nigeria, maize (Zea mays L.,) is annually cultivated in about 5.33 million hectares of land yielding about 7.5 million tons of maize (FAO, 1992). It is one of the most important cereal crops in sub-Sahara Africa. According to Food and Agricultural Organization (FAOSTAT, 2012) data, 872 million tons of maize was produced world-wide in the year 2012. The United States of America was the largest producer, having 31.4 % of the world production and Africa produced 8 % (IITA, 2002). Nigeria was the second producer of maize in Africa in the year 2012 with 9.41 million tons, South Africa being the largest producer with production of 11.8 million tons.

Maize, also referred to as corn is an important cereal grown in Nigeria because of its wide use and important role in the diet of majority of people. The maize grain could be used to produce variety of dishes that require preliminary preparations such as soaking in water, dehulling, fermentation, germination, drying and milling to produce fine flour and grits. The treatment used depends on the product to be produced. Hydration through soaking is the most common preliminary process applied to cereals, legumes and grains during the production of various cereals, legumes and grains based food product such as thin porridge pap (*ogi*) (Apena et al., 2006), alcoholic and non-alcoholic beverages (Ayo and Obeya, 2004; Igyor et al., 2006) as well as an important operation in rice parboiling (Engels et al., 1986).

During the soaking of food materials, liquid water is progressively absorbed. The extent of water absorption or the amount of water absorbed into the food material during soaking depends primarily on the soaking water temperature, time, initial moisture content, variety of the seeds, soaking duration, acidity level of the water and physicochemical properties (such as seed structure, size etc) of the food material ((Hsu et al., 1983; Singh and Kulshrestha, 1987; Karapantsios et al., 2002; Shittu et al., 2004; Laria et al., 2005; Tunde-Akintunde, 2010.

The understanding of water absorbing characteristics is considered theoretically and practically important in the food processing industry (Hsu, 1983; Taiwo et al., 1998). Several investigations have been conducted on the water absorbing characteristics of various foods such as soybean, spaghetti and rice (Kubota et al., 1984; Yanagiuchi et al., 1996; Mizuma et al., 2007). Furthermore, investigations on how temperature, pH, physiochemical properties and other nutritional composition affect water absorption capacities of grains and beans have been conducted. Researchers have demonstrated that increasing the temperature of the soaking medium is an effective way to accelerate water uptake by various seeds and hence, shorten the soaking time (Quast and da Silva, 1997; Abu-Ghannam and Mckenna, 1997). Also, many studies have reported the influence of temperature on moisture diffusivity into soybean, amaranth grains and maize kernels, respectively (Hsu, 1983; Calzetta-Resio et al., 2003; Addo et al., 2006). However, effects of varietal variations and processing variables on the rate of water uptake and moisture diffusivity in some cereals grown in Nigeria, such as maize and its processed form have not been clearly established.

Thus, from a processing and engineering point of view, it is highly desirable and of practical importance to know how fast the absorption of water can be accomplished, how it will be affected by processing variables (Verma and Prasad, 1999), and also, how one can predict the soaking time under given conditions. Hence, quantitative data on the effect of processing variables are necessary for practical applications to optimize and characterize the soaking conditions, design food processing equipment and predict water absorption as a function of time and temperature (Taiwo et al., Abu-Ghannam and Mckenna, 1997; Bhattacharya, 1995). This, however, depends on the availability of moisture diffusivity data for the variety being considered (Seyhan-Gurtas and Evranuz, 2001).

It is therefore, the purpose of this study to show how temperature and types affect the water absorption characteristics of Nigerian maize type and its processed form.

2. Materials and Methods

Dent corn (white and yellow), corn flour (white and yellow), popcorn and sweet corn were obtained from the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. Grains were manually selected to remove foreign material and damaged ones prior to experiment. The selected grains were kept in nylon bags. The initial moisture content of maize was determined by oven drying method of whole kernels in triplicate at 120^{o}C for 8 h and expressed on dry basis. The principal dimensions (viz. length, breadth and thickness) were measured with a vernier caliper having least count of 0.02 mm [23]. The shape of the maize is irregular and the nearest shape that can be assumed for the maize is a sphere. Thus, the volume of 50 kernels was measured in triplicate by water displacement in a graduated cylinder. Average volume was equated to the volume of a spherical object as given in Eq. (1), and the equivalent radius R was obtained (Seyhan-Gurtas and Evranuz, 2001).

$$v = \frac{4\pi R^3}{3} \tag{1}$$

The volume-surface ratio (v/s) was calculated from Eq. (2) [23]:

$$\frac{v}{s} = \frac{v^{1/3}\phi}{4.836} \tag{2}$$

Where ϕ is the sphericity

The sphericity of the grains was computed using Eq. (3) (Mohsenin, 1970):

$$\phi = \frac{(LBT)^{1/3}}{L} \tag{3}$$

Where L is the length (mm), B , breadth (mm) and T , thickness (mm).

2.1 Water Soaking Experiment

Moisture content changes of the six species of maize during soaking in water were measured at four different water temperatures (30, 40, 50, and 60°C). Five replicates of 10 ± 0.5 g samples weighed with a digital balance were each placed in a net and soaked in a water bath. The samples were removed from the water bath at each predetermined time, and blotted with tissue paper to remove residual liquid on the surface of the kernels (Seyhan-Gurtas and Evranuz, 2001), and then reweighed. These operations were conducted at each predetermined time until the test was completed. The increase in sample mass during soaking in water was considered to be an increase in sample moisture content (Tagawa et al., 2003). The initial moisture content of the different maize species was determined by oven drying method in triplicate at 103°C for 24 h (AOAC, 1980) and expressed as kg/kg (db). The moisture gain was calculated from the gain in weight of the sample to an accuracy of 0.001 g using digital balance.

