Application of Peleg's Equation to Model Water Absorption in Sorghum and Millet During Tempering

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ABSTRACT

Sorghum and millet water absorption characteristics at temperature range 20 to 50°C were investigated using the Peleg's model or equation. Two sorghum varieties and one pearl millet variety were used in this investigation. Water absorption characteristics of the grain were investigated by soaking samples of the grain in distilled water at temperatures of 20, 30, 40 and 50 °C and determining the amount of water absorb after every one hour soaking duration. The data obtained was compared to the one predicted by Peleg's model. The model was able to predict the hydration process adequately within the temperature range studied. Peleg's constant K_1 was found to be inversely related to soaking temperature while Peleg's constant K_2 was unaffected by the soaking temperature. Temperature dependency of the reciprocal of K_1 was investigated using the Arrhenius function. The activation energy for sorghum and millet during tempering was found to be in the range 24.6 - 39.5 $kJmol^{-1}$. Based on the Peleg's model and Arrhenius function, a general model for prediction of water absorption in sorghum and millet at any specified temperature was developed. The developed model was able to simulate the experimental data very well.

KEY WORDS: modelling, water absorption, Peleg's model, sorghum and millet

1.0 INTRODUCTION

Soaking is an important pre-conditioning step in grain processing operations depending upon its end use. The grain is soaked in order to bring it to the desired moisture level so that further processing steps can be enhanced or carried out more efficiently. In some operations such as dehulling, it is beneficial to wet or soak the grain for a short period, normally referred to as tempering. This process allows water to penetrate only the outer bran layer so that the texture of this layer is changed and the adhesion of this layer to the underlying endosperm is reduced and hence its removal in the dehulling operation become much easier. Usually, a trial and error method is adopted to determine the optimum soaking duration or the amount of water to be added.

There have been many attempts directed towards analyzing hydration data and modes of water transport in cereal grains. Liquid diffusion models for drying have been reported for wheat (Becker and Sallans, 1955; Jaros *et al.*, 1992), soybeans (Haghighi and Segerlind 1978) and paddy (Steffe and Sing, 1980; Lu and Siebenmorgen, 1992). Most of these analyses were based on the Fick's laws of diffusion (Cranks, 1975). These laws involve numerous functions and parameters, which make it very difficult to describe the water absorption process in simple terms. In an attempt to simplify the analysis of water absorption in food grains, a two parameter non-exponential empirical model was developed by Peleg (1988) and became known as the Peleg's model or equation. Peleg's model is a simple empirical mathematical model of water absorption during soaking of food grains. The main interest in this model lies in its simplicity compared to other models and its ability to accurately predict water uptake. The applicability of Peleg's model has been demonstrated for some food grains such as soybeans, cowpeas, and peanuts (Sopade and Obekpa 1990), chickpea and field peas (Hung *et al.*, 1993), and showed to agree well with the experimental data.

Soaking or tempering is an important pre-treatment in sorghum and millet dehulling process, especially in traditional dehulling system. The water absorption characteristics of these two grains during tempering are not well known. Sopade *et al.* (1992) investigated the soaking characteristics of different cereal grains including maize, soybeans and cowpeas. However, as soaking conditions vary depending upon the particular grain under study and the conditions under which soaking is carried out, for practical application, it was necessary to carry out investigation to asses the suitability of the Peleg's model in modelling the sorption characteristics of sorghum and millet during tempering at different temperatures. The objectives of this paper were therefore, (i) to examine the capability of Peleg's model in modelling the water absorption behaviour of sorghum and millet during tempering process and (ii) to develop a general model, which can describe and predict water absorption in sorghum and millet during tempering at different temperatures.

Peleg's model

Peleg's model or equation can be expressed as:

$$M = M_0 + \frac{t}{K_1 + K_2 t} \quad \text{.......... 1}$$

where M is moisture content at time t (% db), t is the soaking duration (h), M_o is the initial moisture content (% db), K_1 and K_2 are constants.

