`**Modelling Water Absorption Kinetics of *Abrohemaa, Omankwa,* and *Akposoe* Maize Varieties**

ABSTRACT

The study investigated the effect of temperature and variety on water absorption kinetics of three Ghanaian maize varieties (*Abrohemaa, Omankwa,* and *Akposoe)* during soaking and also to generate the required moisture diffusivity data for the varieties. The study employed a gravimetric method at four different temperatures of 30ºC, 40ºC, 50ºC, and 60ºC. Varying soaking temperature affected the water absorption rates and behaviours and rates of the varieties and that soaking duration could be reduced by increasing the soaking water temperature. The differences in rate of water absorption by the varieties could be attributed to kernel characteristics such as physiochemical and nutritional composition. The Fick's diffusion law satisfactorily predicted the absorption kinetics of the varieties at all temperatures and that variety and temperature were the most important factors controlling water absorption rate of the maize kernel. The moisture diffusivities of the kernels varied in the order of *Abrohemaa* > *Omankwa* > *Akposoe* and increased as the soaking temperature increases with values ranging from 2.91- 3.93 x 10^{-10} m^2/s for *Akposoe,* 3.19 - 4.33 x 10^{-10} m^2/s for *Omankwa* and 3.66–4.74 x 10^{-10} for *Abrohemaa*. The Arrhenius equation was able to describe the effects of temperature on the diffusion coefficient with activation energy values of 7.04 for Abrohemaa and 8.31 kJ/mol for both Akposoe and Omankwa

KEYWORDS: ~~Modelling~~, Temperature, Water absorption, ~~Kinetics~~, Diffusion, Maize, Soaking

1 Introduction

Maize (*Zea mays L.)* is one of the many cereal crops grown and marketed in many parts of the world and plays major economic role in Sub-Saharan Africa (SSA)[1]. It is regarded as dominant cereal and staple crop produced and consumed across Africa regions and in many parts of America. Govaerts [2][3] put the daily consumption per capita as 290g in Guatemala and Mexico while consumption per capita in Venezuala and Colombia was estimated as 100g/day. The Maize kernel serves as inexpensive source of protein and cheap energy and therefore becomes a good replacements or add-on to the major food staples. FAOSTAT [4] maintained that maize constitutes 40% of the total cereal production and 80% of the total production is consumed as food in the SSA regions. It is also believed that maize could become the food for the next generation and [3] argued that the consumption of maize in the Sub-Saharan regions is likely to increase threefold by the year 2050. Nuss et al [5] observed that, Sub Saharan Africans derived 30% of the energy intake from maize. Cereals contribute immensely to agricultural production and help to provide the needs of Africa's growing population. This accession indicates that the consumption of maize will remain extremely important for years to come. In Ghana, more than 1 million (20%) of estimated 5 million small scale farming households gain main income from the production of maize [6]. In 2018/2019 growing season, Ghana achieved a production level of 1.09 billion metric tons in maize.

Maize processing often requires rehydration of the kernels to make it easy for further operations such as milling, cooking and also to achieve desired palatability. Thus, the knowledge of absorption of water by the kernels is extremely important to the food industries [7].

The rate and amount of moisture imbibed by kernels during rehydration is determined by numerous factors; including the initial moisture content, thickness of outer bran layer, variety of kernel, kernel size, soaking duration as well as temperature and soaking water acidity [8]. Studies have shown that the rate at which water is absorbed by kernels is greatly influenced by temperature and soaking period [9]. A rise in soaking temperature produces higher water absorption rate [10][11].

From a processing and engineering prospective, food processors are not only interested in determining how fast water absorption can be achieved, but also, how processing parameters, including temperature, affect the process [7][12] as well as how soaking time could be predicted at a specific processing condition. The models obtained from Fick's laws of diffusion and the Peleg model are widely employed to characterize the soaking of cereals and legumes kernels [13]. Modelling the absorption kinetics during maize soaking is important since it offers industry players the opportunity to manipulate the operation to optimize industrial processing of maize-based dishes.