2.2 Modelling of Water Absorption

Modeling the process of water absorption by agricultural seeds helps in understanding the dynamic and kinetic of this process and this knowledge is valuable for proper management of their soaking processes. A number of equations have been proposed to describe the water absorption characteristics of food materials. An equation was developed by Peleg (1988) to model the mode of water absorption by food materials. It is a two-way parameter, non-exponential, empirical equation which has been reported to describe the water uptake in food materials especially that of soaked cereals and leguminous food grains accurately (Shittu et al., 2004; Sopade and Obekpa, 1990; Sopade et al., 1992; Hung et al., 1993; Maharaj and Sankat, 2004; Sanni et al., 2003). The Peleg equation is:

$$M_t = M_o + \frac{t}{K_1 + K_2 t} \tag{4}$$

where M_t is moisture content (%) at time t (h), M_o is initial moisture content (%), K_1 is the Peleg rate constant (h%$^{-1}$), and K_2 is the Peleg capacity constant (%$^{-1}$). In Eq. (4), "±‘‘becomes ‘‘+’’ if the process is absorption or adsorption and ‘‘-’’ if the process is drying or desorption.

If $t = 0$

$$\frac{dM_t}{dt} = \frac{1}{K_1} \tag{5}$$

As soaking proceeds, i.e. $t \rightarrow \infty$, Eq.(1) gives the relation between equilibrium moisture content (M_e) and K_2

$$M_e = M_o + \frac{1}{K_2} \tag{6}$$

Values of K_1 and K_2 are obtained from the linearized form of the equation.

Furthermore, moisture diffusion into the grains is primarily caused by concentration gradient. This gradient tends to move the water molecules to equalize concentration. Becker (1960), using Fick's law of molecular diffusion, proposed the following mathematical model (Eq. (7)) for diffusion in solids of arbitrary shape to correlate the moisture gain by wheat kernel during soaking in water

$$MR = \frac{m_s - m}{m_s - m_o} = 1 - \frac{2}{\sqrt{\pi}} X + BX^2 \tag{7}$$

Where MR is moisture ratio, m , m_o and m_s are average moisture contents at any given soaking duration, initial moisture content and moisture content at the bounding surface respectively. For small values of X, Eq. (7) can be approximated to Eq. (8):

$$1 - MR = (\frac{2}{\sqrt{\pi}})X \tag{8}$$

Where

$$X = (s/v)\sqrt{D\theta} \tag{9}$$

in which s/v is surface to volume ratio

Combining Eqs. (7) – (9), we get

$$m - m_o = \alpha_b \sqrt{\theta} \tag{10}$$

Where

$$\alpha_b = (\frac{2}{\sqrt{\pi}})(m_s - m_o)(s/v)\sqrt{D} \tag{11}$$

or

$$D = \frac{\alpha_b \sqrt{\pi}}{[2(m_s - m_o)(s/v)]^2} \tag{12}$$

In Eq. (12), m_o and m_s are constants for a particular type of grain and the ratio of volume-to-surface area (s/v) may be taken as constant irrespective of moisture content (Becker, 1960). A plot of ($m_s - m_o$) with $\sqrt{\theta}$ would give a straight line of slope (α_b) for a particular water temperature of soaking (Eq. 10). At different water temperatures the slope (α_b) would vary. Moisture diffusivity, D, can be determined at different temperatures using different values in Eq. (12).

3. Results and Discussion

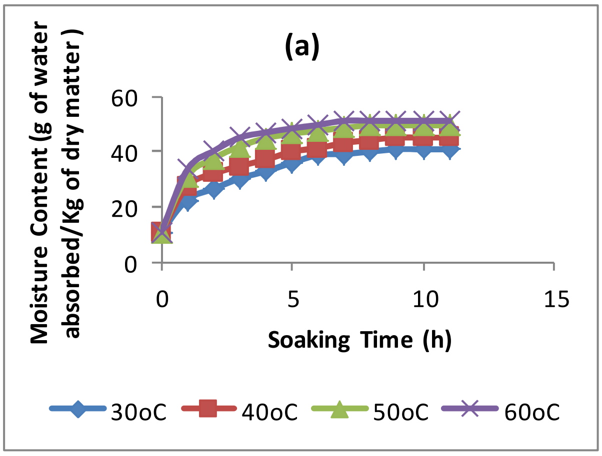
The physical properties of the maize kernels are listed in Table 1.

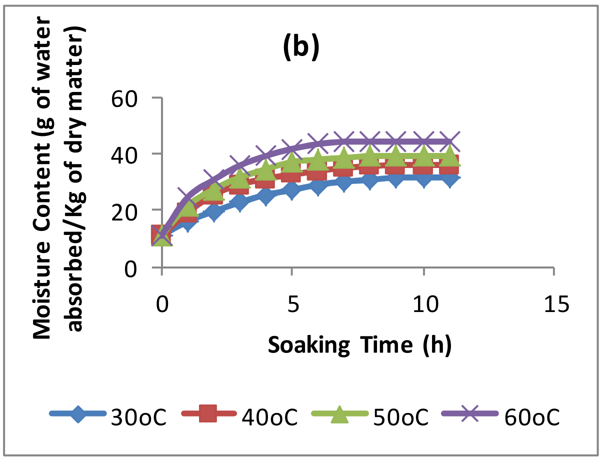
Table 1. Physical properties of six maize types

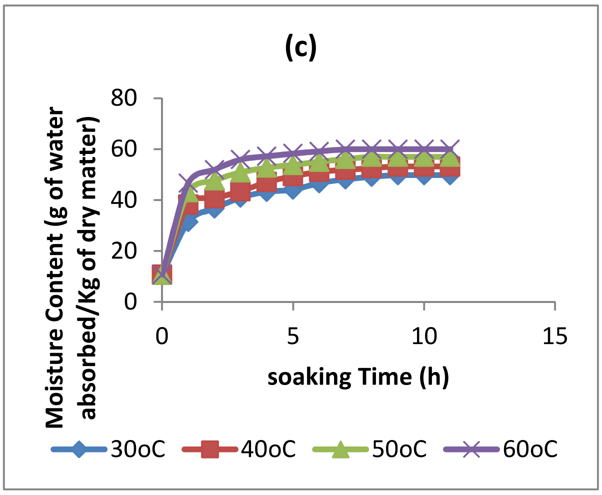
Parameter	Dent White Corn	Dent Yellow Corn	White Corn Flour	Yellow Corn Flour	Sweet Corn	PopCorn
Moisture Content (%db)	10.92±0.1	10.94±0.1	10.65±0.1	10.88±0.1	10.49±0.1	10.96±0.1
Length (mm)	11.36±0.1	8.75±0.1	10.39±0.1	10.00±0.1	10.81±0.1	7.74±0.1
Width (mm)	9.42±0.1	8.75±0.1	8.75±0.1	9.34±0.1	8.13±0.1	5.54±0.1
Thickness (mm)	3.69±0.1	4.55±0.1	3.88±0.1	4.23±0.1	3.86±0.1	3.66±0.1
R (mm)	6.7	6.6	6.7	6.6	4.5	4.6