Equation (1) can be rearranged to:

$$\frac{t}{M - M_0} = K_1 + K_2 t \quad \text{.......... 2}$$

Plotting $\frac{t}{(M - M_0)}$ against t and fitting a straight line gives K_1 as the y-intercept, and K_2 as the gradient of the fitted line. Such a plot apart from testing the applicability of the model to the given absorption data, also allows the effect of temperature and other parameters on the values of the constants to be studied. Sopade and Obekpa (1990) observed that K_1 is a function of temperature and K_2 is a constant for a particular food material and, hence, could be used as a characteristic sorption parameter. It appears that K_1 could be linked to a diffusion coefficient, although K_1 decreases, rather than increases as temperature increases.

An Arrhenius type function can be used to describe the temperature dependence of the reciprocal of constant K_1 in the following manner

$$\frac{1}{K_1} = K_0 \exp\left(-\frac{B_P}{T}\right) \quad \text{.......... 3}$$

where K_0 is a constant, $B_P = E_a R'$, E_a is the activation energy (Jmol^{-1}), R is the gas constant (J kg^{-1}mol^{-1} K^{-1}), T is the absolute temperature (K).

From equation (3) the activation energy of the process can be determined and the temperature sensitivity of the constant assessed, thus giving an indication of the temperature sensitivity of the sorption characteristics of the test sample.

2.0 MATERIALS AND METHODS

Two sorghum varieties namely, *Dionje* (white seed coat, hard endosperm variety from Tanzania) and *Jumbo* (brown seed coat, soft endosperm variety from Australia) and one pearl millet variety (*IM*, from India) were used for water absorption experiments. Foreign matter, broken, cracked, and damaged grains were manually separated and discarded. Experimental samples were then taken using the quartering procedure. The official methods of the Association of American Cereal Chemists (AACC) were used to determine the proximate composition of the test samples (AACC, 2000). Physical properties of the grain such as weight of 1000 grain kernels, major and minor diameter values were also determined for each grain variety.

Water absorption characteristics of sorghum and millet were investigated by soaking 5g samples in beakers containing 20ml of distilled water. The soaking temperatures studied were 20, 30, 40, and 50^{0}C. The beakers containing the samples were placed in a thermostatically controlled water bath fixed at the required soaking temperature ($\pm 1\ ^0$C). Moisture absorption over a period of up to 10 hours was determined. After every one hour soaking duration, the grain samples were removed from the soaking water, quickly blotted with a paper towel to remove surface water and weighed, the increase in weight being taken as the amount of water absorbed during the given soaking period. After weighing the grain was quickly returned into the soaking water. All samples were studied in triplicate and the average moisture gain converted to percent moisture content on wet basis.

3.0 RESULTS AND DISCUSSION

The physical properties and proximate composition of the grain used in this investigation are given in Table 1. Millet had the smallest grain size and was conical in shape (pear shaped), while the sorghum grains were bigger in size and approximately spherical. The values of proximate composition obtained were all within the range of values given in literature for these grains (Serna-Saldivar and Rooney, 1995).

Table 1. Proximate and physical characteristics of sorghum and millet grains

Parameter	*Dionje*	*Jumbo*	*IM*
Moisture content (% db)	12.30	12.01	11.97
Crude protein (N×6.25)	9.06	13.06	10.18
Crude fat (%)	2.85	4.19	5.47
Crude fibre (%)	4.81	6.12	7.17
Ash (%)	1.95	1.66	1.98
Carbohydrates (%)[a]	69.04	62.98	63.23
1000 grain weight (g)	30.10	33.47	14.37
Major diameter (mm)	4.96	5.27	3.56
Minor diameter (mm)	3.87	4.24	2.48
Thickness (mm)	2.23	2.58	2.47

[a] by difference

All three-grain varieties investigated exhibited a characteristic moisture sorption behaviour (Figure 1), with an identical initial high rate of water absorption followed by a slower absorption rate in the later stages. Similar curves were obtained by Hsu (1984) during the soaking of soybeans, Engels *et al.* (1986) during soaking of rice, and Becker (1960) during the soaking of wheat. This characteristic shape of the absorption curve could be due to the filling of the capillaries on the surface of the seed coat and hilum, resulting in high absorption rate at the initial stages of soaking (Hsu 1983). As the process of water absorption proceeded, the soaking rate slowly declined due to the filling of free capillaries and intercellular spaces within the grain kernel. Subsequently, the amount of water absorbed during further soaking stages became smaller and smaller until equilibrium was attained.

