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The Hydration Kinetics of Selected Ghanaian Maize (*Zea mays* L.) Hybrids

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Abstract

Water absorption characteristics of maize (*Abotem*, *Abeleehi*, and *Dorke SR)* hybrids grown in Ghana were investigated using models obtained from Fick's law of diffusion. The maize kernels were soaked in water at four different temperatures of 30˚C, 40˚C, 50˚C and 60˚C to evaluate their water absorption behaviours. The results indicated that temperature and variety were the major factors controlling water absorption patterns. The diffusion coefficients of the hybrids were found to differ in the order of *Dorke SR* > *Abeleehi* > *Abotem* and increased as the soaking temperature increased. The calculated water diffusivities varied from $(2.54 - 3.49) \times 10^{-10}$ m^2/s for *Abotem*, $(2.64 - 3.59) \times 10^{-10}$ m^2/s for *Abeleehi*, $(3.21 - 4.20) \times 10^{-10}$/s for *Dorke SR*. The Arrhenius-type equation was able to describe the strong effect of temperature on the diffusion coefficient of the hybrids. The activation energy values obtained were7.50 kJ/mol for *Abeleehi*, 6.27 kJ/mol for *Dorke SR* and 9.09 kJ/mol for *Abotem*. Results indicated that temperature and variety were the major factors controlling water absorption patterns.

Keywords

Maize, Water Absorption, Diffusion Coefficient, Activation Energy

1. Introduction

Maize is an essential member of the cereal family and important food crop produced worldwide including savannas of Sub-Saharan Africa (SSA). Maize is a major source of protein and energy and can be used as a substitute for major food staples. Many people believe that maize could become the future food for Africans. In SSA, maize contributes 40% to cereal production, where more than 80% is used as food [1]. At least 30% of the calorie intake in SSA is supplied by maize [2]. In Ghana, more than 1 million (20%) of estimated 5 million small scale farming households gain main income from the production of maize.

Generally, it is often necessary to soak maize kernel in water for a period of time before further processing takes place [3] to enhance processing operations such as milling, fermentation and to reduce cooking time as well as achieving desired palatability. Thus, absorption of water by agricultural materials is of practical importance to maize-based processing industries [4].

Demirhan *et al.* [5] [6] and Hsu *et al.* [7] gave different factors influencing amount of water absorbed by seed during soaking as the kernel size and variety, soaking time, temperature, initial moisture content and acidity level of the water. Shafaei and Masoumi [8] supported the assertion by indicating that temperature and soaking time largely influence the rate at which seeds absorb water.

From engineering perspective, maize processors are not only interested in determining water absorption capacity and rates, but also the effects of processing parameters such as temperature [4] [9] and also how soaking time can be predicted. However, this can only happen when there is availability of data on moisture diffusivity of kernels. For the purposes of designing equipment for food processing, and determining favourable conditions to accomplish soaking process, it is very necessary to have access to documented data which describe the effect of the processing variables on agricultural materials. However, the hydration model on effects of temperature and variety on water absorption rate and data on diffusion coefficient of some maize hybrids such as *Abotem*, *Dorke SR and Abeleehi* have not been adequately documented. Thus, the purpose of this study was to investigate the effects of variety and temperature on the water absorption behaviours of these maize hybrids grown in Ghana.

2. Material and Methods

2.1. Preparation of Samples

Three samples of the maize hybrids (*Abotem*, *Abeleehi* and *Dorke SR*) were obtained from the Crop Research Institute's (CRI) experimental farm situated at Fumesua, Kumasi. The samples collected were graded and only good kernels were used for the experiment. Each sample was packed separately in an air-tight polythene bag, sealed and stored at 4˚C to maintain moisture and prevent re-contamination.

2.2. Determination of Moisture Content

The initial moisture content of the sampled kernels were estimated using the Standard Oven drying method proposed by [10]. Three samples of 5 g each were measured, placed in dishes and numbered. The dishes containing the samples were heated for 4 h at a temperature of 103˚C in the oven. For each sample, the method was repeated three times and the mean value determined.

2.3. Determination of Length, Width and Thickness

The principal dimensions of each maize kernels were determined following [11] approach with slight changes. Hundred (100) kernels were randomly selected for each sample and their dimensions taken using a digital micrometer screw gauge. Thus, the major diameter was taken as length, the intermediate diameter as width, and the minor diameter as thickness of the kernel. Length was taken on 100 kernels and width and thickness on 50 kernels as specified by [12].

