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Water diffusion co-efficient of paddy, rice, black gram and dhal

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ABSTRACT : A hydration experiment for BPT 5204 paddy, NLR 92 paddy, BPT 5204 rice, NLR 92 rice, black gram and dhal was conducted by soaking in water at temperatures of 30, 40, 50, 60 and 70^{0}C in water bath up to 180 min. The moisture content for all the samples increased with increase in soaking time and temperature. Hydration data were analyzed using Fick's second law of diffusion model to estimate effective diffusivity which plays an important role in developing guidelines for soaking operation. The effective diffusivity varied from 2.63 x 10^{-11} to 3.75 x 10^{-11}, 1.99 x 10^{-11} to 3.33 x 10-11, 3.21 x 10^{-11} to 4.84 x 10^{-11}, 3.2 x 10^{-11} to 4.57 x 10^{-11}, 1.16 x 10^{-11} to 1.0 x 10^{-10} and 3.06 x 10^{-11} to 7.28 x 10^{-11} m^2/s from the soaking temperature 30 to 70^{0}C for BPT 5204 paddy, NLR 92 paddy, BPT 5204 rice, NLR 92 rice, blackgram and blackgram dhal, respectively. It was observed that effective diffusivity was increased as temperature increased from 30 to 70^{0}C.

KEY WORDS : Paddy, Rice, Black gram, Dhal, Hydration, Fick's diffusion equation, Effective diffusivity

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Rice (*Oryza sativa* L.*)* is a staple food of people in many parts of the world. It is cultivated in over 100 countries. India is one of the world's largest producers of white rice, accounting for 20% of all world rice production. Rice production of India was about 104.32 million tons during the year 2011-2012 (FAO, 2012). The traditional parboiling process involves soaking paddy overnight or longer in water followed by steaming and sun drying before storage and milling. Modern methods involve the use of a hot water soaking for few hours (Kaddus *et al.,* 2002).

Black gram (*Vigna mungo* L) or*Urad* is one of the important pulse crops in India. India is the largest producer of the blackgram product, which roots mostly from the fact that it's also the largest consumer of this particular pulse. In India, blackgram was grown in about 31.92 lakh ha area and production was about 18.3 lakh tones in 2011- 2012. Blackgram is essential in papad preparation, together with rice; it is also used in prepararion of *idli* and *dosa.* It is a rich protein food which contains about 26% protein, almost three times that of cereals, 1.2% fat and 56.6 % carbohydrates (Anonymous, 2012).

Absorption of water into these materials is of both theoretical and practical importance to processing industries. Control of this process may be improved with better knowledge of the distribution and movement of moisture within the kernel. Soaking is an important operation during the processing of many grains as final quality depends on this process (Kashaninejad and Kashiri, 2007). Theoretically soaking of grains is done at or below gelatinization temperature (73 - 86^{0}C). In India, parboiling of paddy is usually carried out by soaking at 70^{0}C to 75^{0}C. Paddy soaked in water at ambient temperature between 20 to 30^{0}C will take 36 to 48 hours to reach 30% moisture content in rice. In hot water at 60 to 65^{0}C it will take only two to four hour depending on paddy variety. Excessive soaking causes extensive quantitative leachate loss and qualitative, colour and smell changes. Grain Soaking process depend on temperature. If soaking time is too long, part of grain dissolve in water, and seed begins to germinate, and starch fermentation occurs. During cold soaking, starch fermentation occurs because of respiration of grains and release of carbon dioxide. This can cause an off flavor and can lead to excessive fungi and other micro organism in grains (Karunarathna *et al.*, 2010).

Mathematical modeling of hydration process is known to be important for the design and optimization of food process operations. Many researcher applied Fick's diffusion model to study the hydration behavior based on different geometry for different grains but use of model based on spherical geometry is simple to study the hydration behavior. Molecular diffusion is the main water transport mechanism and to predict the water transfer in food materials diffusion models based on Fick's second law are used. Moisture diffusivity is an important physical transport property which is useful in the engineering analysis of basic food processing operations such as soaking. Diffusion phenomena are extremely complex, so reliable data are scarce. As a consequence, traditional food processing involving diffusion has been mainly based on experimental knowledge. Accurate data on moisture diffusivity of food products are essential for efficient and effective design of food processing operations. Effective moisture diffusivity describes all possible mechanisms of moisture movement within the foods, such as liquid diffusion, vapour diffusion, surface diffusion, capillary flow and hydrodynamic flow (Kashaninejad *et al.*, 2007).