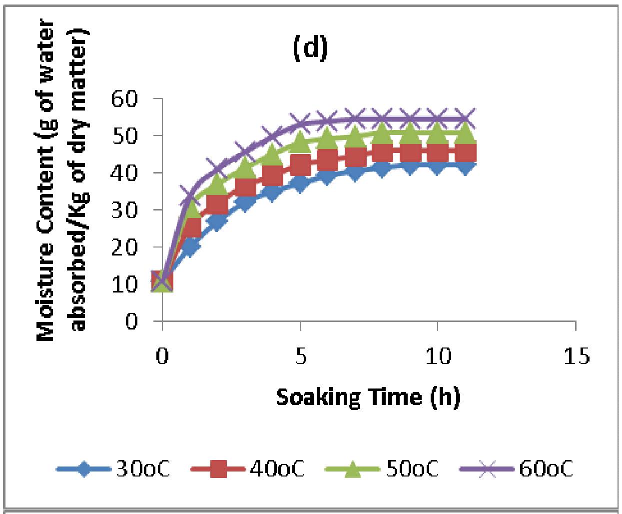
3.1 Water absorption curves of six maize types

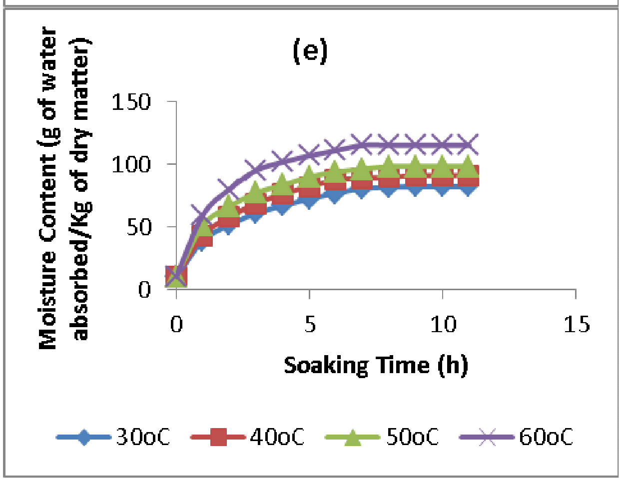
The time variations in water absorption by six maize types at different temperatures are shown in Fig. 1(a - f).






(c)
Moisture Content (g of water absorbed/Kg of dry matter)
80
60
40
20
0
0
5
10
15
soaking Time (h)
30oC
40oC
50oC
60oC


(d)
Moisture Content (g of water absorbed/Kg of dry matter)
60
50
40
30
20
10
0
0
5
10
15
Soaking Time (h)
30oC
40oC
50oC
60oC


(e)
Moisture Content (g of water absorbed/Kg of dry matter)
150
100
50
0
0
5
10
15
Soaking Time (h)
30oC
40oC
50oC
60oC

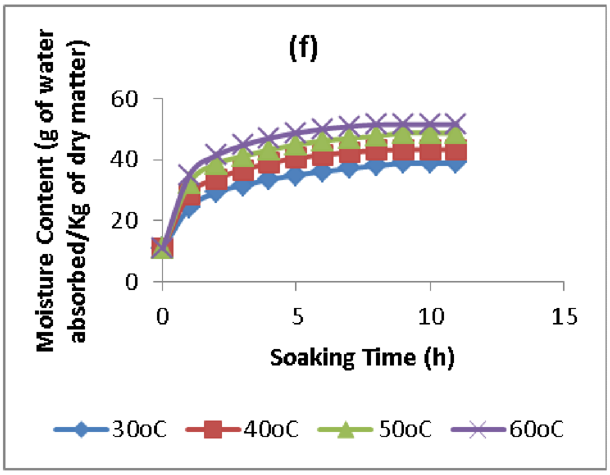


Fig. 1: Water absorption characteristics for (a) dent white corn (b) dent yellow corn (c) white flour corn (d) yellow flour corn (e) sweet corn (f) popcorn