Hence, availability of quantitative data on processing parameters is necessary for optimization of the soaking conditions, design of food processing equipment as well as predicting water absorption behaviour of maize kernels. Nevertheless, the available literature provides little or no data on the moisture absorption kinetics of *Abrohemaa, Omankwa,* and *Akposoe* maize varieties grown in Ghana. Consequently, the current study was designed to investigate the temperature and variety effects on these varieties during soaking and also to generate the required moisture diffusivity data for these three Ghanaian maize varieties.

2 Materials and Methods

2.1 *Collection and preparation of maize kernels*

Five hundred gram (500g) each of the three maize varieties (*Abrohemaa, Omankwa,* and *Akposoe*) was obtained from the experimental farm of Crops Research Institute (CRI), Fumasua, Kumasi. The kernels of the varieties were prepared manually and only whole and good kernels were selected for the experiment. Each sample was packed separately into zip-lock polythene bags and placed in a refrigerator to prevent moisture loss or gain.

2.2 *Estimation of initial moisture content*

The initial moisture content of the kernels was estimated by the standard oven drying procedure described by [14]. The three varieties of sample size 5g was weighed using Electronic Compact Scale, SF-400C and placed in labelled dishes. The dishes, together with the samples were placed in standard oven and uniformly heated to a temperature of 103ºC$\pm$2ºC for 4h. The weight loss of the sample was monitored with the electronic Compact Scale, until subsequent weight loss was less than 0.01g. The weight loss by the sample was taken as the weight of water in the sample before drying. The procedure was triplicated and the average value was estimated.

The initial moisture content (M_d) on dry basis was then computed as follows:

$$M_d = \underline{W_w} \times 100\% \quad (1)$$

W_d

$W_d = W_t - W_w$

Where:

W_t = weight of sample before drying,

W_d = weight of sample after drying (dry matter)

W_w = weight of water loss

2.3 *Measurement of length, width and thickness of kernel*

The length, width and thickness of the kernel were determined by the method described by [15]. Hundred (100) kernels were picked at random and their principal diameters were measured along three directions with a digital micrometer screw gauge with accuracy of 0.01 mm. The major diameter was equated to the length of the kernel, the intermediate diameter equated to the width, and the minor diameter equated the thickness of the kernel. The micrometer screw gauge was held at right angle to the direction of the dimeter being measured. Hundred kernels were selected and used to determine the average value of the length while 50 kernels were used for both width and thickness as proposed by [16]. For the sake of irregularity and non-uniformity of the shape of the kernels, the highest values of the dimensions were recorded and used.

2.4 *Estimation of equivalent radius (r)*

The equivalent radius was evaluated from the average volume of the kernels. The volume of a kernel was calculated based on the assumption that the volume of the kernel can be approximated to the volume of a spherical object.

The volume of the kernel was determined by filling a 100-ml measuring cylinder with 50 ml of water. Then, 50 kernels were immersed in the water. The amount of water displaced was recorded. The procedure was replicated and the true volume of a kernel was calculated.

The average volume of a kernel was equated to the volume of a sphere (V = $\frac{4}{3}\frac{4}{3}$ πr^3) and equivalent radius (r) was obtained.

Thus,

$$r = \sqrt[3]{\frac{3v}{4\pi}} \qquad (2)$$

2.5 *Determination of saturation moisture content* (Ms)

Three set of sample size 5g±0.0 for each variety was soaked at four different water temperatures in a portable water bath fixed with temperature control system. The samples were situated separately in a labelled nylon mosquito net and placed into the water bath at a pre-determined temperature of 30ºC±2ºC, 40ºC±2ºC, 50ºC±2ºC, and 60ºC±2ºC. The sample was removed at time interval of 1h, and quickly wiped out the residual water on the surface of the kernels [17] and then reweigh [18]. The weight gain of the sample was monitored at each time interval using the electronic Compact Scale. The moisture content of the sample at specific time interval was calculated and recorded. The saturation moisture content (M_s) was computed when the subsequent weight gain of the sample was ≤ 0.01g.

