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^{0}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 ^{0}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, $B_P = E_a R^{-1}$, 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 (±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.

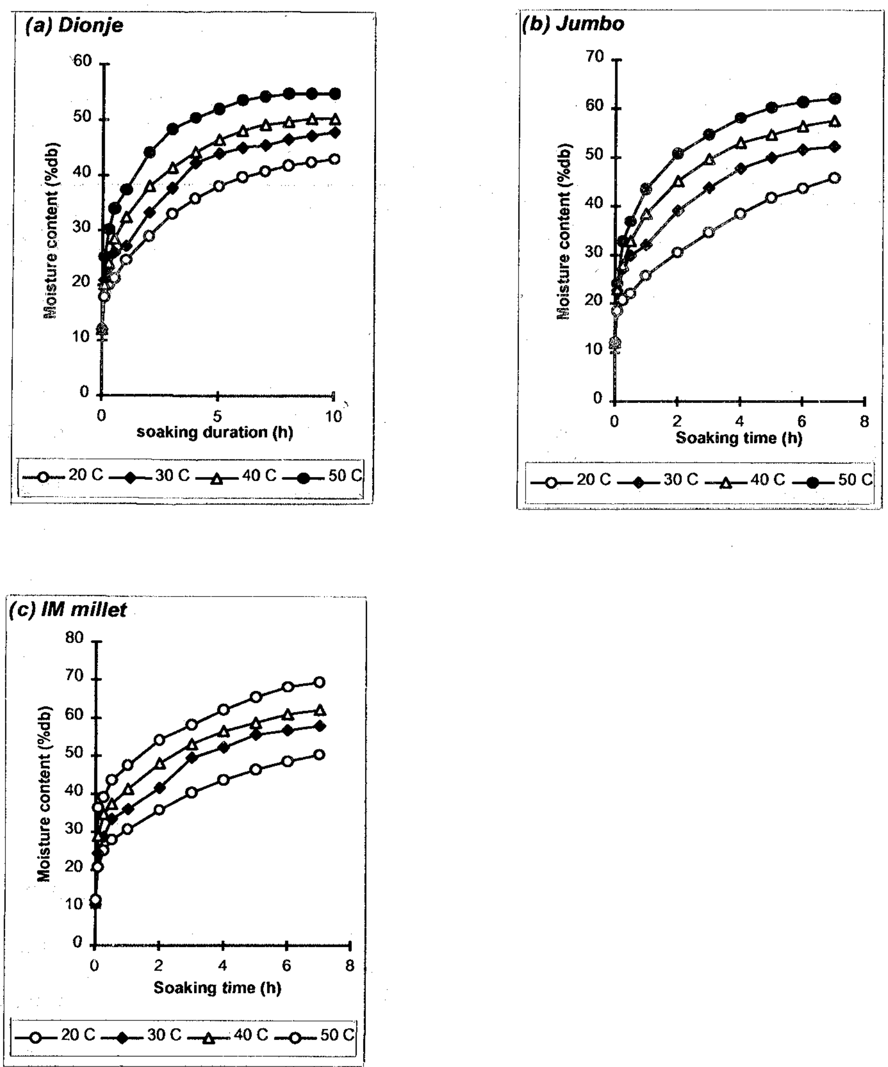

Figure 1. Water absorption characteristics of sorghum and millet during soaking at different temperatures

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 tọ 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