The amount of water absorbed increased with the increase in temperature for all grain varieties investigated (Fig. 1). Temperature has also been reported to have a significant effect on the rate of moisture absorption during soaking of other grains such as soybeans (Hsu, 1984), and rice (Steffel and Singh, 1980; Engels *et al.*, 1986). The increase in absorption rate might have been due to an increase in water diffusion rate as temperature increased.

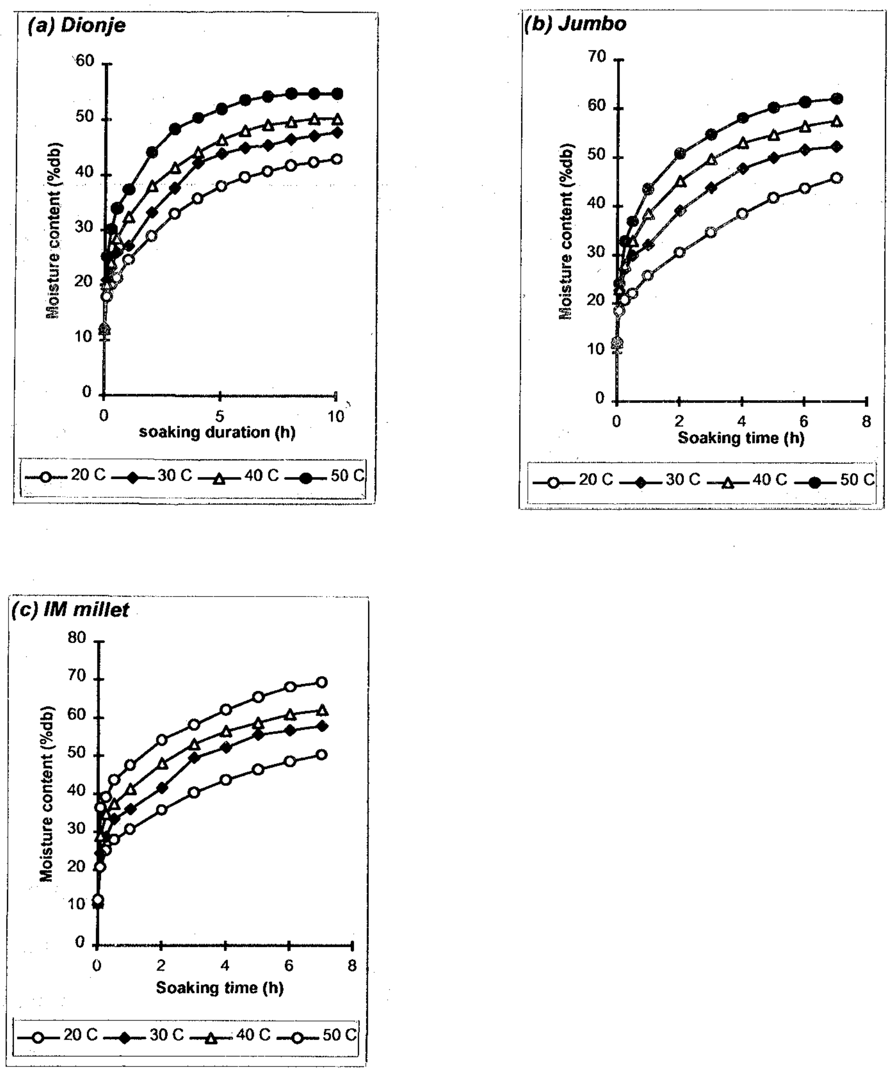

Figure 1. Water absorption characteristics of sorghum and millet during soaking at different temperatures

However, irrespective of temperature increase, millet had the highest water absorption rate followed by *Jumbo* (soft sorghum variety) and *Dionje* (hard sorghum variety) had the least. This chronological order may have been caused by the physical as well as chemical properties of the grains. Millet, being the smallest in size, had the largest surface area exposed to the diffusing liquid and hence was able to absorb more water than *Jumbo* and *Dionje* despite having lower protein content than *Jumbo*. *Jumbo*, being softer than

Dionje, had more loosely packed structure and hence more spaces to absorb moisture than *Dionje.*