2.6 *Modelling of absorption kinetics*

At constant temperature, it is assumed that diffusion process follows Fick's second law of diffusion. Therefore, Fick's three-dimensional equation can be applied for an axisymmetric diffusion:

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} + \frac{\partial^2 M}{\partial z^2}\right) \quad \textbf{(3)}$$

Where, D is the diffusion coefficient and M is the water content at time t. The equation (3) was re-arranged to obtain a solution for an object with a sphere shape (Seyhan-Curtas *et al*.,2001),

$$\text{MR} = \frac{M - M_i}{M_e - M_i} = 1 - (\frac{6}{\pi^2})\sum_{i=1}^{\infty}(\frac{1}{i^2})\exp(-Di^2\pi^2\frac{t}{r^2}), \quad \textbf{(4)}$$

where,

MR = moisture ratio,

M_i = initial moisture content,

M_e = equilibrium moisture contents.

Di = effective diffusion coefficient,

i = number of terms in the summation

r = equivalent radius of the kernels and

t = soaking time.

In this case, only a finite number of Eq. (4) was used for estimating the MR values. All moisture terms were computed on dry basis.

The effective diffusion coefficient, Di was evaluated from the slope of a curve, 1-Mr against the soaking time t.

The temperature dependency of diffusion coefficient (D_i) was evaluated using an Arrhenius equation:

$$Di = D_o e^{-Ea/RT} \quad (5)$$

where:

D_o = diffusion constant (m^2/s),

Ea = activation energy (kJ/mol),

R = general gas constant (8.314 J/mol K) and

T = absolute temperature (K).

The Ea values for the selected varieties were calculated from the linear regression of D*i* against reciprocal of soaking time (1/T). The constant D_o and the slope Ea/R were computed. The Ea values were obtained by multiplying the gas constant (8.314 J/mol K) by the value of the slope.

3 RESULTS AND DISCUSSION

3.1 *Moisture content and dimensions*

The initial moisture contents (M_i) in percentage dry basis (%db), length (L), width (W), thickness (T), equivalent radius (r) and surface area (SA) of the kernels are presented in **Table 1.**

Table 1: Initial Moisture Content and Physical Properties of Maize Varieties

Maize	M_i (%db)	L(mm)	W(mm)	T(mm)	r(mm)	SA(mm^2)
Aborohema	11.76	11.03	8.98	4.74	4.04	596.65
Omankwa	11.76	10.47	9.02	4.53	4.02	560.79
Akposoe	13.66	10.20	8.80	4.10	3.65	507.23

Table 1 shows values for length (l), width (W), thickness (T) and surface area (SA) of the kernels used in this study. The SA ranged from 507.23 mm^2 to 596.65 mm^2. These values are in agreement with values documented by [19]. In general, for different varieties one would anticipate an inverse relation between the absorption rate and kernel size, since a larger kernel yields a smaller specific surface area for moisture movement [20].

3.2 *Saturation moisture content and diffusion coefficient*

The water absorption curves of maize varieties soaked at temperatures are illustrated in **Figure 1a, 1b and 1c.**