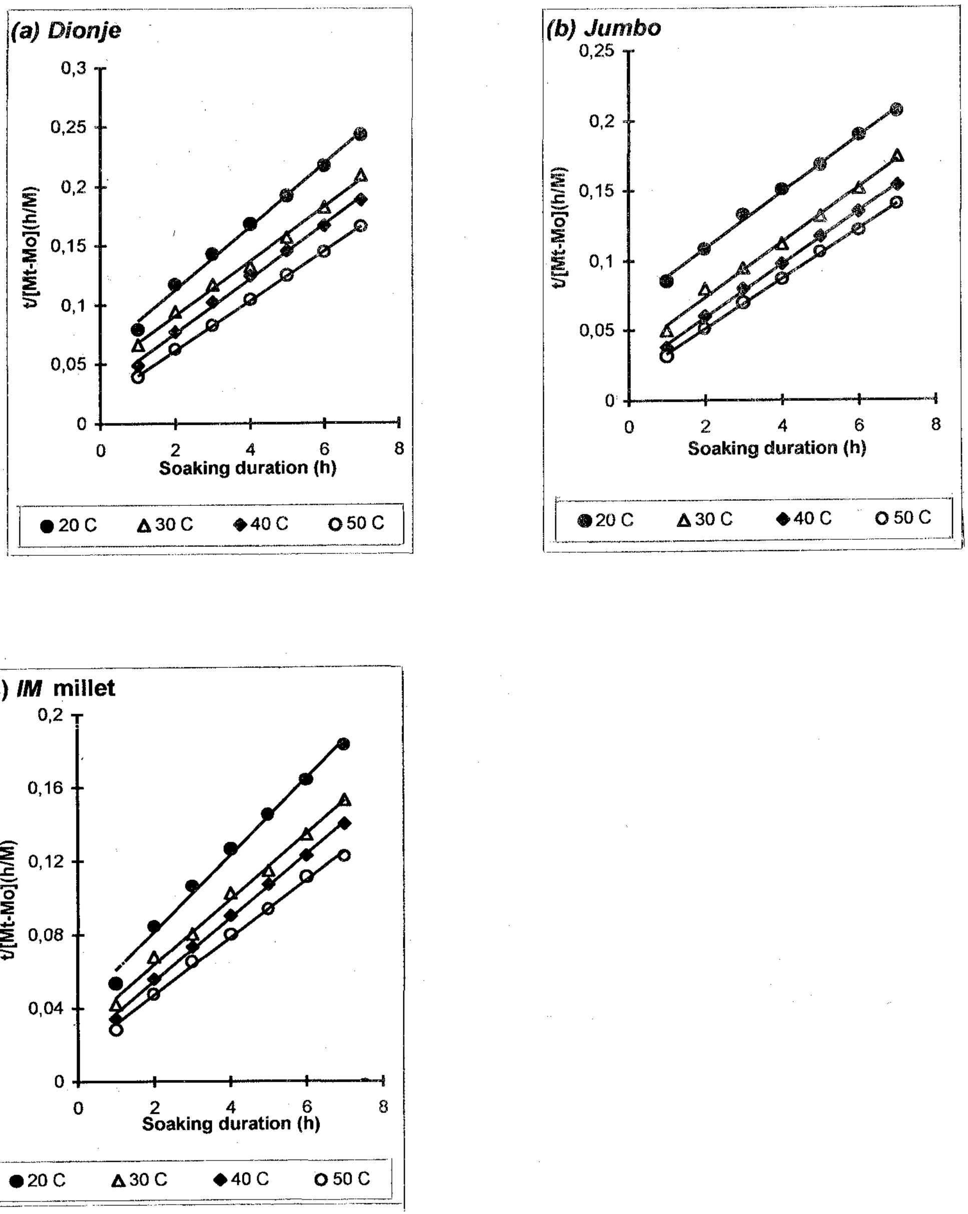

Figure 2. Fit of experimental moisture absorption data of sorghum and millet by Peleg's model

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.

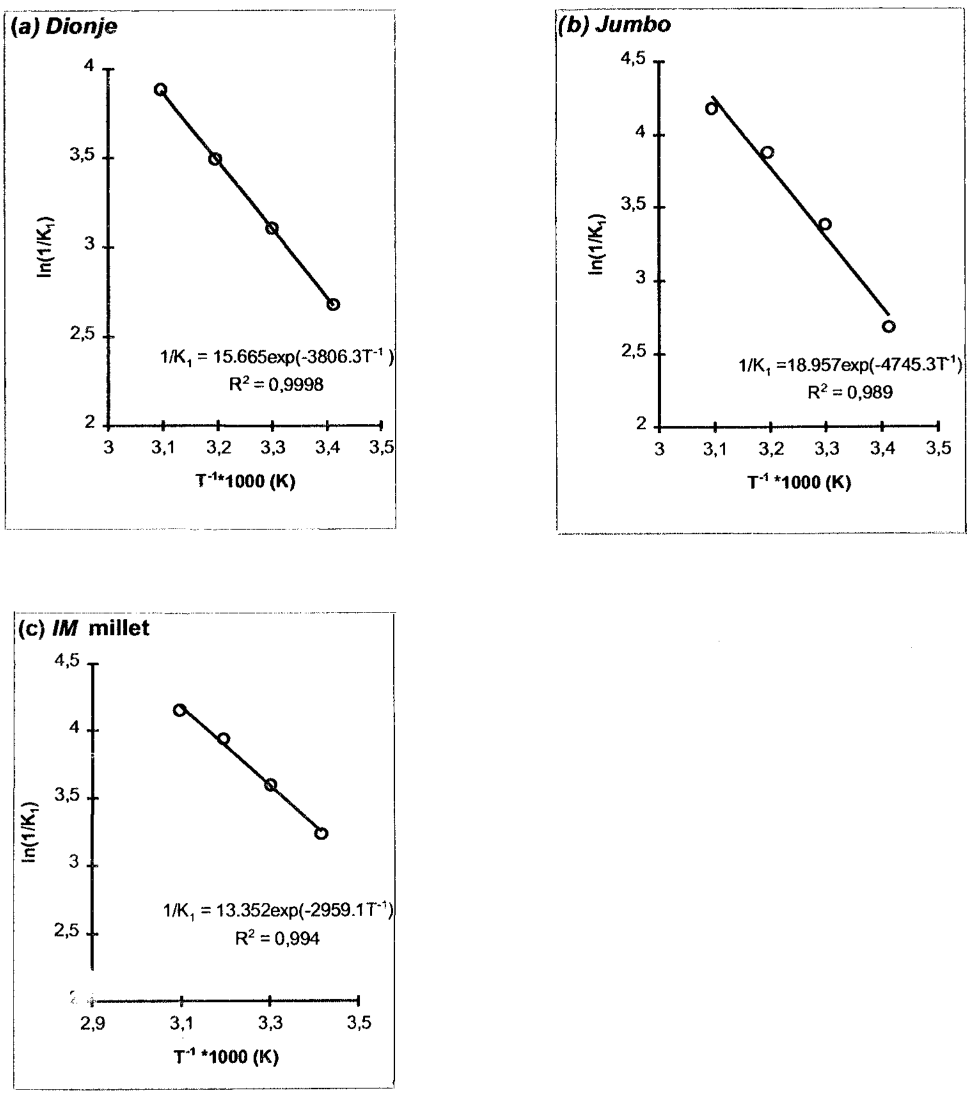

Figure 3. The effect of temperature on Peleg's K1 constant during tempering of sorghum and millet

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 - 50^0C 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:

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

Which can be simplified to;

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

The values of K_0 and B_p were obtained from the Arrhenius fit of $1/K_1$ 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).