The fit of the experimental data in fig. 1 by Peleg's model is shown in figures 2(a), (b) and (c) for *Dionje*, *Jumbo* and *IM* millet, respectively. The linear regression analysis parameters for the fitted lines are given in Table 2. The coefficient of determination, (R^2) varied between 0.992 to 0.999 indicating a very good fit between the model and experimental data for all the three grain varieties within the temperature range investigated in this study. It was also observed that Peleg's constant K_2 was fairly constant within the temperature range investigated (the difference between different temperatures was not statistically significant at P<0.5). On the other hand, K_1 decreased as temperature increased (Table 2). The results are in good agreement with observations from previous researchers like, Sopade and Obekpa (1990) for soybeans and cowpea and Abu-Ghannam and McKenna (1997) for red kidney beans.

Table 2. Value of the constants in Peleg's equation for sorghum and millet at different temperatures

Grain Type	Soaking temperature (^{0}C)	K_1	K_2	Mean K_2	R^2
(a) Sorghum					
Dionje	20	0.069	0.024		0.999
	30	0.045	0.023	0.0229	0.996
	40	0.030	0.023		0.997
	50	0.021	0.021		0.998
Jumbo					
	20	0.068	0.020		0.997
	30	0.034	0.019	0.0192	0.995
	40	0.021	0.019		0.999
	50	0.015	0.018		0.999
(b) Millet					
IM	20	0.039	0.020		0.992
	30	0.027	0.018	0.0180	0.995
	40	0.019	0.018		0.998
	50	0.016	0.017		0.995