The present study was undertaken, to study water absorption behavior of BPT 5204, NLR 92 paddy, BPT 5204, NLR 92 rice, blackgram LBG 752 and blackgram dhal during soaking and determine effective diffusivity of all the samples using Fick's diffusion equation.

METHODOLOGY

Sample preparation:

Paddy (*Oryza sativa* L) varieties namely, BPT 5204 and NLR 92 and Black gram (*Vigna mungo* L.) of variety LBG 752 used in this study were procured from local market. Both samples were cleaned manually to remove all the chaff, foreign matter and broken grains in order to obtain kernels of uniform size. A part of paddy samples were dehusked in the laboratory rubber roll sheller to obtain brown rice. Dhal was prepared by overnight soaking of the blackgram in water and followed by sun drying for two days (Singh and Sahay, 2007). Milling was done to obtain dhal using mini dhal mill (Indosaw, India). The broken grains and dust were separated from the grains using standard mesh.

Determination of equivalent radius:

As grains are irregularly shaped, the equivalent sphere radius was employed to represent grain size for the mathematical model used in this study. For this purpose the total volume of 100 grains was measured with a cylinder using toluene as fluid. The average volume was calculated by dividing the total volume by the total number of grains. The equivalent sphere radius was then computed from the formula (Eq.1) for the volume of a sphere ($4\pi r^3/3$) using the average grain volume (Kashaninejad and Kashiri, 2007).

$$\mathbf{r} = \sqrt[3]{\frac{\mathbf{3v}}{\mathbf{4\pi}}} \qquad (1)$$

where, r is equivalent sphere radius (mm) and v is average grain volume (mm^3).

Experimental procedure:

The soaking test was conducted in a constant temperature water bath which was adjusted the required temperature of soaking. Hydration of grains was determined by soaking 10 ± 0.1g of samples in 200 ml glass bottles containing 50 ml of water. The soaking temperature studied was 30, 40, 50, 60 and 70^{0}C. Before performing hydration experiment the glass bottles with water placed in water bath at required soaking temperature to reach thermal equilibrium. The completion of temperature equilibrium was inspected by using digital thermometer (-50 to 150°C range). Then, grains were poured into the glass bottle and metal cap was fixed on it to prevent evaporation. The grains were soaked at each temperature for 3 hours and bottle with soaked samples were withdrawn from the water bath at regular time intervals of 15 min for moisture content determination. The soaked grains were allowed to drain through 14 mesh wire gauge for 1 min and the grain surface adsorbed water was eliminated by slight rubbing in a tissue paper. Then, the soaked grains were weighed with a digital weight balance with 0.01 g accuracy and the grains were placed in an oven at 130^{0}C for 1 hour for moisture content determination. This procedure was followed at each predetermined time for every experimental temperature. The experiment was replicated thrice.

Determination of equilibrium moisture content by extrapolation method:

The experimental determination of the equilibrium moisture content is time consuming, since the transient values converge very slowly towards an equilibrium state. It was, therefore, not possible to determine this parameter experimentally. Hence, the equilibrium moisture content was estimated by extrapolating a linear plot of the rate of change of moisture (dm/dt) against the moisture content (M) to the point where dm/dt= 0. It was expected that as time tends to infinity by assuming dm/dt = 0, gives value for EMC at a particular temperature for paddy, rice, black gram and black gram dhal (Kashiri *et al.*, 2010; Kashaninejad *et al.*, 2007).

Calculation of effective diffusivity:

During a diffusion process at constant temperature, it is assumed that the process follows Fick's second law of moisture diffusion. The governing Fick's three dimensional (3D) equation for axisymmetric diffusion is given as follows (Crank, 1975).

$$\mathbf{D}\left(\frac{\partial^2 \mathbf{m}}{\mathbf{r}^2} + \frac{\partial^2 \mathbf{m}}{\mathbf{r}\partial \mathbf{r}} + \frac{\partial^2 \mathbf{m}}{\partial \mathbf{z}^2}\right) = \frac{\partial \mathbf{m}}{\partial \mathbf{t}} \qquad (2)$$

where, D is diffusion co-efficient (m^2/s), m is moisture content (%, d.b.), r is radial coordinate (m), z is axial coordinate (m) and t is time variable.