The maize samples exhibited the typical water absorption characteristic as previously described for other food materials (Shittu et al., 2004; Addo et al., 2006; Peleg, 1988; Sopade et al., 1992; Hung et al., 1993; Maharaj and Sankat, 2000). There is an initial very rapid rate of water absorption which was later followed by a slower rate in the later stages as the saturation moisture content (SMC) was approached at all four temperatures. SMC was attained at a higher time (11 h) for soaking water temperature of 30ºC but reduced as the water temperature increased for all the maize types studied. This is because temperatures above the gelatinization temperature of starch (approximately 60ºC) can result in starch gelatinization and protein denaturation (Eckhoff and Tso, 1991). Also, it was observed that the water absorption rate was affected by soaking temperature. The water absorption rate increased with increase in soaking temperature as this is due to increased water diffusion rate. Similar observations have been reported (Sopade and Obekpa, 1990; Lu et al., 1994; Sanni et al., 2003; Shittu et al., 2004; Addo et al., 2006; Addo and Bart-Plange, 2009; Tunde-Akintunde, 2010; Agu et al., 2013; Udoro et al., 2014). However, the rates of increment between the initial and final soaking temperatures were not the same for the different maize types. This could be as a result of the difference in nutritional composition of the maize types considered. Addo et al. (2006) made similar observation when they studied the water absorption characteristics of maize (Obatanpa and Mamaba) as well as Shittu et al. (2004), and Ali et al. (1974) when they studied the water absorption characteristics of rice. The soaking water temperature and concentration of starch in food material determines starch behaviour in water (Addo et al., 2006; Tunde-Akintunde, 2010). Generally, starch grains have very little uptake of water at room temperature and their swelling power is also small. As the temperature increases, the water uptake increases and starch granules collapse leading to solubilization of amylose and amylopectin to form a colloidal solution. Thus, the increase in water absorption as temperature increased. At each soaking temperature, sweet corn had a relatively higher moisture gain (water absorptivity) than all the maize varieties used in this study. This is relatively followed by white corn flour, yellow corn flour, dent white corn, popcorn and dent yellow corn, respectively. This observed difference in the water absorption capacity of the different maize variety may probably be due to difference in their size and initial water content, respectively. Sopade and Obekpa (1990) and Tang et al. (1994) reported that the smaller a seed is, the larger is its water absorption capacity because of the increased specific surface area for absorption. This phenomenon was observed in this study for four of the varieties (sweet corn, white flour, yellow flour and dent yellow corn) which had different size and initial water content. Sweet corn, which has smaller size and lower initial water content as compared to white corn flour, yellow corn flour and dent yellow corn, had a higher uptake of water. While dent white corn and popcorn which has very similar smallest size (3.66 mm/3.69 mm) and highest initial water content (10.92% /10.96%) showed no significant difference in their maximum water uptake at the temperature of 50 ^{o}C and 60 ^{o}C, respectively. More also, at each of the soaking water temperature, the maximum water uptake by the dent white corn and popcorn was lower than that of white flour, yellow flour and sweet corn, respectively. That is, white corn flour, yellow corn flour and sweet corn which are relatively larger in size with lower initial water content had higher water absorption capacity than dent white corn and popcorn with smaller size and higher initial water content. A similar observation has been reported for Obatanpa and Mamaba maize type (Addo et al., 2006).This observation may probably be due to the difference in severity of disorderliness arising from the different levels of temperature used as a result of differences in nutritional composition (Addo et al., 2006). Also, this observation could indicate a strong possibility of white flour, yellow flour and sweet corn having higher starch content than the rest of the maize types. Addo et al. (2006) observed similar behaviour when they reported that the higher starch content in Obatanpatype of maize was responsible for the higher uptake of water even though Obatanpa seed is larger than Mamaba maize type. Nevertheless, the results presented suggest that maximum water absorption is shown by smaller grains with lower initial water content. Knowledge of water absorption capacity and the required corresponding time to attain it is very pertinent in the processing of food. The chemical composition of food materials contributes significantly to its water absorption process (Moss, 1977; Busk, 1984). The chief components of food materials that absorb water are the protein and carbohydrates while proteins have a higher capacity to absorb water more than carbohydrates. Hence, at the same temperature, grain-seeds that have higher protein content would have higher water absorption capacity and probably faster absorption rates. High water absorption capacity is desirable for food grain subjected to processing operations such as wet milling (Tunde-Akintunde, 2010). This is because when grain-seeds approach water saturation it reduces the mechanical stress required for wet milling (Ituen et al., 1986) as well as enhances the extraction of important constituents such as starch in cereal grains. Therefore, it will be more efficient to soak maize grains at high soaking temperature of 60 ^{o}C during maize processing into oat-like or slurry form and other forms that require wet milling.

3.2 Water absorption modelling

3.2.1 Fitting of Peleg's model

The experimental data were fitted to Peleg's model (Eq. (4)) as shown in Fig. 2 (a – f)