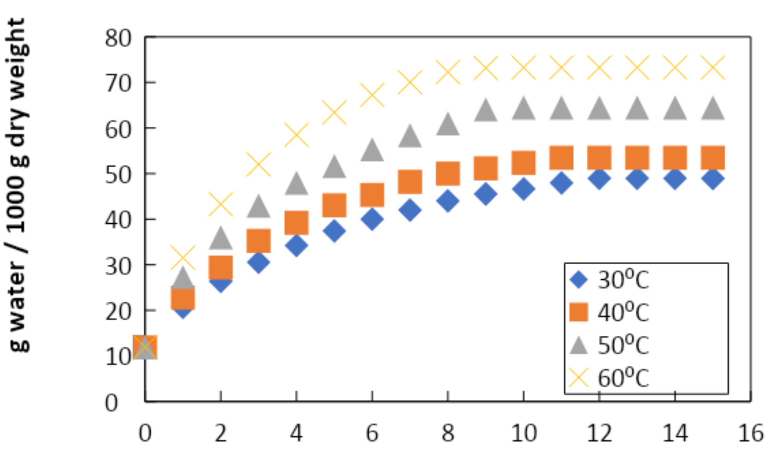

Figure 1a: Water absorption curves of *Abrohemaa*

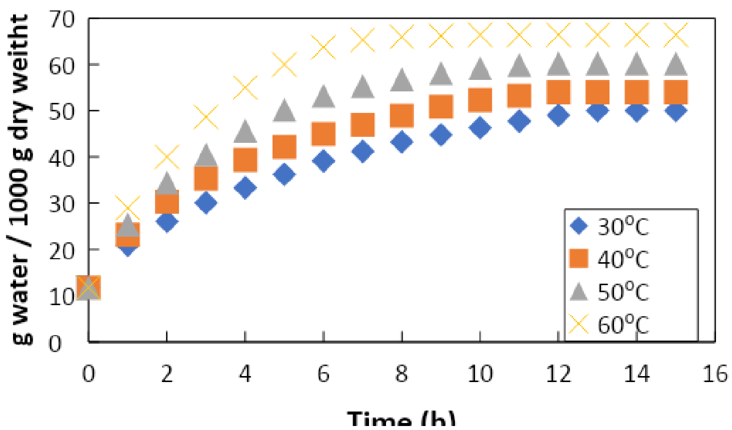

Figure 1b: Water absorption curves of *Omankwa*

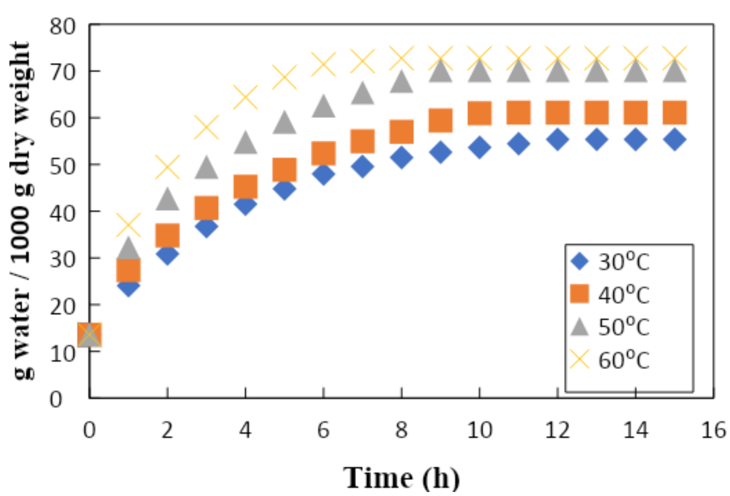

Figure 1c: Water absorption curves of *Akposoe*

The maize varieties showed moisture absorption behaviour similar to what has been published by [7][17][27]. The initial water absorption was rapid, immediately followed by a slower rate and at later stages asymptotically got to the saturation point (M_s). Moisture saturation was reached within 12h of soaking at temperature of 30ºC but soaking time was shortened to 8h as soaking temperature rises to 60ºC. This observation was in line with reports by other published studies [21].

The rate at which water was absorbed by these kernels was found to increase with increasing soaking temperature as a result of increased diffusion rates. Also, high water temperature could cause damage to cell tissues leading to an increased opening of the pores which will consequently increase the rate of water absorption. Identical findings have been documented by [22] [23][24][25][26]. Reports by other researchers such as [17][27] derived similar hydration curves for red kidney beans, selected Turkish legumes, wheat and barley.

The study also found that water absorption capacity increased as the soaking temperature increases and that the rates of moisture increment differ for the varieties considered. The observed phenomenon could be attributed to the difference in varietal characteristic such as nutritional composition of the varieties. This confirms earlier reports on the water absorption behaviour of rice by [28][29].

The study further observed that Akposoe had moderately higher water gain than the other varieties. At temperatures of 30ºC and 40ºC, *Abrohemaa* recorded the least water gain as anticipated while *Omankwa* recorded minimum water gain at 60ºC. Generally, water absorption rates were seen to be influenced by temperature. The observed effect of temperature on absorption rates agreed with other published studies [30][17][27]. Shafaei et al. [21] made identical observation after studying water absorption characteristics of chickpea and soybean.