2.4. Determination of Equivalent Radius (*r*)

The equivalent radius for each variety was measured based on the assumption that the volume of the maize kernel could be approximated to the volume of a sphere with radius being half of the diameter of the kernel. Fifty kernels of each variety were immersed in the water and volume of water displaced was recorded. The average volume obtained was equated to the volume of a spherical object [13] and r in mm calculated from $V = \frac{4}{3}\pi r^3$.

Thus,

$$r = \sqrt[3]{\frac{3v}{4\pi}} \tag{1}$$

2.5. Soaking Experiment

Water absorption behaviour of the hybrids was evaluated essentially by immersing the kernels into water at four different temperatures of 30˚C, 40˚C, 50˚C, and 60˚C in a thermostatic water bath. Three replicates of sample size 5 ± 0.02 g each was separately placed in nylon mosquito net, tied and labelled. The mosquito net containing the samples were separately placed into the bath and removed at predetermined time interval of 1 h. The moisture content (Mc) of the kernels at each interval, was determined from the difference between the initial weight and the final weight. The moisture content at saturation point (SMC) was calculated when there was no significant change between the initial weight and the final weight.

2.6. Hydration Kinetics

At constant temperature, the diffusion process was assumed to follow the Fick's second law of diffusion, where Fick's three-dimensional equation given by:

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

where, M represent instantaneous Mc at time t and D_f the diffusion coefficient. A solution proposed for a spherical shaped object with radius r presented by [13] and [14], as

$$\text{MR} = \frac{M - M_i}{M_e - M_i} = 1 - \left(\frac{6}{\pi^2}\right)\sum_{i=1}^{\infty}\left(\frac{1}{i^2}\right)\exp\left(-Di^2\pi^2\frac{t}{r^2}\right) \tag{3}$$

where, MR represent moisture ratio,

M_i and M_e being the initial and the equilibrium moisture content respectively, *i* the number of terms in the summation,

Di, the effective water diffusion coefficient,

r is the radius of the kernels and

t the soaking time.

The problem was then formulated as a root finding equation:

$$f(Di) = \mathrm{MR}_{\mathrm{expt}} - \mathrm{MR}_{\mathrm{calc}}$$

and searched for the *Di* value which made the function $f(D_f) = 0$. With $\mathrm{MR}_{\mathrm{expt}}$ and $\mathrm{MR}_{\mathrm{calc}}$ representing moisture ratio from experimental data and the model predictions respectively.

Activation energies (*Ea*) of the hybrids were evaluated using an Arrhenius-type equation [15]:

$$D_f = D_o e^{-Ea/RT} \quad (4)$$

where:

D_f (m²/s), D_o (m²/s), *Ea* (kJ/mol), *R* (8.314 J/mol K), *T* (K) represent diffusion coefficient, diffusion constant, activation energy, gas constant and absolute temperature respectively.

The D_o and the slope (E_a/R) were obtained from the linear regression analysis of D_f vs. $1/T$ and (*Ea*) of the varieties were calculated.

3. Results and Discussion

3.1. Physical Properties

The physical properties, initial moisture contents of the maize hybrids investigated are presented in Table 1.

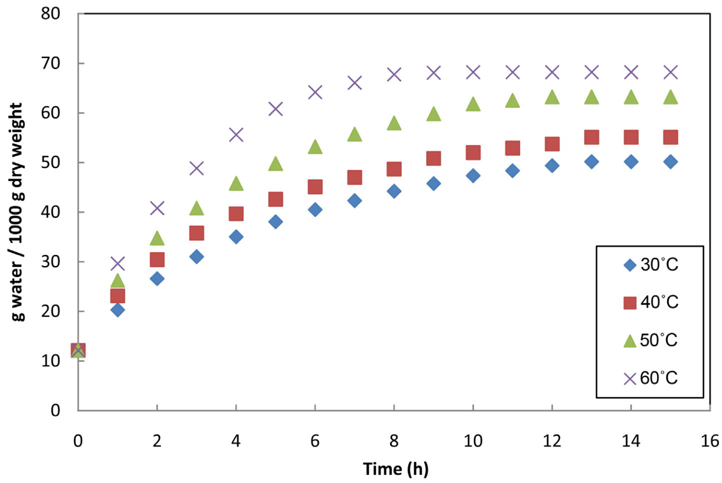
Generally, the values presented in Table 1 agree with those reported by [16]. From Table 1, the surface (SA) varied from 521.34 mm² (*Dorke SR*) to 537.62 mm² (*Abeleehi*). In general, for different cultivars of a cereal, one will expect an inverse relationship between kernel size and rate of water absorption, since a large kernel produce smaller surface area per unit mass [7].