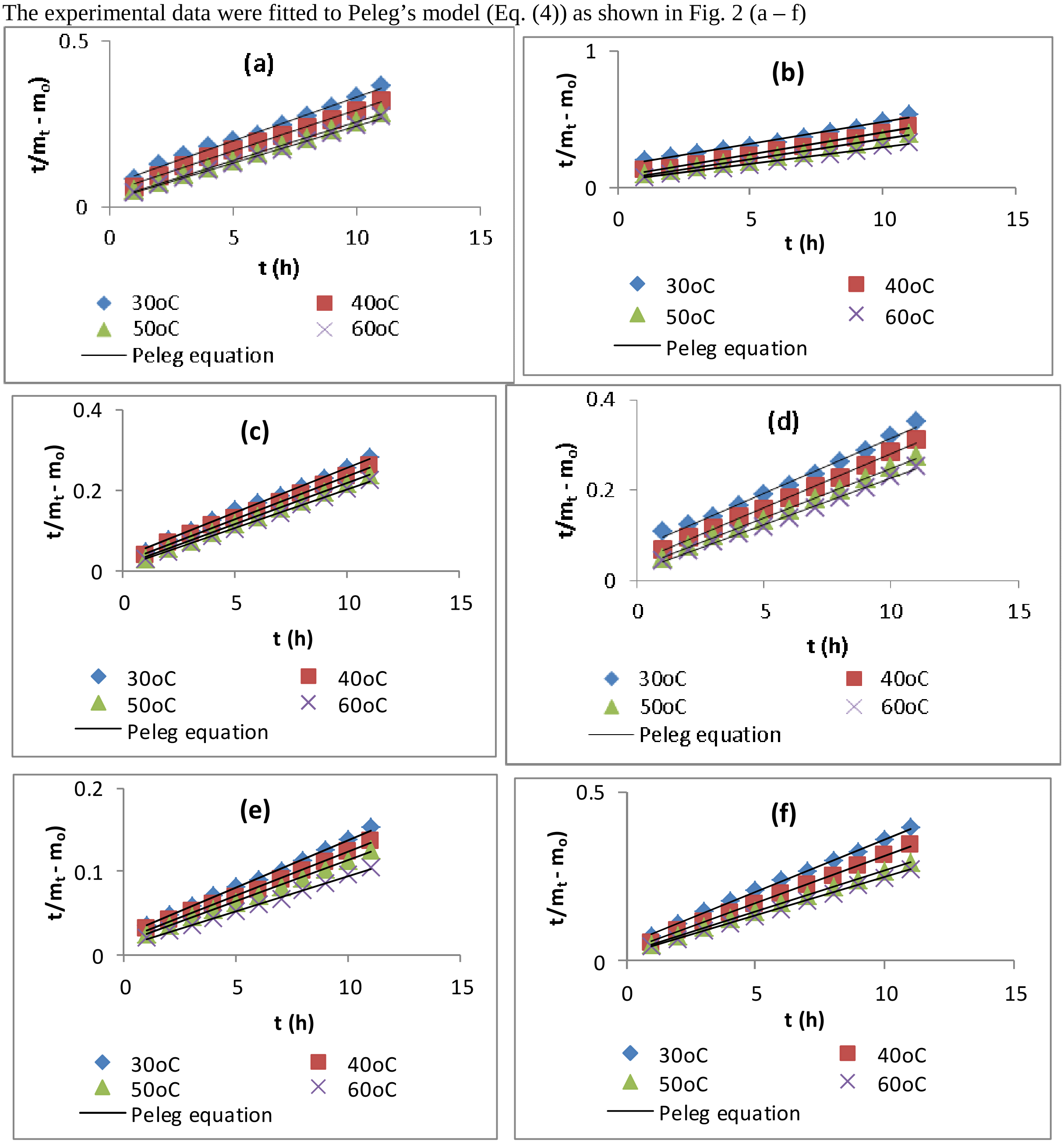


Fig. 2: Fitted Peleg equation to the water absorption data for (a) dent white corn (b) dent yellow corn (c) white flour corn (d) yellow flour corn (e) sweet corn (f) popcorn

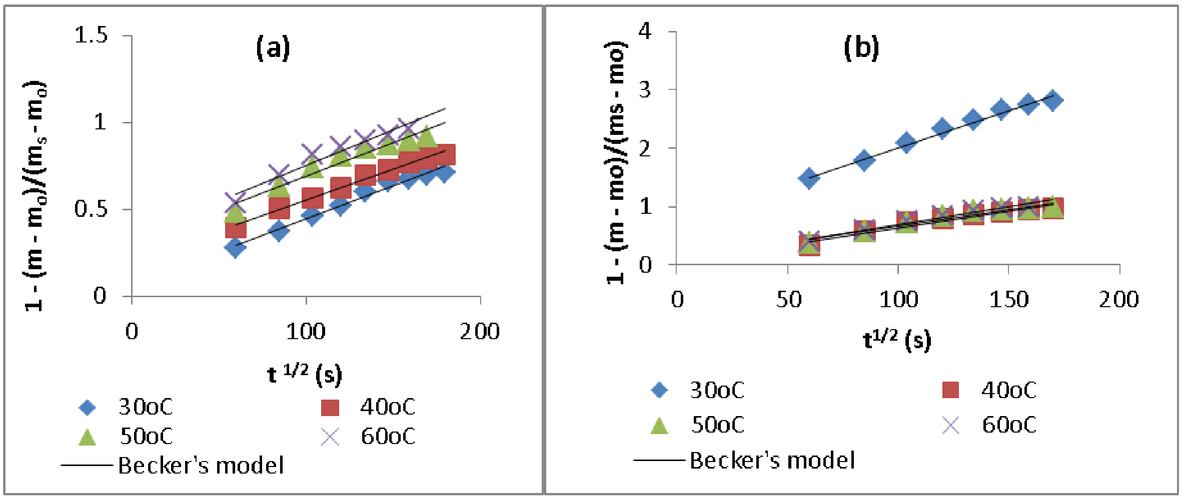
The estimated Peleg's constants are presented in Table 2. The determination coefficient (R^2) varied from 0.9858 to 0.9997 indicating a good fit to the experimental data. This suggests the suitability of Peleg's model for describing the water absorption behaviour of six maize types in the hydration temperatures investigated (i.e. 30 to 60 ^oC). From Table 2, it could be seen that as the hydration temperature increased from 30 to 60 ^oC for each of the six maize types, the Peleg rate constant K_1 generally decreased significantly, suggesting an increase in the initial water absorption rate. That is, K_1 is a constant related to mass transfer rate, e.g., the lower the K_1 , the higher the initial water absorption rate and its sensitivity to temperature is indicative of the positive effect of increased temperature on the rate of water absorbed (Tunde-Akintunde, 2010). Similar observation has been reported (Sopade et al., 1994; Maharaj and Sankat, 2000; Turhan et al., 2002; Tunde-Akintunde, 2010; Quicazan et al., 2012). This temperature sensitivity was more pronounced at water soaking temperature of 60 ^oC where the K_1 value was lowest (Table 2). The initial water absorption (hydration) rate as determined by K_1 values was highest at the soaking temperature of 60 ^oC which is consistent with the hydration curves of Fig. 1 (a - f). In addition, for each of the six maize varieties, the Peleg capacity constant K_2 also decreased as the temperature of the soaking water increased. Similar observation has been reported for Hazelnut kernel and whole Hazelnut (Lopez et al., 1995), Acha (Tunde-Akintunde, 2010), Pearl millet grains and Hungry rice (Agu et al., 2013). Nevertheless, there are mixed reports on the effect of temperature on water absorption capacity of food materials, namely on K_2 , and this depends on type of material and if soluble solids loss during soaking is considered in the calculation of moisture content of samples (Abu-Ghannam and Mckenne, 1997b; Sayar et al., 2001). Sopade and Obekpa [30]; Sopade et al. (1992); Hung et al. (1993); Sopade et al. (1994); Quicazán et al. (2012); Abu-Ghannam and McKenna (1997b); Maharaj and Sankat (2000), in their previous water absorption studies using the Peleg model had reported that there was no effect of temperature on K_2 . While Turhan et al. (2002) reported an increase in K_2 as temperature increased during Chickpea water absorption studies. K_2 is a constant related to maximum water absorption capacity, i.e., the lower the K_2 , the higher the water absorption capacity (Sopade and Obekpa, 1990; Turhan et al., 2002; Tunde-Akintunde, 2010). Thus, soaking each of the six types of maize at higher temperatures results in increased absorption capacity and higher equilibrium water content of hydration as indicated by K_2 values and as shown in Fig. 1 (a – f). The hydration equilibrium water content was determined using Eq. (6) and the predicted values are shown in Table 2. The observed SMC values were taken as the asymptotes of the rehydration curve in Fig. 1 (a – f). There is no significant difference in the values of the observed and predicted equilibrium moisture content that was determined by experimental or predictive methods based on curvilinear experimental data only and Peleg's equation. This corroborates the observations of Maharaj and Sankat (2000) and Tunde-Akintunde (2010).