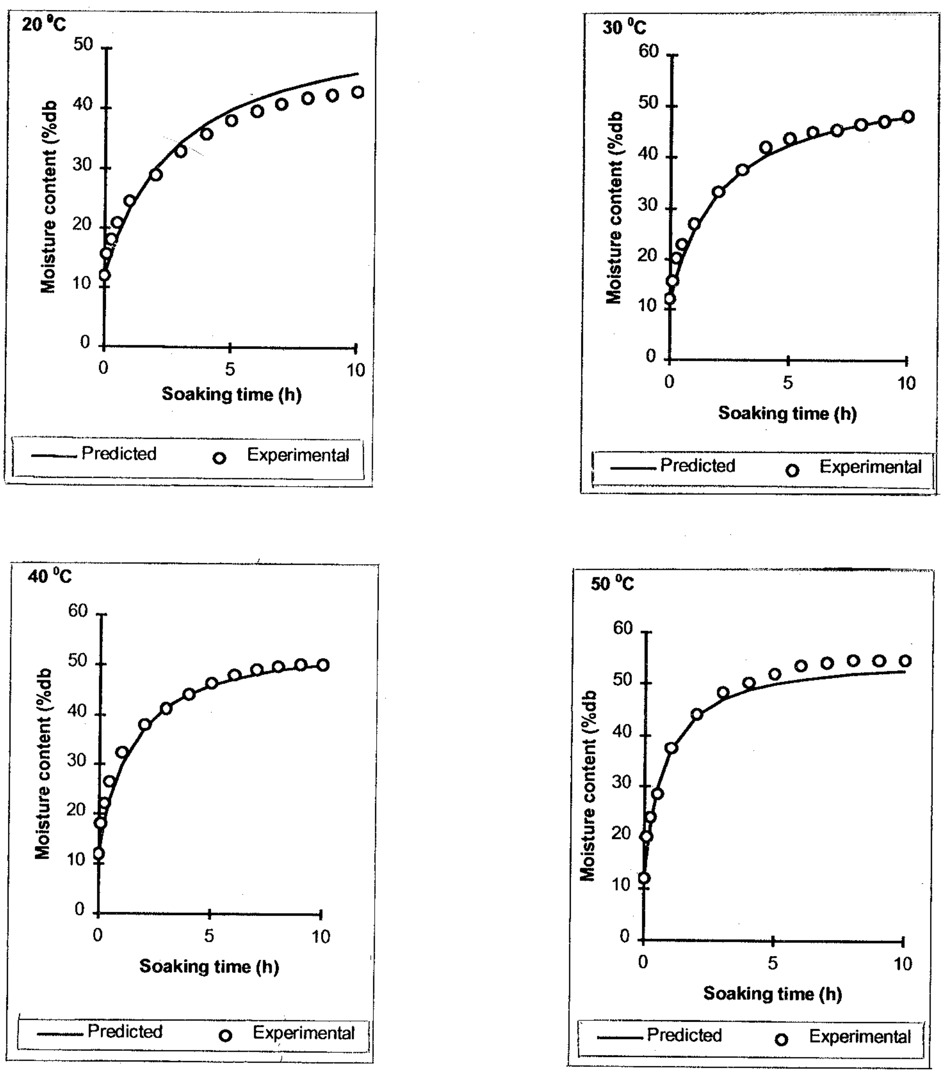

Figure 4. Experimental and predicted moisture content of sorghum (*Dionje*) at different temperatures using the derived general equation

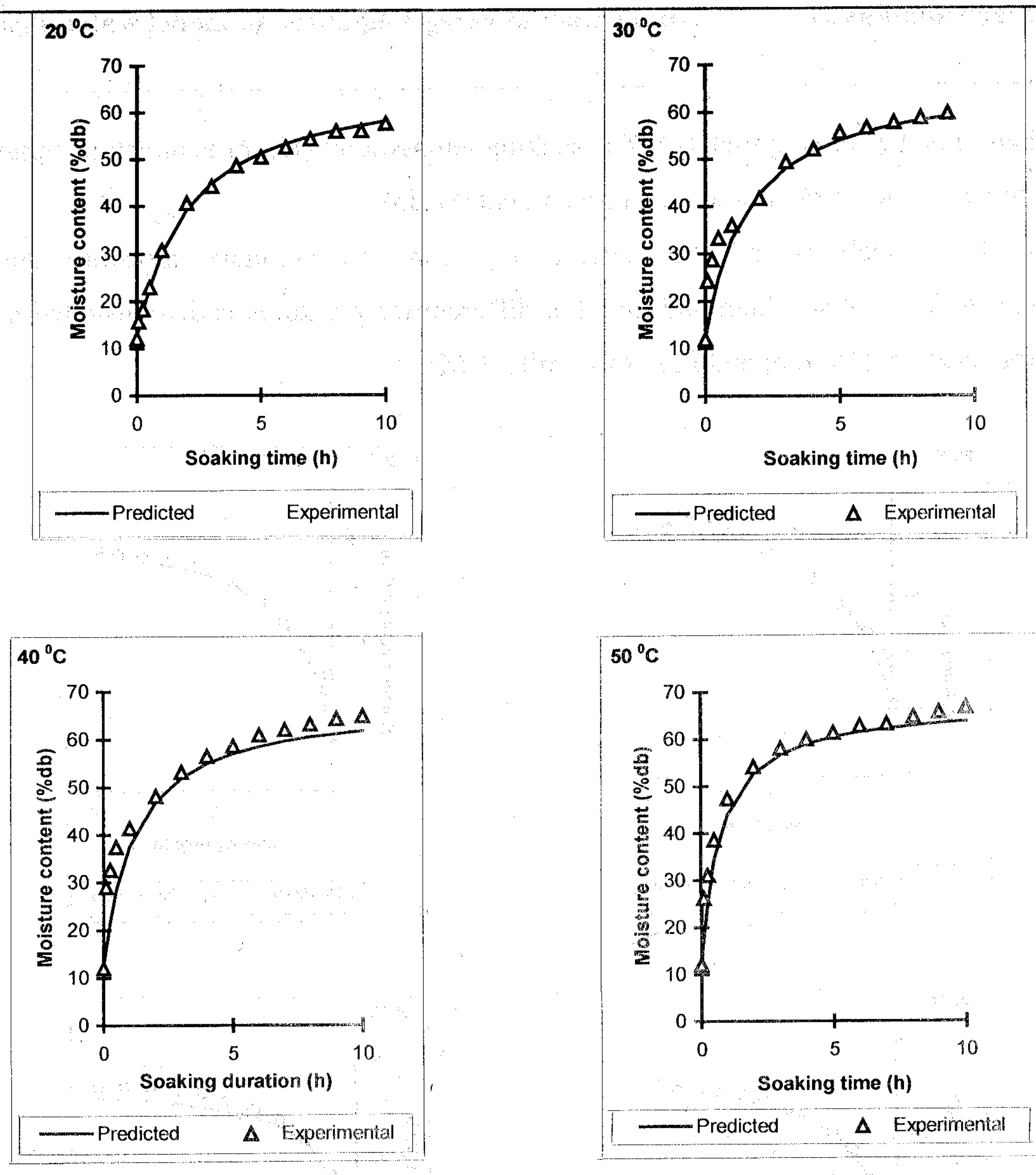

Figure 5. Experimental and predicted moisture content of millet (*IM*) at different temperatures using the derived general equation

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^{0}C. 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.