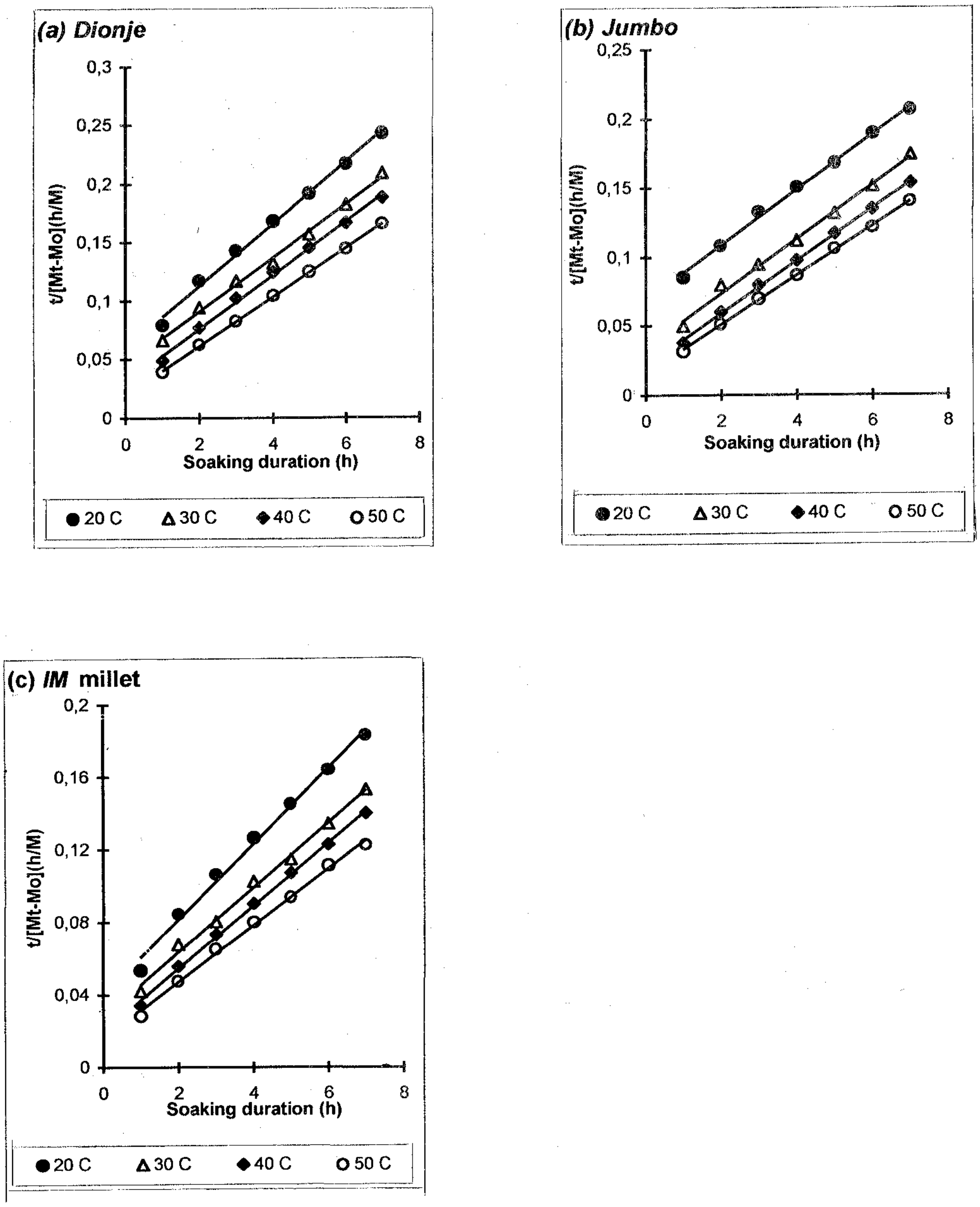

Figure 2. Fit of experimental moisture absorption data of sorghum and millet by Peleg's model

Previous studies by Sopade *et al.* (1992) and Hung *et al.* (1993) have shown that Peleg's constant K_1 was a temperature dependent constant. As shown in Table 2, for all three grain varieties, K_1 was inversely related to temperature. Previous analyses of water uptake in cereal and legumes by Hsu 1984 and Becker 1960 established that temperature affects the diffusion of moisture in grain according to the Arrhenius law, with activation energies ranging from 12.6 - 50.4 kJ mol^{-1}, depending on the type and variety of the grain. The temperature dependency of K_1 in this study was modeled as an Arrhenius type function (equation 3) and the relationship between $ln(K_1^{-1})$ and T^{-1} is shown in Fig. 3. The good fit of a linear regression (R^2 = 0.98 - 0.99) indicates that $1/K_1$ is an Arrhenius function of temperature. The values of activation energy calculated from the obtained equations were 31.7, 39.5 and 24.6 kJ mol^{-1} for *Dionje*, *Jumbo* and millet respectively. These values are within the range of activation energies quoted by Hsu (1984), i.e. 12.6 - 50.4 kJ mol^{-1} for different cereal grains during moisture absorption.