An increased specific surface promotes higher absorption capacity due to smaller nature of kernel size [13]. This phenomenon was noticed in the current study. *Akposoe* had a small kernel size in relation to Omakwa and *Abrohemaa* therefore recorded higher water absorption capacity as expected. In contrast, *Abrohemaa* kernel was relatively bigger but recorded the upmost absorption capacity at temperatures 50ºC and 60ºC. This behaviour could be attributed to variations in severity of disorderliness brought about by different temperature levels to bear on the nutritional composition. The observed occurrence could suggest a high probability of *Abrohemaa* containing more starch content than *Akposoe* and Omakwa. Addo *et al.* [7] made similar observation that high starch content of *Obatanpa* was accountable for its higher water absorption capacity although *Mamaba* kernel was relatively smaller than *Obatanpa.* Many reports, including Ituen et al. [31], have shown that kernel characteristics and temperature are the most important factors responsible for variations in equilibrium moisture content values. Brennan et al. [32] also made similar assertion that the extent to which protein and starch (water holding constituents) have been destroyed by temperature during drying principally influenced reconstitutability of dried food products.

3.3 *Water absorption rates of maize Hybrids*

The data on moisture ratio obtained from the soaking experiment were plotted against the square root of soaking period. Based on eqn. (4), the effective diffusivity values for the varieties during water absorption process was determined. The moisture contents (M_s) employed in eqn. (4) and the coefficient of determination (R^2) are indicated in **Table 2.**

Table 2: Effective diffusion coefficient (D_i) values and Saturation Moisture Content (M_s)

	30ºC			40ºC			50ºC			60ºC		
Variety	D_i*	R^2	M_s	D_i*	R^2	M_s	D_i*	R^2	M_s	D_i*	R^2	M_s
Abrohemaa	3.66	0.99	48.95	3.96	0.98	53.47	4.21	0.99	64.5	4.74	0.98	73.27
Omankwa	3.19	0.99	50.02	3.48	0.99	54.00	3.75	0.97	60.27	4.33	0.94	66.41

Akposoe	2.91	0.97	55.37	3.13	0.99	61.10	3.38	0.99	70.12	3.95	0.96	72.74

* x10^{-10} m^2/s,

Estimated D_i values of the selected varieties at various water temperatures are indicated in **Table 2** above. Generally, the experimental data fitted the diffusion equation with high accuracy. The R^2 values obtained from the linear regression analysis varied from 0.94 to 0.99. The D_i of *Abrohema* varied from 3.66 – 4.74 x 10^{-10} m^2/s; *Omankwa,* 3.19-4.33 x 10^{-10} m^2/s and *Akposoe* varied 2.91-3.95 x 10^{-10} m^2/s. The observed differences in D_i could be attributed to differences in kernel characteristics due to varietal variations of the maize. Agarry et al [33] attributed the kernel's propensity to absorb water to the two main constituents (protein and carbohydrate) with protein possessing a higher capacity to absorb water than carbohydrate.

Therefore, variations in nutritional characteristics of the kernels could provide another explanation for *Abrohemaa* variety having higher diffusion coefficient than *Omankwa,* and *Akposoe* varieties. It is also probable that *Abrohemaa* kernel contains high protein concentrations than *Omankwa* and *Akposoe*, causing it to soak up more water than the two varieties within the same temperature and time conditions. In comparison with other studies, the D_f values obtained in this work is marginally higher than those documented by [7] for *Mamaba* and *Obatanpa* but were lower than values reported by [8]. The observation could possibly be attributed to variations in the physiochemical and nutritional characteristics of the varieties studied. Addo et al. [7] and Agidi et al. [34] agreed to this assertion when they reported that seed's size and nutrient are primarily responsible for water uptake in seeds soaking. Additionally, Webb [35] also disclosed that among the starch, amylose content has been found to be the most well-known property for forecasting rate of moisture gain. The rates of water absorption of the selected varieties are presented in **Fig. 2a, 2b and 2c.**