Table 2: Estimated values of Peleg's constants and determination coefficients (R^2) obtained from the fitting of Peleg's model to the water absorption data for different maize types

Maize Type	Temperature (°C)	$K_1 \times 10^{-2}$ (h%$^{-1}$)	$K_2 \times 10^{-2}$ (%DM)	Observed SMC	Predicted SMC	(R^2)
Dent White Corn	30	6.79	2.63	40.93	48.94	0.9932
	40	4.54	2.48	45.15	51.24	0.9960
	50	2.58	2.31	49.58	54.21	0.9990
	60	2.03	2.26	51.27	55.17	0.9989
Dent Yellow Corn	30	15.29	3.22	31.65	42.00	0.9858
	40	7.34	3.20	36.08	42.19	0.9908
	50	5.58	2.92	39.24	45.19	0.9934
	60	3.10	2.63	44.30	48.96	0.9934
White Flour	30	3.06	2.25	49.79	55.09	0.9985
	40	2.16	2.14	53.16	57.38	0.9979
	50	1.27	2.03	56.96	59.91	0.9996
	60	0.82	1.94	59.92	62.20	0.9997
Yellow Flour	30	7.25	2.43	42.19	52.03	0.9928
	40	4.39	2.38	45.99	52.90	0.9975
	50	2.90	2.19	50.84	56.54	0.9978
	60	2.14	2.06	53.38	59.42	0.9969
Sweet Corn	30	2.38	1.14	82.49	98.21	0.9969
	40	1.90	1.04	90.93	106.64	0.9963
	50	1.46	0.98	98.31	112.53	0.9979
	60	1.06	0.84	115	129.54	0.9975
Popcorn	30	4.87	3.12	38.82	43.01	0.9988
	40	3.04	2.78	42.41	46.93	0.9993
	50	2.53	2.40	48.73	52.63	0.9994
	60	1.93	2.26	51.48	55.21	0.9975

3.2.2 Fitting of Becker's model

The experimental data were also fitted to Becker'smodel (Eq. (7)) as shown in Fig. 3 (a – f)



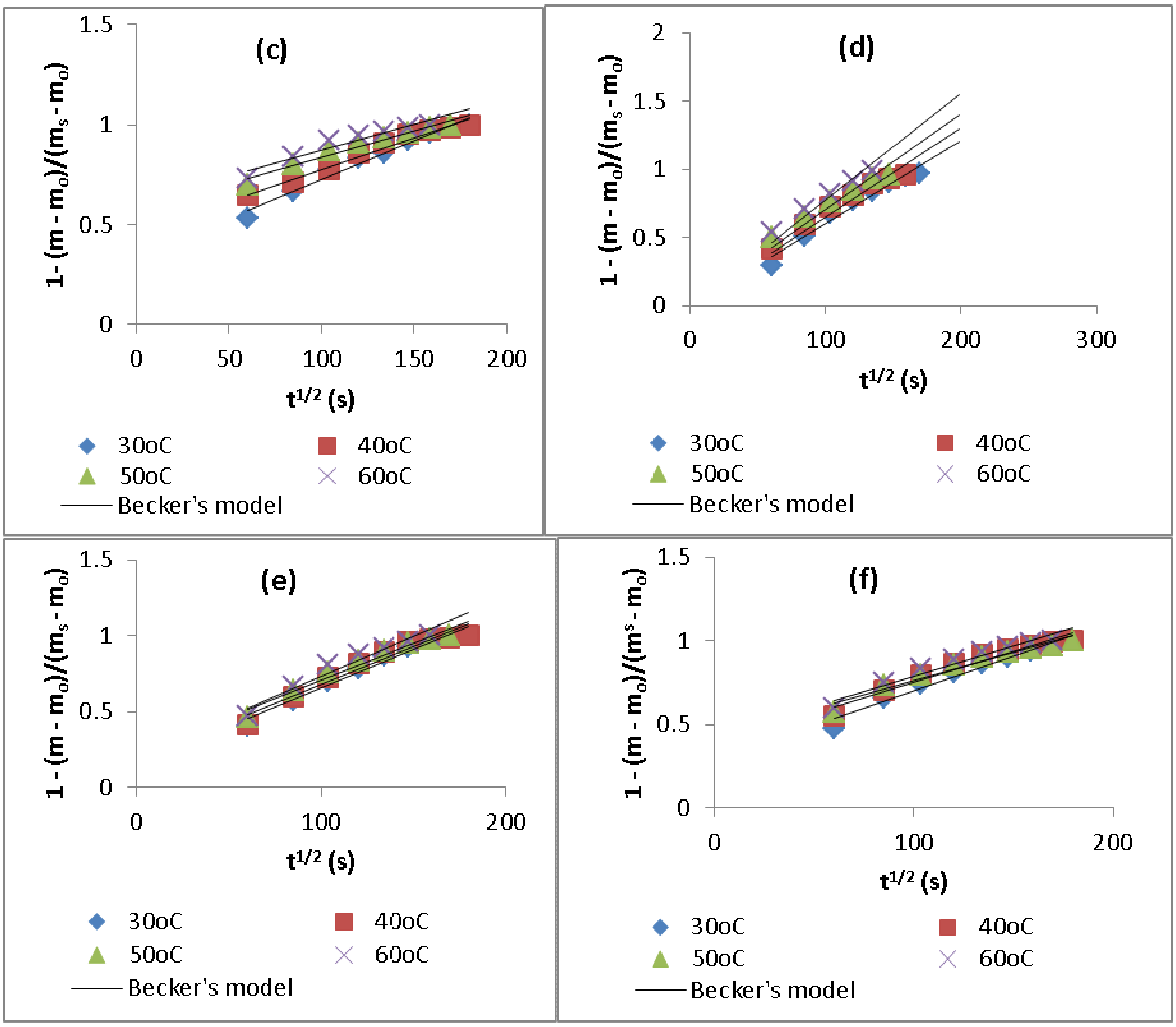


Fig. 3: Fitted Becker's model to the water absorption data for (a) dent white corn (b) dent yellow corn (c) white flour corn (d) yellow flour corn (e) sweet corn (f) popcorn