Acknowledgement

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Improvement of the Dehulling Efficiency of Sorghum and Millet using Hydrothermal Treatments

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ABSTRACT

Conditioning of grain with heat and moisture is known to loosen the adhesion of the seed coat from the endosperm and therefore improve the dehulling efficiency of some grains such as beans, cowpea and canola. This study investigated the effect of hydrothermal treatment on the improvement of dehulling efficiency of sorghum (Dionje and Jumbo varieties) and pearl millet (IM). Hydrothermal treatments investigated included, soaking the grain in distilled water, treating the grain with saturated steam for three different durations (5, 10, 15 minutes) followed by drying using either ambient air at 20^{0}C, or heated air at 60^{0}C. Abrasive dehulling of the pre-treated grain was accomplished using a Tangential Abrasive Dehulling Device (TADD). The effect of different hydrothermal treatments on the dehulling efficiency was evaluated based on the extent of seed coat removed and crude fibre reduction in the dehulled grain. Findings from this study showed that hydrothermal treatment of sorghum and millet improved the dehulling efficiency of Jumbo and Dionje sorghum varieties by an average of 10%, 7% respectively and pearl millet by 20% over unconditioned grain in terms of seed coat removal. In terms of crude fibre reduction in the dehulled grain, hydrothermal pre-treatments improved the dehulling efficiency by 14.5%, 27.3% for Jumbo and Dionje sorghum varieties respectively and by 13.7% for pearl millet over the unconditioned grain.

KEY WORDS: Sorghum, millet, dehulling efficiency, hydrothermal treatment

1.0 INTRODUCTION

Sorghum and millet grains have been dietary staples for centuries in parts of Africa, Asia and China. Today these crops are significant contributors to the protein and energy requirements of millions of poor people living in these areas, and in future they will need to feed many more. For human consumption, sorghum and millet needs to be dehulled to remove the seed coat, which is high in crude fibre and contains anti-nutritional factors such as tannin and phytic acid. Since all the anti nutritional compounds are concentrated in the seed coat, its removal significantly reduces their concentration with corresponding increase in nutritional quality, palatability, appearance and acceptance of products from these grains (Deshpande *et al.*, 1982). Dehulling process for these grains is accomplished either traditionally by hand pounding in a wooden mortar or mechanically using abrasive type dehullers. However, present levels of recovery for both methods are very low and the quality of the final product is often poor due to low dehulling efficiency.

The need to reduce the dehulling losses and improve the dehulling efficiency of these grains has led to the exploration of different dehulling methods, which are more efficient than those in current use. Seed coat removal, especially from those varieties with a soft floury (soft) endosperm, is a serious problem due to the fact that the grain tends to disintegrate during the dehulling process before the seed coat is removed. Under such circumstances materials other than the seed coat are removed from the grain kernel and lost with the bran leading to unacceptably low levels of recovery and poor dehulling efficiency.

Ideally, the most desirable dehulling process would remove only the seed coat and leave the high protein germ and aleurone layer with the endosperm. The ease with which this can be achieved depends mainly on the degree of adhesion of the seed coat to the endosperm and the ability of the grain to withstand mechanical action without shattering during the dehulling process. The seed coat in sorghum and millet is tightly attached to the endosperm and hence requires a large amount of force to remove it during the dehulling process. When this force exceeds the grain breaking strength; it results in the breakage of the grain kernel. Reducing or loosening the adhesion between the seed coat and the endosperm so that less compressive and abrasive force is needed to remove the seed coat should increase dehulling efficiency and improve recovery levels in sorghum and millet substantially.

Several pre-treatment methods have been developed for various cereal grains to improve their dehulling efficiency and hence the quality of their final products, these include:

(i) Pre-treatment with chemicals e.g. alkali, urea, etc. (Ehiwe and Reichert, 1987)

(ii) Tempering with cold water, hot water or steam (hydrothermal treatment) (Sefa Dedeh & Stanley, 1979; Singh, 1995).

(iii) Treatment with biological agents such as enzymes to digest the pericarp (Simons, 1962).

1.1 Hydrothermal treatment

Hydrothermal treatment refers to the addition or removal of moisture and heat to or from a material. Hydrothermal treatment has been shown to have a significant effect on loosening or breaking the seed coat-endosperm bond thus leading to improved dehulling efficiency of different grains. Sefa Dedeh and Stanley (1979) found that heat treatment of moistened beans and cowpeas made the hull much more easier to remove due to the fact that the cotyledons tended to shrink more than the hull during this process resulting in the hull being loosened from the cotyledons and hence easier to remove. Ehiwe and Reichert (1987) studied the effect of hydrothermal treatment on seed coat removal in field peas by using a rubberized aluminium disc in a Tangential Abrasive Dehulling Device (TADD). They found that seed coat removal from the cotyledons was much easier after hydrothermal treatment. Singh (1995) working with canola (rapeseed) found that hydrothermal treatment improved the dehulling efficiency by 41% compared to unconditioned seeds.