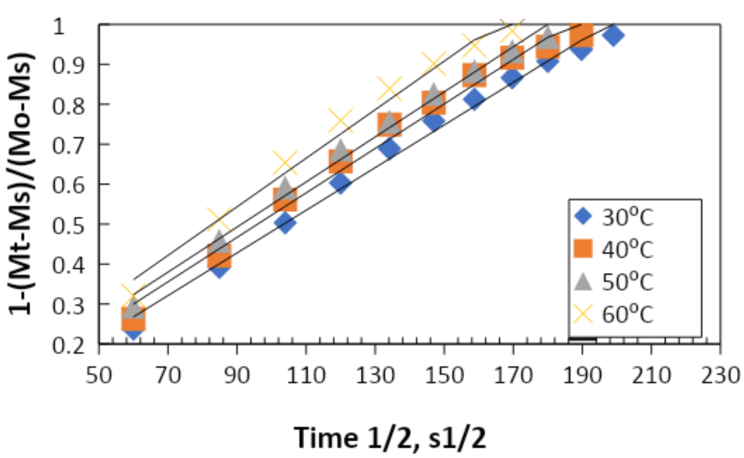

Fig. 2a: Water absorption rate for *Abrohemaa*

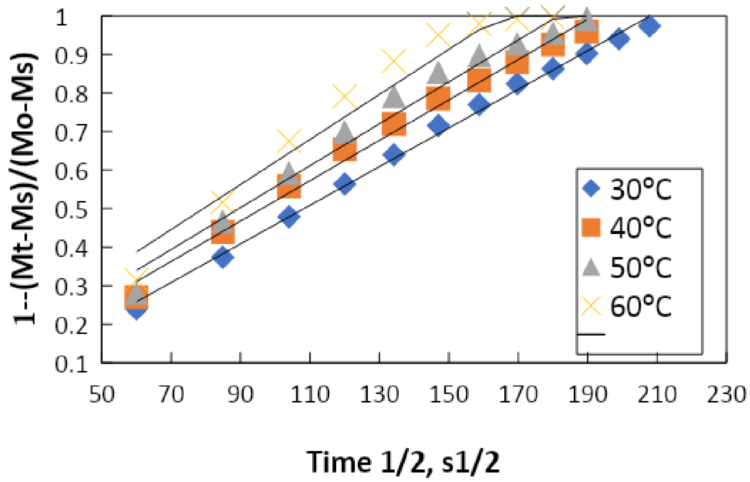

Fig. 2b: Water absorption rate for *Omankwa*

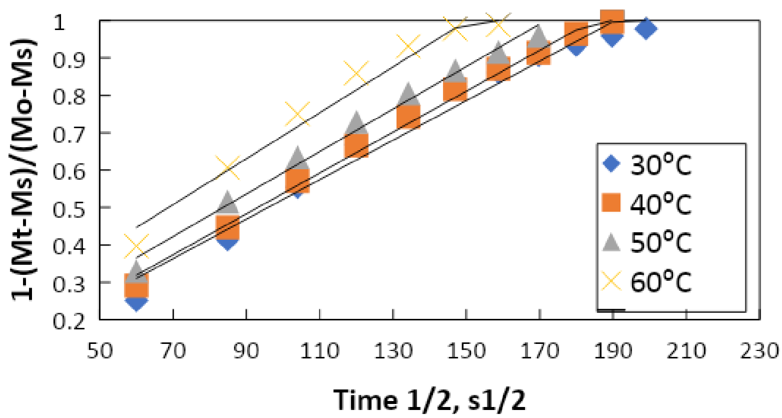

Fig. 2c: Water absorption rate for *Akposoe*

3.4 *Activation Energies (Ea) of selected maize varieties*

The values of diffusion coefficients of the selected maize were fitted into an Arrhenius-type relationship (eqn. (5)) in order to relate the temperature effect to moisture diffusivity of the maize kernels. A plot of D_f versus reciprocal of absolute temperature are presented in **Figure 3.** The $\mathbf{R^2}$ obtained varied from 0.96 to 0.98 which represents a good fit of the experimental data.