and the estimated diffusion coefficients and determination coefficients (R^2) are presented in Table 3. The determination coefficient varied from 0.9618 to 0.9984 also indicating a good fit to the experimental data. Consequently, this also suggests the suitability of Becker's model for describing the water absorption or moisture diffusivity behaviour of six maize types in the hydration temperatures investigated (i.e. 30 to 60 °C).The SMCs (α_b) used in Eq. (7) are listed in Table 2 for each maize type and soaking temperature. The water absorption rates for the six types of maize are shown in Fig. 3 (a-f). From Table 3, the diffusion coefficients for sweet corn (10.6 – 13.5 × 10^{-11} m^2/s) are comparatively higher than the corresponding values for other maize types. This is relatively followed by the values for white corn flour (6.74 – 8.88 × 10^{-11} m^2/s), yellow corn flour (5.27 – 7.09 × 10^{-11} m^2/s), popcorn (4.44 – 5.79× 10^{-11} m^2/s), dent white corn (4.25 – 5.69 × 10^{-11} m^2/s) and dent yellow corn (3.28 – 4.68 × 10^{-11} m^2/s), respectively. This could be attributed to the differences in the kernel characteristics of the different maize types (Haros et al., 1995). Verma and Prasad (1999) reported that the moisture diffusivity of `Kisan' maize varied from 1.108 × 10^{-11} to 3.313 × 10^{-11} m^2/s in the temperature range of 30 − 60°C. Haros et al. (1995) also reported diffusion coefficient ranges of 2.499 × 10^{-11} to 6.498 × 10^{-11} m^2/s, 2.499 × 10^{-11} to 6.804 × 10^{-11} m^2/s, and 1.888 × 10^{-11} to 4.999 × 10^{-11} m^2/s for dent, semident and flint maize hybrids during plain water soaking at a temperature range of 45 − 65°C. Addo et al. (2006) also reported diffusion coefficient ranges of 7.31 × 10^{-12} to 9.33 × 10^{-12} m^2/s for Obatanpa and 6.30 × 10^{-12} to 8.25 × 10^{-12} m^2/s) for Mamaba, respectively.

Table 3: Estimated values of diffusion coefficients and determination coefficients (R^2) obtained from the fitting of Becker's model to the water absorption data for different maize types and their activation energies (E_a)

Maize Type	Temperature (°C)	Diffusion Coefficient ($D \times 10^{-11}$) (m^2/s)	R^2	E_a (kJ/mol)
Dent White Corn	30	4.25	0.9783	8.17
	40	4.42	0.9984	
	50	4.95	0.9876	
	60	5.69	0.9848	
Dent Yellow Corn	30	3.28	0.9881	9.59
	40	3.47	0.9727	
	50	3.85	0.9928	
	60	4.68	0.9768	
White Flour	30	6.74	0.9839	7.83
	40	7.65	0.9898	
	50	8.38	0.9851	
	60	8.88	0.9839	
Yellow Flour	30	5.27	0.9755	8.45
	40	5.70	0.9916	
	50	6.38	0.9958	
	60	7.09	0.9625	
Sweet Corn	30	10.6	0.9860	6.61
	40	11.2	0.9895	
	50	12.0	0.9918	
	60	13.5	0.9949	
Popcorn	30	4.44	0.9884	8.01
	40	4.73	0.9618	
	50	5.51	0.9968	
	60	5.79	0.9883	

3.2.3 Temperature dependence of moisture diffusivity

The temperature dependence of the diffusion coefficient for the maize types was expressed by the Arrhenius–type of equation (Eq. (13)) (Addo et al., 2006; Fan et al., 1963):

$$D = D_o \exp(-\frac{E_a}{RT}) \qquad (13)$$

Where D is diffusion coefficient (m^2/s); D_o , diffusion constant (m^2/s); E_a , activation energy (kJ/mol); R , gas constant (8.314 × 10^{-3} KJ/ (k mol)); and T , temperature (K).

Eq. (13) shows that the relationship between the diffusion coefficients and the reciprocal of the absolute temperature was linear on a semi–logarithmic plot. Fig. 4(a – f) shows the Arrhenius relation for the diffusion coefficients of the six maize types. Arrhenius equation was sufficient to describe the temperature effect on the moisture absorption, as the regression coefficient was 0.91or higher (Table 3). The activation energy values were 8.17, 9.59, 7.83, 8.45, 6.61 and 8.01 kJ/mol for dent white corn, dent yellow corn, white corn flour, yellow corn flour, sweet corn and popcorn, respectively (Table 3). The activation energy values obtained were comparatively lower than the reported values of 35069.55 kJ/kg mol K for Kisan maize [23], 45.75 kJ/mol for 'Hi-starch' maize (Cheran and Prasad, 1996), 28.66, 31.69 and 34.15 kJ/mol for 'K- 4' hybrid popcorn, `K-1859' hybrid maize and `Gold Rash' sweet maize [53], 19.25 kJ/mole for husk, 31.50 kJ/mole for paddy and 37.32 kJ/mole for brown rice [55], 44.0 kJ/mol for wheat and 45.9 kJ/mol for barley (Tagawa et al., 2003). However, the values for dent white corn, dent yellow corn, white corn flour, yellow corn flour and popcorn are relatively higher than the values of 6.54 kJ/mol and 6.82 kJ/mol for Obatanpa and Mamaba maize varieties (Addo et al., 2006) and 0.35 kJ/mol for acha (Tunde-Akintunde, 2010). Nevertheless, the lower value for the six maize types suggests that their rate of water absorption is faster when compared to other cereals mentioned with higher activation energy. These lower values may probably be due to their small particle size and their high starch content.