A grain kernel undergoes several physical changes when subjected to hydrothermal treatment. Moisture absorption or temperature rise causes swelling whereas moisture loss or cooling causes contraction. Since a grain kernel is a composite structure made of different components, each component of the kernel expands or contracts to a different degree when the kernel is subjected to hydrothermal treatment. The expansion or contraction of the seed coat (which is mainly cellulose) is different from that of the endosperm (which is mainly starch and protein). As a result, during hydrothermal treatment internal slips occur which result in partial separation of the seed coat from the endosperm thus making it possible for less force to be used to remove the seed coat during the dehulling process.

Four important conditioning factors namely; grain moisture content, temperature and the rate of change of moisture and temperature have a significant effect on the change of physical-chemical properties of the grain and the extent of debonding which may be achieved during hydrothermal treatment. The objective of this study was to investigate the effects of hydrothermal treatments on the dehulling efficiency of sorghum and millet using a tangential dehuller.

2.0 MATERIALS AND METHODS

Two varieties of sorghum, *Dionje,* a hard endosperm white branned sorghum variety from Tanzania and *Jumbo*, a large grain red branned, soft endosperm sorghum from Australia and one pearl millet variety (*IM*) from India were used in this study.

2.1 Seed conditioning

Hydrothermal treatments applied consisted of; (a) soaking the grain in distilled water at ambient temperature (20^{0}C) for three different durations (b) steam treatment of the grain also for three different durations. To avoid clogging of the dehulling mill, the conditioned samples were then dried to safe dehulling moisture content of around 12% db (Reichert and Young, 1976).

Three samples of each grain variety, each weighing 20g, were soaked in distilled water at ambient temperature (20^{0}C ± 0.2^{0}C) for 15, 30 and 60 minutes. Steam treatment of the grain was carried out in specially designed steaming unit, which consisted of a steam generator and a wire mesh basket sample holder. Three different steaming durations of 5, 10, and 15 minutes were used. After steaming the samples were also divided into two sub-samples and dried to 12% db.

Two different drying rates were used to induce thermal stress in the pre-treated grain and to reduce the moisture content to safe dehulling moisture content (around 12% db). They included, slow drying using ambient air at 20^{0}C, and fast drying using an air oven at 60^{0}C [the oven temperature of 60^{0}C was used here to avoid heat damage to the grain, while 15 minutes minimum soaking period was used as is the actual tempering duration usually employed in traditional dehulling method (Eggum *et al.* 1982). Higher tempering or periods resulted in softening of the endosperm leading to excessive breakages during the dehulling process (Lazaro, 1999).

2.2 Determination of seed coat content of sorghum and millet grain

The seed coat content of whole sorghum and millet grain kernel was determined by manual dehulling of the seed coat from the grain kernels after soaking them in distilled water for 15 minutes. The peeled kernels and the seed coat were then air dried to constant weight. Their proportions were then determined as percentage of the whole kernel. Three samples of 2g for each grain type before conditioning were used to determine the percentage of seed coat of each grain variety.

2.2 Evaluation of dehulling efficiency

Following hydrothermal treatment, samples were dehulled for 2 minutes using a laboratory TADD model 4E-220 (Venables Machine works Ltd., Saskatoon, Saskatchewan, Canada) with a No. 80 grit disk running at 1500rpm. Details of machine design and operation were described by Reichert *et al.* (1986). The quality of the dehulled grain and the dehulling efficiency were evaluated in terms of seed coat removed, kernel breakage and yield obtained after dehulling.

Dehulling efficiency here refers to the extent to which the seed coat has been removed from the endosperm at a given dehulling duration. To evaluate the dehulling efficiency it was necessary to quantify the effect of seed coat removal from the endosperm. Different methods have been used to evaluate dehulling efficiency. These includes determination of the extent of removal of the seed coat, measurement of components which are more concentrated in the seed coat than in the starchy endosperm such as crude fibre or ash content and the use of optical methods to measure the change in colour of the final product as a result of dehulling (Reichert and Young, 1976; Murty and Dietz, 1974). In this study, two methods were used to evaluate the dehulling efficiency. These were the ratio of the mass of the seed coat to the initial mass of the grain before dehulling and the reduction of crude fibre in the dehulled grain.

2.2.1 Dehulling efficiency based on seed coat removal

In this method, dehulling efficiency was based on the extent to which the seed coat was removed from the endosperm. Replicate samples (5 replicates) each of 2g were taken from the dehulled grain and the seed coat remaining on partially dehulled grain was manually removed and weighed. The percent seed coat removed from the dehulled grain was determined from the following equation (Ehiwe and Reichert, 1987):

$$\%\,\text{seed coat removed} = 100 - \left(\frac{\%\,\text{seed coat in partially dehulled grain}}{\%\,\text{seed coat in whole grain}} \times 100\right) \quad \ldots\ldots\ldots 1$$

Kernel breakage was another important factor that needed to be considered during the evaluation of the dehulling efficiency because it reflects the quality of the dehulled grain. The percentage of broken kernels was determined by sifting 5g of dehulled grain on a 2mm mesh and 1mm mesh screens for sorghum and millet respectively. The weight percentage of kernels passing through these screens gave the relative measure of broken kernels in the sample. Dehulling efficiency (D_{eff}) for different hydrothermal treatments was then calculated by taking into consideration all the factors as follows:

$$D_{eff} = C_n \times C_w \times C_y \times 100 \quad \ldots\ldots\ldots 2$$

where C_n is the coefficient of dehulling, C_w is the coefficient of wholeness of dehulled grain kernels, and C_y is the yield factor. The coefficient of dehulling is defined as the extent of seed coat removal from the endosperm, and was calculated from

$$C_d = \left(1 - \frac{M_h}{M_t}\right) \quad \ldots\ldots\ldots 3$$

where M_p is percentage seed coat removed, and M_w is the percent seed coat content of the undehulled grain. The coefficient of wholeness defines the quality of the recovered endosperm and was determined from;

$$C_W = \frac{K}{K+b} \quad \ldots\ldots\ldots 4$$

where K is the mass of the whole grain kernels in the dehulled grain and b is the mass of broken kernels in the dehulled grain. The yield factor is defined as the proportion of dehulled material recovered with respect to the expected yield, and was calculated from;

$$C_y = \frac{Y_a}{Y_e} \quad \ldots\ldots\ldots 5$$

where Y_a is the actual yield of dehulled grain recovered (%) and Y_e is the expected maximum yield of dehulled grain (%) these were determined from;

$$Y_a = \frac{x}{M} \times 100 \qquad \text{...............................} \quad 6$$

and

$$Y_e = (100-u) \qquad \text{...............................} \quad 7$$

where x is the mass of dehulled grain obtained (g), and M is the mass of grain sample before dehulling, and u is the percent seed coat content of undehulled grain (%). The maximum expected yield is the yield, which would have been obtained if only the seed coat was removed from the grain without any loses of endosperm i.e. 100% recovery of the endosperm.