3.2. Saturation Moisture Content (SMC) and Diffusion Coefficient (D_f)

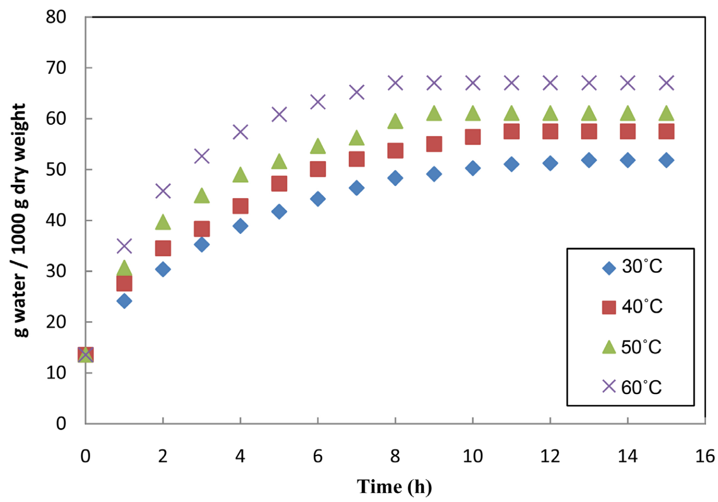
Water absorption curves of dry kernels at four soaking temperatures are presented in Figures 1(a)-(c).

Table 1. Moisture content and physical properties of selected local maize grown in Ghana.

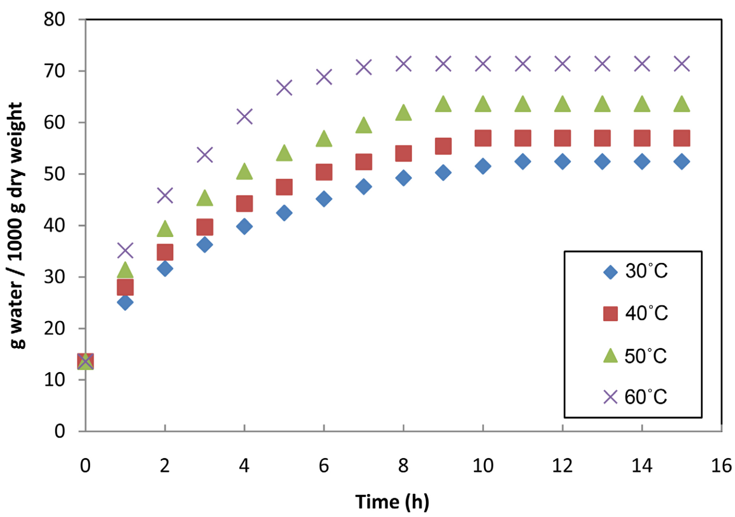
Cereal	Moisture content (% db)	Length (mm)	Width (mm)	Thickness (mm)	Radius (mm)	surface Area (mm²)
Abotem	12.13	10.10	8.61	4.50	3.91	527.62
Abeleehi	12.60	11.40	8.80	4.00	3.93	537.34
Dorke SR	13.49	10.50	8.50	4.30	3.86	521.21



(a)



(b)



(c)

Figure 1. (a) Water absorption characteristics of *Abotem*; (b): Water absorption characteristics of *Abeleehi*; (c): Water absorption characteristics of *Dorke SR*.

Characteristically, the samples showed a normal moisture absorption behaviour. The initial water absorption was rapid, and was followed by a slower rate before it asymptotically reached the SMC at later stage. The SMC was reached at 12 h for water temperature of 30˚C but the soaking duration was reduced to 8 h when the temperature was raised to 60˚C as shown in **Table 2**.

The water absorption rate of the kernels increased as soaking temperature increased. A. Addo *et al.* [4] generated similar curves for two varieties of maize—*Obatanpa and Mamaba*. Studies by [13] [17] and [18] documented similar curves when they investigated the soaking behaviour of red kidney beans, wheat, selected Turkish legumes, and barley respectively.