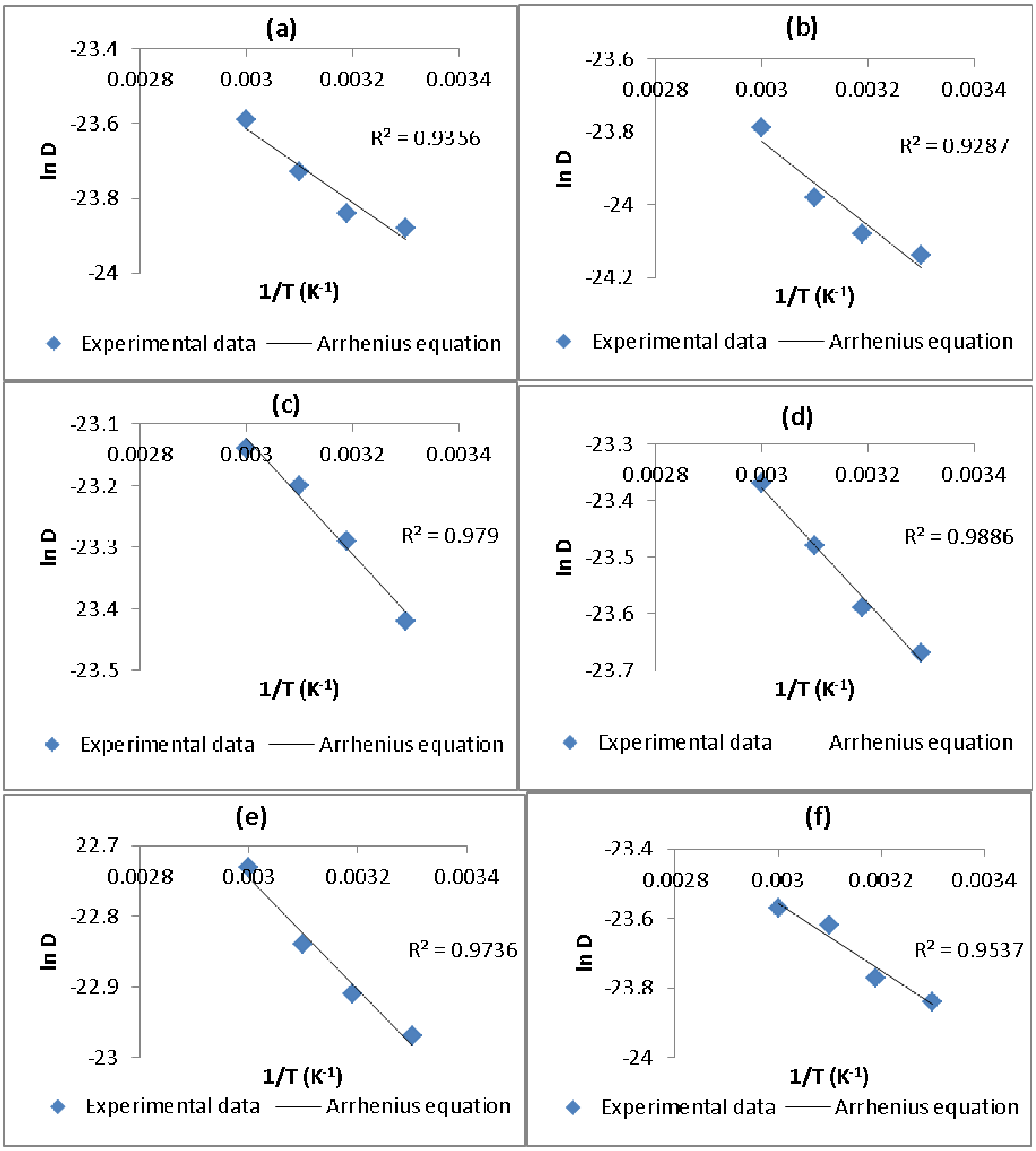


Fig. 4: Temperature dependence of moisture diffusivity for (a) dent white corn (b) dent yellow corn (c) white flour corn (d) yellow flour corn (e) sweet corn (f) popcorn

Conclusion

The period of reaching saturation or equilibrium moisture content during water soaking for dent white corn, dent yellow corn, white corn flour, yellow corn flour, sweet corn and popcornwas reduced from 11 h to 8 h by the increase in water soaking temperature from 30 to 60ºC.The water absorption behaviour of dent white corn, dent yellow corn, white corn flour, yellow corn flour, sweet corn and popcornat different water soaking temperatures were adequately modelled by Peleg's model and Becker's model (Fick's law of diffusion), respectively. An increase in the water soaking temperature resulted in a decrease in Peleg's K_1 constant for each of the maize variety. The initial hydration rate, which is determined by the inverse of K_1, increased with increase in water soaking temperature. The Peleg's K_2 constant increased with decrease in water soaking temperature. Thus the water absorption capacities of the six types of maize or their saturation moisture content increased with increase in water soaking temperature since both are determined from the inverse of Peleg's K_2 constant. Also, for each of the six maize type, the water diffusion coefficients increased with increase in water soaking temperature and this varied from 10.6 to 13.5 × 10^{-11} m^2/s for sweet corn, 6.74 to 8.88 × 10^{-11} m^2/s) for white flour, 5.27 to 7.09 ×

10^{-11} m^2/s for yellow flour, 4.44 to 5.79× 10^{-11} m^2/s for popcorn, 4.25 to 5.69 × 10^{-11} m^2/s for dent white corn and 3.28 to 4.68 × 10^{-11} m^2/s for dent yellow corn, respectively, within the temperature range of 30 − 60ºC. An Arrhenius-type of equation described the strong effect of temperature on the diffusion coefficient with activation energy values of 8.17, 9.59, 7.83, 8.45, 6.61 and 8.01 kJ/mol for dent white corn, dent yellow corn, white flour, yellow flour, sweet corn and popcorn, respectively. Water soaking of dent white corn, dent yellow corn, white corn flour, yellow corn flour, sweet corn and popcorn at $60^{O}C$ is recommended because of the increased absorption capacity and higher saturation moisture content of hydration obtained at this temperature and subsequently the mechanical stress required for wet milling is reduced at this temperature.

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