2.2.2 Dehulling efficiency based on reduction in crude fibre content

The second method used to evaluate dehulling efficiency was the degree of reduction of crude fibre content of the dehulled grain pre-treated using different hydrothermal treatments in comparison to the crude fibre reduction in the manually peeled sample. The amount of crude fibre reduction in manually peeled grain was considered as the maximum which could be achieved by an ideal dehulling process, therefore was used as a base line to compare the effectiveness of different hydrothermal treatments. The dehulling efficiency was calculated according to the following equation:

$$D_{eff} = \frac{\text{crude fibre reduction by the dehulling process}}{\text{crude fibre reduction by hand peeling}} \times C_y \times 100 \qquad \text{..................} \quad 8$$

2.2.3 Proximate composition of the dehulled grain

The main interest in dehulling sorghum and millet grain is to improve the overall quality of the final product in terms of its nutritive value, digestibility and palatability by removing the unwanted fibrous part of the grain or harmful components such as tannin and phytic acid. Different dehulling methods and hydrothermal treatments tend to affect the composition of the dehulled grain differently. It was therefore necessary to determine the proximate composition of mechanically dehulled grain and compare it with that of manually peeled and undehulled grain to find the extent of improvement or loss of different constituents brought about by different hydrothermal treatment methods.

The proximate composition (i.e. protein, oil, ash, and crude fibre content) of sorghum and millet grain pre-treated and then mechanically dehulled, was determined using standard AACC approved methods (AACC, 2000) and was compared to the composition of undehulled grain (control) and that of manually peeled grain.

2.2.4 Statistical analysis

The significance of hydrothermal treatments effects on the dehulling efficiency was determined using T-test comparison as explained by Mead *et al.* (1993).

3.0 RESULTS AND DISCUSSIONS

3.1 Manual dehulling of soaked and steam-treated sorghum and millet grain

Soaking of sorghum and millet grain in cold water for 15 minutes followed by 15 minutes rest to allow the surface moisture to be absorbed into the grain gave the best results for manual dissection, soaking for less than 15 minutes made the seed coat difficult to remove while soaking for more than 15 minutes result in softening of the grain kernel leading to high kernel breakage during dehulling (Lazaro, 1999). However, the ease of removal of the seed coat from the endosperm decreased as the grain dried. Steam treatment for 15 minutes also gave the same results, however, the effect of seed coat loosening by steam treatment diminished very rapidly because the grain tended to dry very rapidly once the steaming process was stopped. This showed that both soaking and steaming were effective in reducing the strong bond between the seed coat and the endosperm as long as the seed coat was removed while the grain was still moist. Therefore to get maximum seed coat loosening effect from either soaking or steaming treatment, the grain needs to be processed while the seed coat-endosperm interface is still wet.

The seed coat contents determined by manual dehulling of the grain were found to be 11.4 %± 0.4 for Jumbo 8.3% ± 0.3 for Dionje and 9.9%± 0.3 for pearl millet. These values are within the range of seed coat content of sorghum and millet reported in literature, which varies from 4.8% - 11.6% for sorghum and from 7.2% - 10.7% for millet (Serna-Saldivar and Rooney, 1995).

3.2 Proximate analysis of the grain samples

The results of proximate analysis of the whole (undehulled) and manually dehulled grain are summarized in Table 1. The values obtained for whole grain are within the ranges of proximate composition of sorghum and millet quoted in literature (Serna-Saldivar and Rooney, 1995).

Table 1. Proximate composition of whole and dehulled sorghum and millet kernels

Grain Type	Treatment	Ash (%)	Oil (%)	Crude fibre (%)	Crude Protein (N × 6.25) (%)
(a) Sorghum		(1.1 - 4.5)[a]	(0.5 - 5.2)	(1.2 - 6.6)	(7.3 - 15.6)
Jumbo	Undehulled	1.66	4.19	6.12	13.06
	M/dehulled	1.32	3.34	3.31	13.90
Dionje	Undehulled	1.95	2.85	4.81	9.06
	M/dehulled	1.39	2.13	2.75	14.18
(b) Millet		(1.6 - 3.6)[a]	(1.5 - 6.8)	(1.4 - 7.3)	(8.6 - 19.4)
IM	Undehulled	1.98	5.47	7.17	10.18
	M/dehulled	1.03	3.14	2.64	11.88

[a]Ranges of proximate composition from literature (Serna-Saldivar and Rooney, 1995). Each data point is an average of 5 replications. M/dehulled = manually dehulled grain

The manually dehulled grain had approximately 45.9%, 42.8% and 63.2% less crude fibre than undehulled grain for Jumbo, Dionje and millet respectively. There was also a decrease in oil (ether extracts) and ash content due to the removal of the seed coat, which had high proportions of pigments and ash. On the other hand the protein contents of the dissected grain was slightly higher than that of the whole grain. This could be due to the relative increase in the proportion of the grain components rich in protein (endosperm and germ) caused by the removal of the seed coat.