As the soaking temperature increased, water absorption capacity also increased for all the hybrids although the extent and rates of increment were not the same. This could be attributed to differences in chemical composition of the hybrids used. This assertion is in line with reports by other researchers such as [19] and [20] after they studies on water absorption behaviours of rice. *Dorke SR* recorded a relatively higher moisture gain at most of the temperatures. This may be due to higher carbohydrate as reported by [4]. *Abotem* recorded the lowest moisture gain at 30˚C and 40˚C whiles *Abeleehi* recorded the lowest moisture gain at temperature 60˚C. The rate of water uptake was influenced by temperature. The greater the soaking temperature, the higher the absorption rate due to increased rate of diffusion. The temperature effects reported in this study agrees with other published studies [4] [13] [15] [19] [21] [22]. S. M. Shafaei *et al.* [23] made similar observation when they studied water absorption behaviours of chickpea and soybean.

J. Tang *et al.* [24] indicated that small kernels have larger water absorption capacity because of an increased specific surface area available for absorption. This phenomenon was exhibited in the present study.

Dorke SR, with a smaller kernel size compared to *Abeleehi, and Abotem* had a higher absorption capacity of water as expected. On the contrary, *Abeleehi* kernel is relatively larger and should have had lower water absorption capacity, but had the highest water absorption capacity at 40˚C. The current observation may be attributed to nutrient composition differences and the severity of dis-orderness resulting from differences in levels of temperature treatment. The present

Table 2. Saturation moisture contents (M_s) and diffusion coefficients (D_f) of selected local maize grown in Ghana.

Maize	30			40			50			60		
	D_f*	R^2	M_s	D_f*	R^2	M_s	D_f*	R^2	M_s	D_f*	R^2	M_s
Abotem	2.54	0.97	50.17	2.76	0.98	55.09	3.61	0.98	63.21	3.49	0.94	68.20
Abeleehi	2.64	0.97	51.85	2.96	0.98	57.52	3.12	0.98	61.10	3.59	0.97	67.06
Dorke SR	3.21	0.98	52.41	3.34	0.98	56.96	3.67	0.99	63.66	4.20	0.98	71.44

*$\times 10^{-10}$ m^2/s, D_f: Diffusion coefficient, M_s: Saturation moisture contents.

observation suggest that *Abeleehi* may possibly have higher starch content than the other two maize hybrids. A. Addo *et al.* [4] documented similar pattern when they reported that higher starch content in *Obatanpa* was responsible for its higher water absorption capacity although *Obatanpa* kernel is bigger than *Mamaba*. This observation confirms earlier report by [25] who indicated that temperature and grain characteristics are the major factors influencing SMC values.

3.3. Water Absorption Rates of Selected Maise Hybrids

The generated data on water soaking of the maize hybrids were plotted against the square root of soaking time. Based on Equation (4), the effective water diffusivities of the hybrids during soaking were evaluated.

The SMCs used in Equation (4) and the evaluated values of D_f at various temperatures are presented in **Table 2**.

Generally, the experimental data for the grain component was able to fit the diffusion equation with high accuracy. The analysis of the linear regression is also presented in **Table 3**. The estimated values of coefficient of determination R^2 of 0.93 to 0.98 suggest that the experimental data fitted into the equation very well. The D_f for the hybrids varied from (2.54 - 3.49) × 10^{-10} m^2/s for *Abotem*; (2.64 - 3.59) × 10^{-10} m^2/s for *Abeleehi*; and (3.21 - 4.2) × 10^{-10} m^2/s for *Dorke SR*. The D_f values documented by [4] for *Mamaba* and *Obatanpa* varieties are lower than values obtained in this study. Kernel's physical characteristics, internal structure, physiochemical and nutrient composition may have accounted for the differences. This observation confirms earlier findings of other researchers such as [4] and [26]. In addition, earlier report by [27] indicated that physiochemical and nutritional components as well as amylose content play key role in predicting rate of moisture gain in rice.

The rates of water absorption in *Abotem*, *Abeleehi*, and, *Dorke SR* are illustrated in **Figures 2(a)-(c)**.

The figures indicate that increasing soaking temperature produces a higher water absorption rate. This phenomenon may probably be due to the increased temperature resulting in more open structures which favoures rapid hydration. Also, the figures show the existence of linear relationship between moisture increase and the square root of time (**Time$^{1/2}$**) during water absorption. This observation confirms earlier report by [28] that the rate of water absorption is a function of time and temperature.