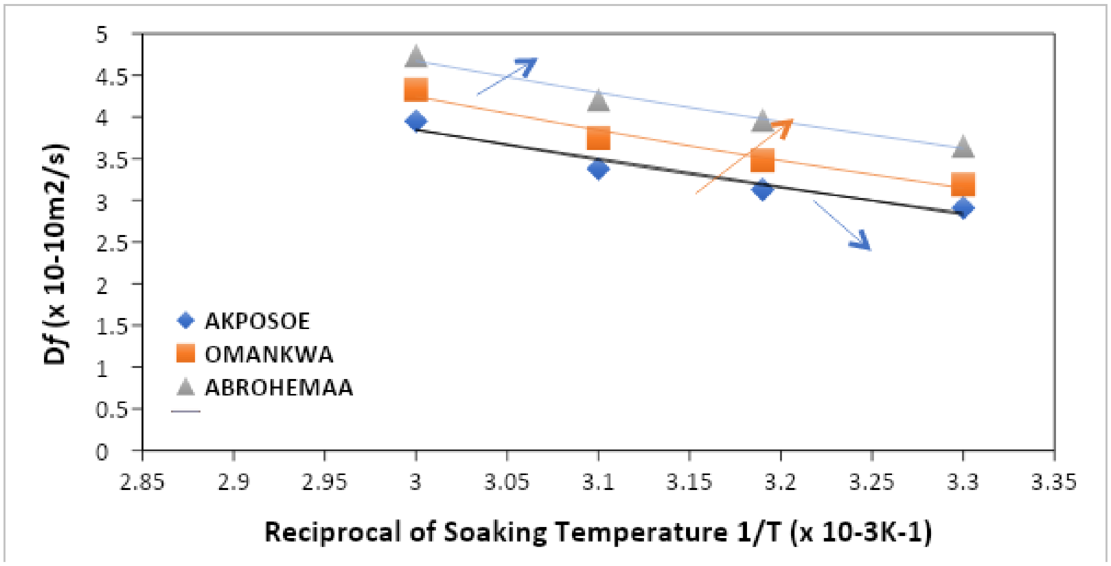

Figure 3: The relationship between water Diffusivity and reciprocal of temperature

Figure 3 portrays the correlation between temperature and the diffusion coefficients of the varieties (*Akposoe, Abrohemaa* and *Omankwa*). The graphs indicate that the Arrhenius equation was able to describe the strong effects of temperature on the water absorption behaviour of the maize varieties. The Ea obtained for the selected Maize varieties are presented in **Table 3**

Table 3: Estimated values of Activation Energy (Ea) of selected maize varieties

Variety	Ea (kJ/mol)	R^2
Akposoe	8.31	0.96
Abrohemaa	7.04	0.98
Omankwa	8.31	0.98

The Ea estimated from the slopes of the curves in **figure 3** shows Ea values of 8.31 kJ/mol for *Akposoe*; 7.04 kJ/mol for *Abrohemaa* and 8.31 kJ/mol for *Omankwa*. The marginally low energy values obtained in this study suggest that the varieties were less sensitive to heat and that there was a heat build-up during the absorption process. In comparison, Ea values obtained in this study were identical to values reported by Addo et al. (2006) for *Obatanpa* (6.54kJ/mol) and *Mamaba* (6.82kJ/mol). Idun-Acquah et al. [36] obtained similar Ea values for *Asontem* (7.27 kJ/mol), *Hewale* (7.26 kJ/mol) and *Asomdwee* (6.26 kJ/mol). In contrast, Verma and Prasad [12]; Charan and Prasad [37] reported large values of activation energies in the range of 33.5-41.56 and 45.75 respectively for certain varieties of maize. These differences in activation energies could be attributed to varietal variations resulting from physiochemical and nutrient composition of the maize varieties.

4. Conclusion

The water absorption kinetics of three maize varieties, *Akposoe, Abrohemaa* and *Omankwa* were studied using phenomenological models deduced from Fick's law of diffusion. The study found that temperature and variety significantly influenced the water absorption rate and capacity of the kernels. The soaking duration could be shortened by raising the water temperature from 30ºC to 60ºC. Variations in rate of water absorption could be attributed to kernel characteristics such as physiochemical and nutritional composition of the varieties. The Fick's diffusion law adequately simulated and predicted the water absorption kinetics of the varieties. The effective moisture diffusivity values varied from 3.66 – 4.74 x 10^{-10} m^2/s for *Abrohema*; 3.19-4.33 x 10^{-10} m^2/s for *Omankwa*; and 2.91-3.95 x 10^{-10} m^2/s for *Akposoe.* The temperature dependency of moisture diffusivity of the varieties was satisfactorily represented by the Arrhenius equation with the activation energies for *Abrohemaa* (8.31 kJ/mol), *Akposoe* (7.04 kJ/mol) and *Omankwa* (8.31kJ/mol).

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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