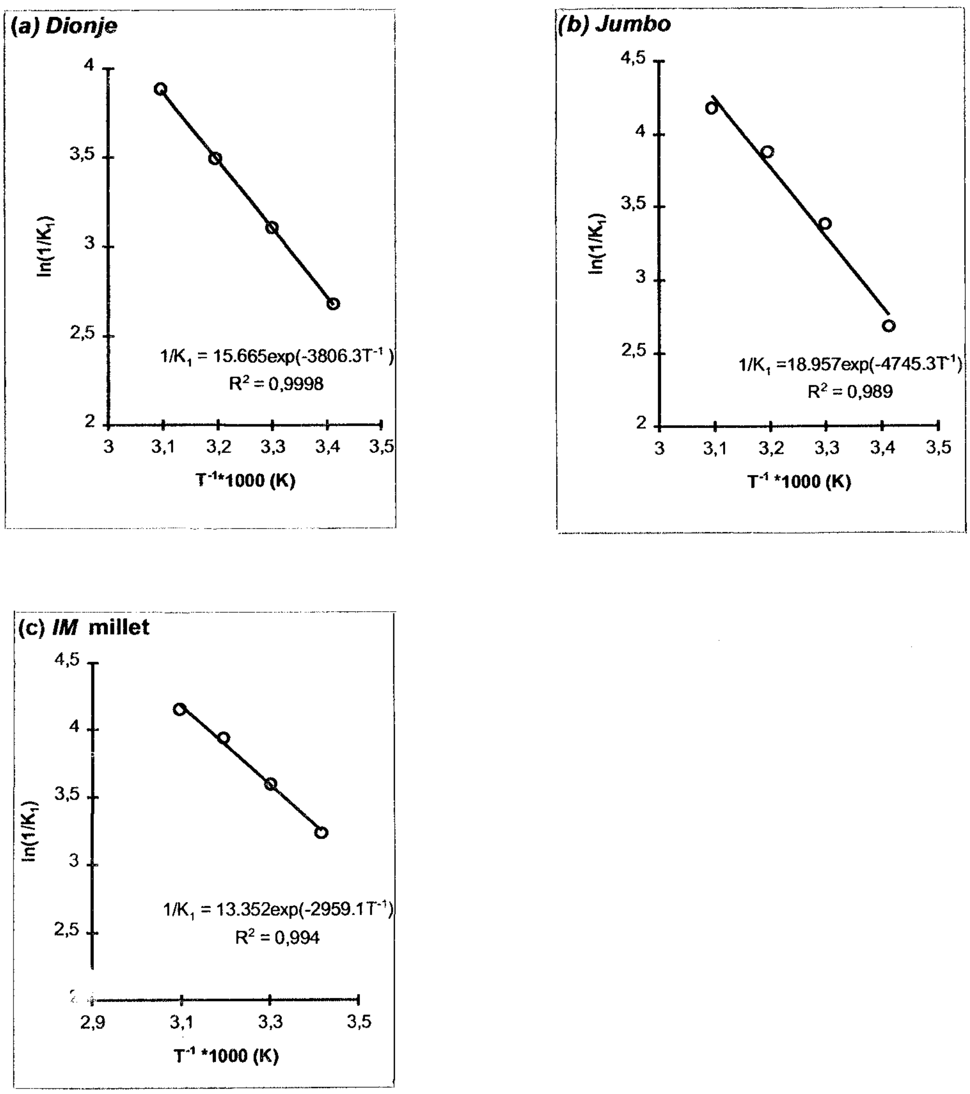

Figure 3. The effect of temperature on Peleg's K1 constant during tempering of sorghum and millet

From Peleg's equation, the units of K_1 are hour per percent weight, the units of $1/K_1$ will therefore be percent weight per hour, hence, the sensitivity of the reciprocal of K_1 to temperature could give an indication of the temperature effect on the rate of water absorbed and how critical temperature control needs to be during moisture absorption process.

Development of predictive equations for modelling water absorption in sorghum and millet at different temperatures

Peleg's model is only applicable for moisture absorption at a specified temperature, in order to develop a model, which could be used to predict water uptake or tempering duration in sorghum and millet during tempering at any temperature within 20 - 50^{0}C temperature range, Peleg's model was modified to include a temperature factor. This was achieved by combining Peleg's model (equation 1) and Arrhenius function (equation 3) to give the following general model:

$$M = M_0 + \frac{t}{\frac{1}{K_0} e^{\frac{B_p}{T}} + K_2 t} \qquad \ldots\ldots\ldots\ldots 4$$

Which can be simplified to;

$$M = M_0 + \frac{K_0 t}{e^{\frac{B_p}{T}} + K_2 K_0 t} \qquad \ldots\ldots\ldots\ldots 5$$

The values of K_o and B_p were obtained from the Arrhenius fit of $1/K_l$ on temperature in Fig. 2. For individuals grain varieties the following equations were derived

(i) *Dionje*: $M = M_0 + \frac{15.7t}{e^{\frac{3.806}{T}} + 0.36t}$ ………… 6

(ii) *Jumbo*: $M = M_0 + \frac{18.95t}{e^{\frac{4.745}{T}} + 0.36t}$ ………… 7

(iii) Millet: $M = M_0 + \frac{18.35t}{e^{\frac{2.959}{T}} + 0.24t}$ ………… 8

where, t is the soaking time (h), T is soaking temperature (K), M is moisture content after time *(t)*, and M_o is the initial moisture content (% db).

The capability of the derived equations to simulate moisture absorption characteristics of sorghum and millet at different temperatures is demonstrated in Figure 4 for sorghum (*Dionje*) and Fig. 5 for millet (IM).