Table 3. Activation energy (*Ea*) of water diffusion during soaking of selected local maize grown in Ghana.

Legume	*Ea* (kJ/mol)	Coefficient of Determination (R^2)
Abotem	9.09	0.98
Dorke SR	7.50	0.93
Abeleehi	8.27	0.98

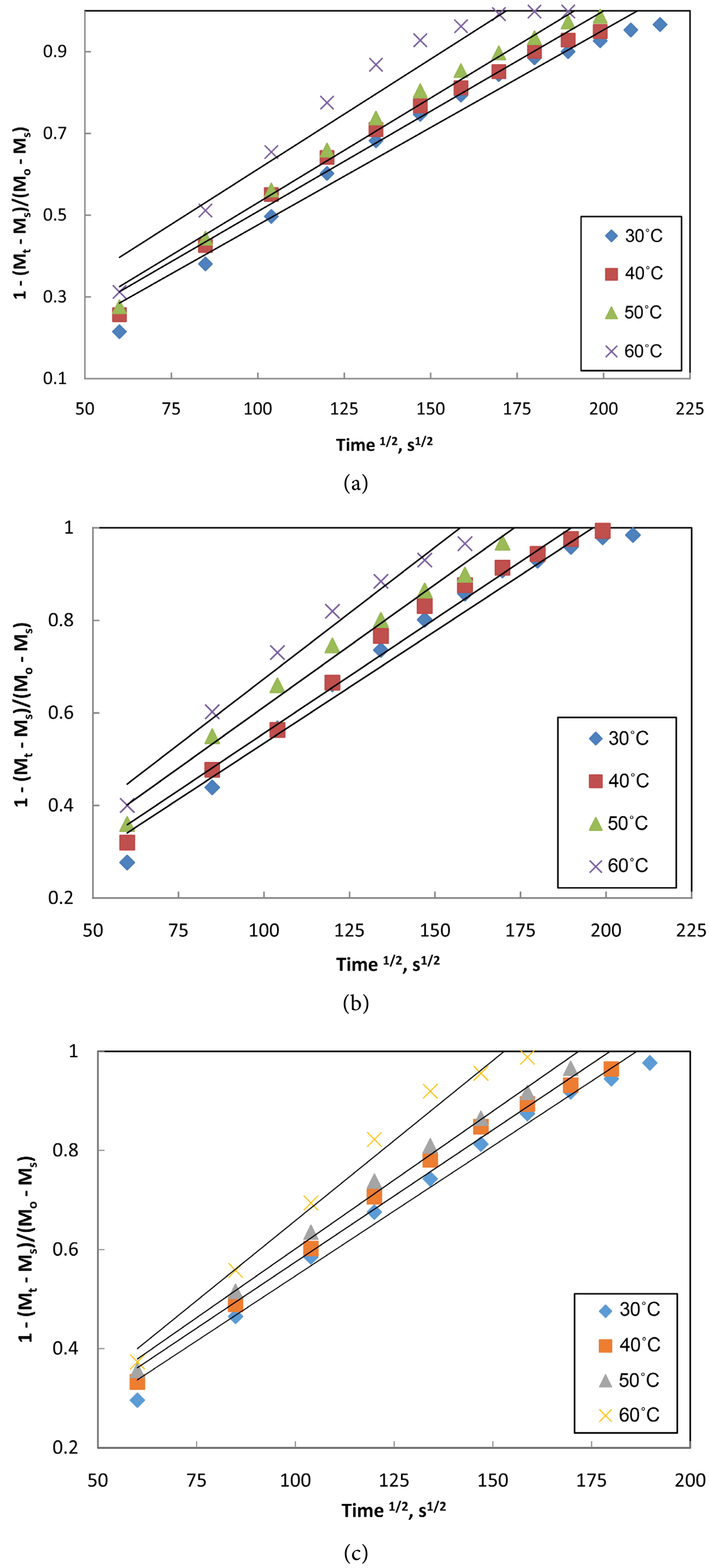


Figure 2. (a) Water absorption rate for *Abotem*; (b): Water absorption rate for *Abeleehi*; (c): Water absorption rate for *Dorke SR*