The proximate composition of mechanically dehulled grain is summarized in Table 2. Both untreated and pre-treated grain had lower ash, oil and crude fibre content after dehulling than undehulled grain. On the other hand, hydrothermal treated grain had slightly lower ash, crude fibre and oil compared to untreated grain, indicating a more complete removal of the seed coat in the hydrothermal treated grain than in the untreated grain.

Table 2. Summary of proximate composition of dehulled sorghum and millet subjected to different hydrothermal treatments

Grain type	Treatment	Drying Method	Ash (%)	Oil (%)	Crude Fibre (%)	Protein (%) (N×6.25)
Jumbo	Un-treated	-	1.49 ±0.06[a]	3.77 ± 0.08	4.05 ± 0.16	11.17± 0.04
	S/treatment	Ambient	1.46 ± 0.05	3.73 ± 0.04	3.78 ± 0.08	12.66 ± 0.13
	S/treatment	Oven	1.49 ± 0.02	3.67 ± 0.08	3.71 ± 0.03	12.47 ± 0.09
	Soaking	Ambient	1.43± 0.08	3.74 ± 0.07	3.56 ± 0.01	12.52 ± 0.24
	Soaking	Oven	1.42 ± 0.04	3.71 ± 0.06	3.37 ± 0.03	12.48 ± 0.09
Dionje	Un-treated	-	1.76 ± 0.02	2.52 ± 0.03	3.30 ± 0.44	8.87±0.014
	S/treatment	Ambient	1.68 ± 0.03	2.48 ± 0.08	3.05 ± 0.03	9.02 ± 0.14
	S/treatment	Oven	1.71 ± 0.02	2.44 ± 0.10	3.10 ± 0.02	9.29 ± 0.15
	Soaking	Ambient	1.53 ± 0.03	2.47 ± 0.04	2.46 ± 0.03	9.00± 0.06
	Soaking	Oven	1.61 ± 0.02	2.49 ± 0.05	2.26 ± 0.04	9.12 ± 0.06
Millet	Un-treated	-	1.56 ± 0.04	3.67 ± 0.11	3.03 ± 0.53	10.43±0.016
	S/treatment	Ambient	1.16 ± 0.01	3.79 ± 0.03	2.90 ± 0.30	10.87 ± 0.16
	S/treatment	Oven	1.07 ± 0.03	3.51 ± 0.10	3.00 ± 0.10	10.39 ± 0.29
	Soaking	Ambient	1.04 ± 0.01	3.68± 0.04	2.97 ± 0.16	10.63 ± 0.1
	Soaking	Oven	1.03 ± 0.08	3.53± 0.07	2.90± 0.14	10.75 ± 0.06

[a]Standard deviation. Each data point is an average of 5 replications

Hydrothermal treated grain had on average 41.1%, 43.6% and 58.1% less crude fibre after dehulling than the undehulled grain for Jumbo, Dionje and millet respectively. While for untreated grain the crude fibre reduction due to dehulling was 34.2% for Jumbo, 31.3% for Dionje and 57.7% for millet. Statistical analysis of the crude fibre results showed that there was a significant reduction of crude fibre in treated grain compared to untreated grain for Jumbo and Dionje ($P<0.05$) while for millet the reduction in crude fibre due to hydrothermal treatment was not significantly different from the untreated grain ($P<0.05$). These results showed that hydrothermal treatments of sorghum before dehulling had a marked effect on crude fibre reduction.

3.3 Kernel breakage

Table 3 summarizes the results of kernel breakage during dehulling of grain subjected to different hydrothermal pre-treatments. For the same retention time in the dehuller, steam treatment and high temperature drying resulted in more kernel breakage than cold water tempering and ambient drying. This could be explained by the fact that both steam treatment and high temperature drying resulted in higher stresses within the grain kernel, leading to development of stress cracks, which eventually led to breakage of the grain during the dehulling process.

Table 3. Kernel breakages during dehulling for different pre-treatments

Grain variety	Treatment	Drying method	% Kernel broken
(a) Jumbo	Soaking	Ambient drying	1.3±0.06
	Soaking	Oven drying	3.3±0.07
	Steaming	Ambient drying	5.9±0.11
	Steaming	Oven drying	7.4±0.08
(b) Dionje	Soaking	Ambient drying	0.3±0.02
	Soaking	Oven drying	2.8±0.04
	Steaming	Ambient drying	4.2±0.07
	Steaming	Oven drying	6.8±0.14

Each data point is an average of 5 replications

3.4 Dehulling efficiency in terms of seed coat removal

The results of dehulling efficiency due to seed coat removal from the dehulled grain subjected to different hydrothermal treatments are summarized in Table 4. From these results soaking followed by oven drying resulted in the removal of most of the seed coat from sorghum giving a dehulling efficiency of 77.0% for Jumbo and 76.3% for Dionje followed by soaking/ambient drying with dehulling efficiencies of 70.4% for Jumbo and 74.4% for Dionje. The least efficient hydrothermal treatment for Jumbo variety was steam treatment/ambient drying (65.5%) and for Dionje was steam treatment/oven drying (65.4%). In terms of seed coat removed, hydrothermal treatments significantly improved the dehulling efficiency of Jumbo and Dionje. On average the dehulling efficiency of Jumbo was improved by 10% and of Dionje by 7% over the untreated grain. However, some hydrothermal treatments resulted in lower dehulling efficiencies notably, steam treatment and high temperature drying in sorghum. For these hydrothermal treatments there was no significant difference ($P<0.05$) between the dehulling efficiencies of treated and untreated grain. This was probably caused by the high rate of kernel breakage due to high temperatures involved

On the other hand, for millet the combination of steam treatment with oven drying resulted in the highest dehulling efficiency of 84.6% followed by steam treatment/ambient drying with dehulling efficiency of 80.5%. Soaking/ambient drying was the least efficient hydrothermal treatment with dehulling efficiency of 78.2%.