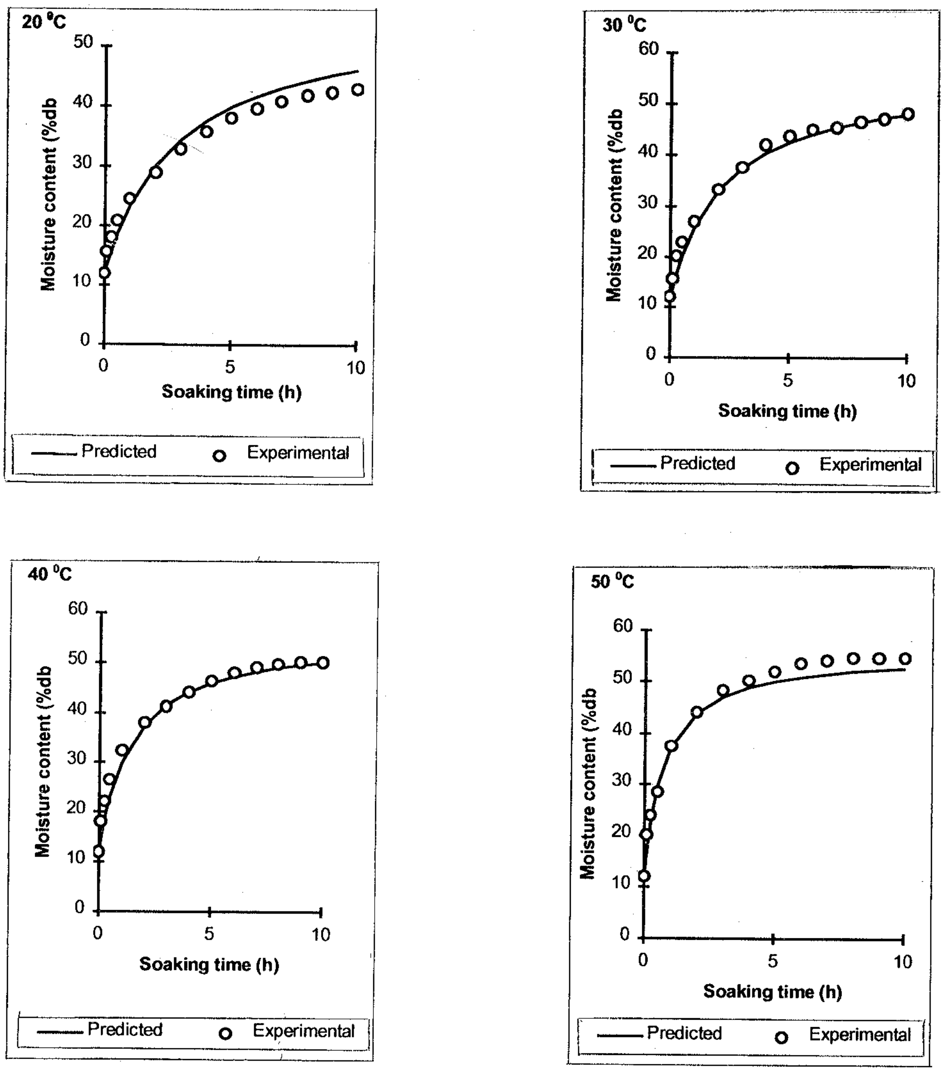

Figure 4. Experimental and predicted moisture content of sorghum (*Dionje*) at different temperatures using the derived general equation