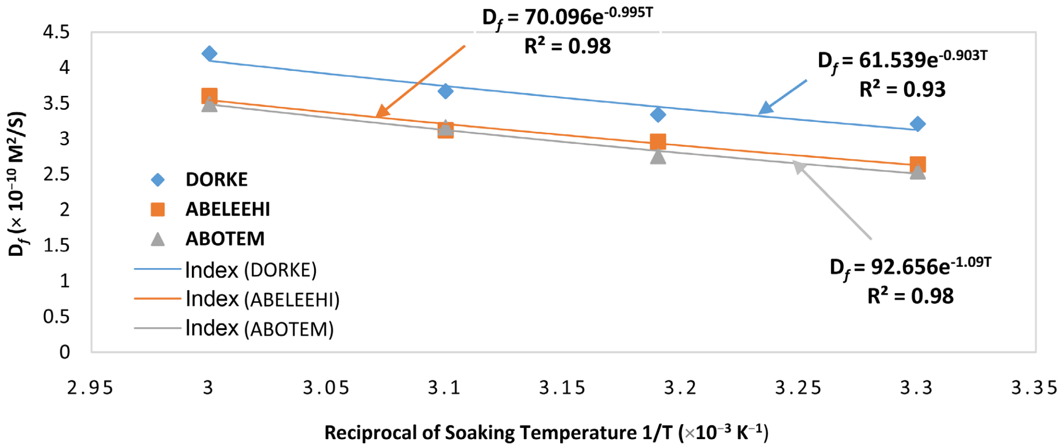


Figure 3. Relationship between diffusion coefficient (D_f) and temperature (T) for *Abotem Abeleehi and Dorke SR*.

4. Activation Energies (*Ea*) of Maize Hybrids

The D_f of *Abotem*, *Abeleehi* and *Dorke SR* hybrids were fitted to an Arrhenius-type equation (Equation (5)). The relationship between D_f and reciprocal of the temperatures are presented in Figure 3.

Figure 3 illustrated that Arrhenius-type equation sufficiently described the temperature effect on water absorption during soaking of *Abotem*, *Abeleehi*, and *Dorke SR*.

From Table 3, the *Ea* values as estimated from the curves, for *Abotem*, *Abeleehi*, and *Dorke SR* were 9.09; 8.27 and 7.50 kJ/mol respectively. The results show that the Ea of *Dorke SR* was relatively smaller. This may probably be due to small surface area of kernel. The higher Ea value recorded by *Abotem* gave an indication that temperature influence on *Abotem* was greater as higher *Ea* correspond to greater influence of temperature.

The *Ea* values reported in current study were similar to the one published by [4] for *Obatanpa* (6.54 kJ/mol) and *Mamaba* (6.82 kJ/mol). The value obtained for Dorke SR (7.60 kJ/mol) is also similar to the results documented by [29] for *Asontem* (7.27 kJ/mol); *Hewale* (7.26 kJ/mol); and *Asomdwee* (6.26 kJ/mol) of cowpea varieties. In contrast, *Ea* values observed in this study were significantly lower than other reported values. Verma and Prasad [9] and O. Bolaji *et al.* [30] reported Ea range of 33.5 - 41.56 kJ/mol and 31.49 - 96.06 kJ/mol for certain varieties of maize respectively.

5. Conclusion

The water absorption characteristics of maize hybrids, *Abotem*, *Abeleehi* and *Dorke SR* were investigated using models derived from Fick's second law of diffusion. The time of reaching SMC during soaking was reduced from 12 h to 8 h as the soaking temperature increased from 30˚C to 60˚C. Experimental data fitted into Fick's law of diffusion satisfactorily and was able to simulate and predict water absorption during soaking of *Abotem*, *Abeleehi*, and *Dorke SR* hybrids.

The values of D_f for *Abotem*, *Abeleehi*, and *Dorke SR* ranged from (2.54 - 3.49) × 10^{-10} m^2/s; (2.64 - 3.59) × 10^{-10} m^2/s and (3.21 - 4.2) × 10^{-10} m^2/s respectively. The effect of temperature on D_f was sufficiently described by Arrhenius-type equation with *Ea* values of 9.09 kJ/mol; 8.27 kJ/mol and 7.50 kJ/mol for *Abotem*, and *Dorke SR* respectively. Temperature had greater influence on *Abotem* variety as compared to *Dorke SR* and *Abeleehi*. Surface area and Temperature played a key role in water absorption rate of the cereals. Data presented in the current study on effective water diffusivity for the selected hybrids can help in better understanding and designing of equipment and sorption process

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare that there was no conflict of interest in respect to the publication of this article.

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