Table 4. Average dehulling efficiency for different hydrothermal treatment in terms of seed coat removal

Grain type	Treatment	Drying method	D_{eff} (%)	Statistical analysis
(1) Sorghum				
(a) Jumbo	Control	-	66.7 ± 0.7^a	
	Soaking	Ambient	70.4 ± 0.8	*
	Soaking	Oven	76.8 ± 0.6	***
	S/treatment	Ambient	65.5 ± 1.7	ns
	S/treatment	Oven	67.6 ± 0.6	ns
(b) Dionje	Control	-	69.2 ± 1.4	
	Soaking	Ambient	74.4 ± 3.1	*
	Soaking	Oven	76.3 ± 2.7	*
	S/treatment	Ambient	72.1 ± 1.1	*
	S/treatment	Oven	65.4 ± 2.5	ns
(2) Millet	Control	-	64.3 ± 1.9	
	Soaking	Ambient	78.2 ± 5.0	*
	Soaking	Oven	79.6 ± 2.7	*
	S/treatment	Ambient	80.5 ± 3.2	*
	S/treatment	Oven	84.4 ± 0.5	***

[a] Standard deviation; Each data point is an average of 5 replications; *** Significant at $P<0.001$; ** Significant at $P<0.01$; * Significant at $P<0.05$; ns = Not significant at $P<0.05$; D_{eff} = Dehulling efficiency; S/treatment = Steam treatment

The untreated millet had a dehulling efficiency of 64.4%. All hydrothermal treatments investigated significantly improved the dehulling efficiency of millet compared to the untreated grain. On average the dehulling efficiency of millet was improved by approximately 20% by the hydrothermal treatments over the untreated grain. In terms of seed coat removal, steam treatment and high temperature drying were more effective for millet than sorghum.

3.5 Dehulling efficiency based on crude fibre reduction

The results of dehulling efficiency based on crude fibre reduction for different hydrothermal treatments are summarized in Table 5. For both sorghum varieties crude fibre analysis tended to confirm the order of dehulling efficiency of different hydrothermal treatments previously determined in terms of seed coat removal. Combination of soaking and oven drying was the most efficient hydrothermal treatment in reducing the crude fibre content of the dehulled grain for both Jumbo and Dionje with dehulling efficiency of 75.0% for Jumbo and 82.2% for Dionje.

The least efficient hydrothermal treatment was Steam treatment/ambient drying for Jumbo (67.3%) and steam treatment/oven drying for Dionje (62.6%).

On the basis of crude fibre reduction all hydrothermal treatments significantly ($P<0.05$) improved the dehulling efficiency of Dionje over the untreated grain, for Jumbo, soaking followed by ambient and oven drying result in significant improvement of dehulling efficiency while for steam treatment, the dehulling efficiency was not significantly different ($P<0.05$) from that of untreated grain.

On average the dehulling efficiency was improved by approximately 14.5% for Jumbo (soaking/oven drying) and by about 27.3% for Dionje (soaking/oven drying). For millet soaking/oven drying was the most efficient in terms of crude fibre reduction followed by soaking/ambient drying and the least efficient was steam treatment/ambient drying.

Table 5. Average dehulling efficiency for different hydrothermal treatment in terms of crude fibre reduction

Grain type	Treatment	Drying method	D_{eff} (%)	Statistical analysis
(1) Sorghum				
(a) jumbo	Control	-	60.5 ± 1.3[a]	
	Soaking	Ambient	73.5 ± 0.4	***
	Soaking	Oven	74.9 ± 0.5	***
	S/treatment	Ambient	67.3 ± 2.8	Ns
	S/treatment	Oven	69.4 ± 1.1	[illegible]
(b) Dionje	Control	-	54.9 ± 1.4	
	Soaking	Ambient	80.5 ± 1.1	***
	Soaking	Oven	82.5 ± 1.7	***
	S/treatment	Ambient	64.8 ± 6.8	**
	S/treatment	Oven	62.6 ± 12.0	**
(2) Millet	Control	-	77.9 ± 4.1	
	Soaking	Ambient	91.2 ± 3.4	*
	Soaking	Oven	91.6 ± 3.6	*
	S/treatment	Ambient	80.4 ± 7.0	*
	S/treatment	Oven	89.2 ± 1.6	*

[a]Standard deviation; Each data point is an average of 5 replications; *** Significant at $P<0.001$; ** Significant at $P< 0.01$; * Significant at $P<0.05$; ns: Not significant at $P<0.05$; S/treatment = Steam treatment; D_{eff} = dehulling efficiency

4.0 CONCLUSIONS

Hydrothermal treatment of sorghum and millet before dehulling improved their dehulling efficiency by an average of 10% over the untreated grain in terms of seed coat removal. Soaking for 30 minutes followed by oven drying to original moisture content (12% db) gave the best dehulling performance for sorghum, while steam treatment for 5 minutes followed by oven drying gave the highest dehulling efficiency for millet in terms of seed coat removal.

In terms of both seed coat removal and crude fibre reduction, soaking significantly improved the dehulling efficiency of all sorghum varieties and millet irrespective of the drying method used. The results from this study showed that hydrothermal treatments could be used beneficially to improve the dehulling efficiency of sorghum and millet using the current mechanical dehulling.

Manual removal of the seed coat from grain kernels of sorghum and millet was greatly facilitated by soaking or steam treatment of the grain prior to its removal, however, this effect of seed coat loosening decreased rapidly as the grain dried up indicating that for maximum benefit from the seed coat loosening effect brought about by hydrothermal treatment of the grain, the removal of the seed coat must take place while the grain kernel is still in moist condition. This suggests that the removal of the grain seed coat while still wet could be a critical factor in the design of more efficient mechanical dehullers for sorghum and millet than the ones currently in market. However, the major problem with most of the dehulling machines currently in the market is that, they are not suitable for dehulling wet grain due to the clogging problem associated with wet grains. There is a need therefore, for the development of new type of dehullers, which can dehull wet grain without clogging if the benefit of hydrothermal treatments like soaking and steaming is to be fully exploited.

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