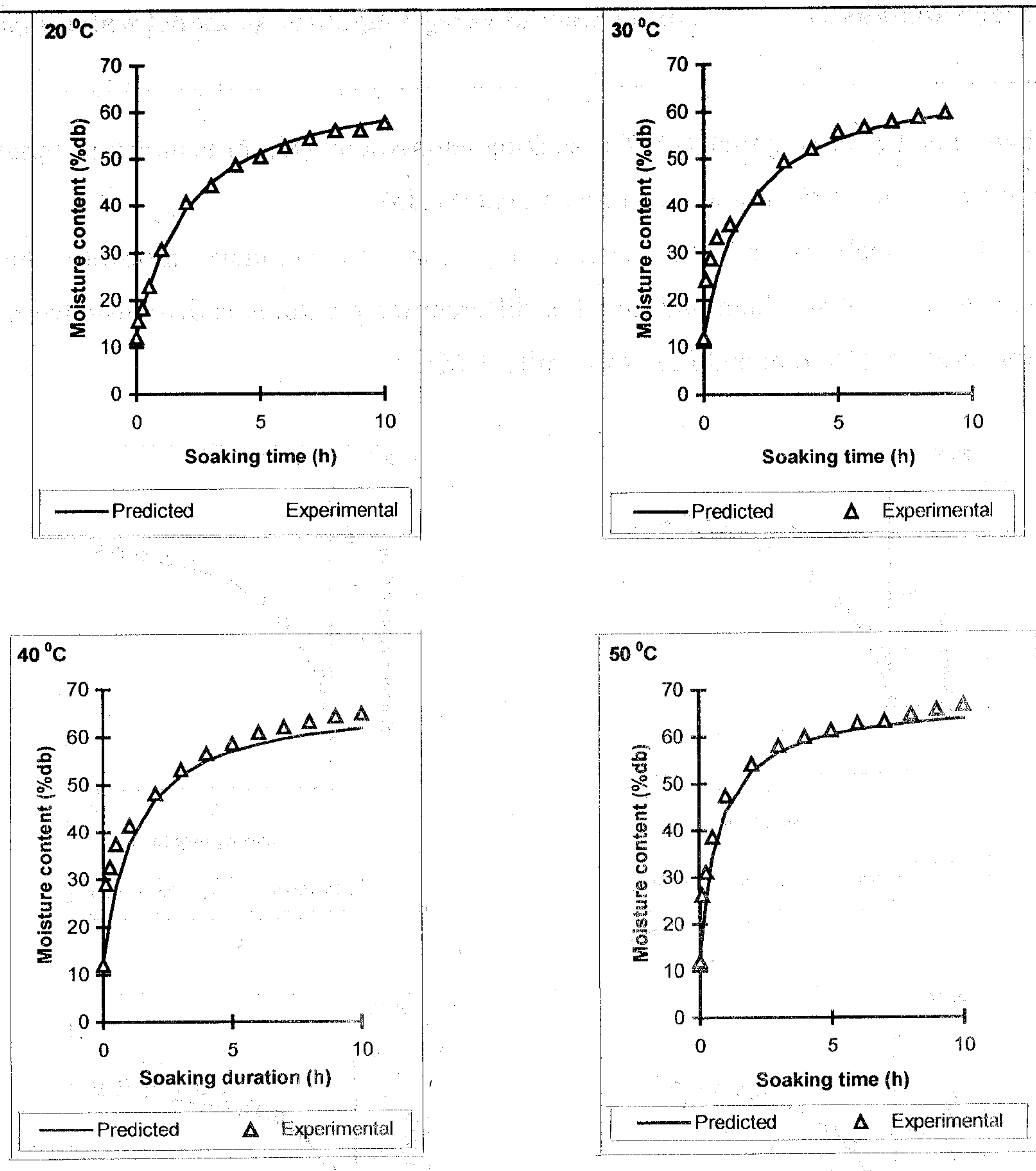

Figure 5. Experimental and predicted moisture content of millet (*IM*) at different temperatures using the derived general equation

The good quality of the fit obtained indicated that the derived equations could be used to model the soaking characteristics of sorghum and millet at different temperatures within the 20 to 50^{0}C temperature range. Thus, if the initial moisture content and the soaking duration are known, the moisture gain can be evaluated at any given temperature within this temperature range. Also, the tempering duration required to attain a given moisture content at a given temperature can also be estimated if the grain initial moisture content is known.

4.0 Conclusion

The results obtained from this investigation showed that Peleg's model could adequately be used to describe the soaking characteristics of sorghum and millet within the temperature range 20 to 50^0C. Also an Arrhenius type model could adequately be used to describe the temperature dependency of Peleg's K_1 constant.

A general model for prediction of soaking characteristics of sorghum and millet based on Peleg's equation was proposed. The proposed model could be used to predict accurately the amount of water absorbed at any specified temperature for a known soaking duration. The model can also be used in the determination of the soaking duration required to attain a given moisture content at a specified temperature. This could be of considerable practical value, because it provides a better method of determining the required tempering duration at a specific temperature instead of the current trial and error method.

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