Analytical solutions of equation (2) for the overall moisture content of a sphere can be obtained directly (Crank, 1975):

$$MR = \frac{M - Me}{M_0 - Me} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \exp\left(-D\pi^2 \frac{n^2}{r^2} t\right) \qquad (3)$$

where, MR is moisture ratio (dimensionless quantity ranging from 0 to 1), M is moisture content at time t (% d.b.), M_0 is initial moisture content (%, d.b.), Me is equilibrium moisture content (%, d.b.) and r is equivalent radius (m).

The slope, co-efficient K, of this model is related to the effective diffusivity D,

$$K = \frac{(D\pi^2)}{r^2} \qquad (4)$$

therefore, $$D = \frac{(Kr^2)}{\pi^2} \qquad (5)$$

The effective diffusivity was calculated by equation (6), using slopes (K) derived from the linear regression of ln (MR) against time by data analysis tool box of Microsoft excel, 2007 software.

RESULTS AND DISCUSSION

The moisture content curves of grains at five soaking temperature (30, 40, 50, 60, and 70^{0}C) are shown in Fig. 1-6. The amount of water absorbed by the cereals and legumes was found to increase with the increase in temperature of the soaking water. It was observed that there was rapid initial moisture absorption followed by a slower rate in the later stages at all the five soaking water temperatures.

The experimental moisture content values for BPT 5204 paddy and NLR 92 paddy (Fig. 1 and 2) during soaking from 0 to 180 min for the temperatures 30, 40, 50, 60 and 70^{0}C were increased from 11.03% d.b. to 30.25 , 32.72, 35.61, 41.86 and 43.65% d.b., and 11.49% d.b. to 29.86, 34.71, 38.68, 41.97 and 46.20% d.b., respectively. During soaking from 0 to 15 min it was observed that for both variety of paddy, there was a rapid increment in water absorption from 11.03% d.b. to 17.83, 19.88, 22.35, 25.09 and 26.6% d.b., and 11.49% d.b. to 21.06, 22.04, 25.01, 25.60 and 26.90% d.b, respectively for the temperatures ranging from 30 to 70^{0}C. In later stages increment in water absorption observed but at lower rate. This behavior may be due to capillary inhibition of external layers from pericarp and/ or by high matrix potential of grain tissue. The initial rapid water uptake may be due to the filling of capillaries on the surface of the seed and at the hilium (Kaddus *et al.*, 2002).

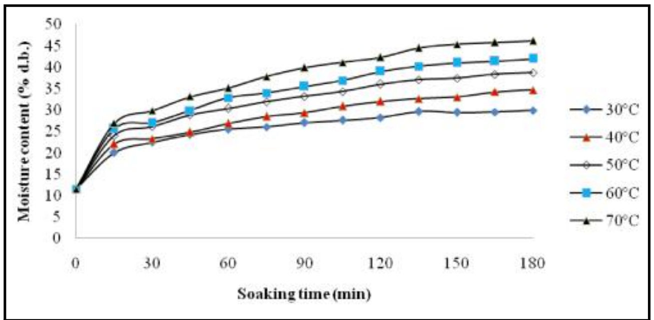

Fig. 2 : Moisture content curve of NLR 92 paddy at different temperatures

The experimental moisture content values for BPT 5204 rice and NLR 92 rice (Fig. 3 and 4)) during soaking from 0 to 180 min for the temperatures of 30, 40, 50, 60 and 70^{0}C were increased from 15.69% d.b. to 36.44, 38.30, 39.91, 42.21 and 51.56% d.b., and 16.64% d.b. to 35.79, 37.62, 39.46, 42.43 and 49.90% d.b., respectively. During soaking from 0 to 15 min for both variety of rice was observed that there was a rapid increment in water absorption from 15.69% d.b. to 19.95, 25.36,

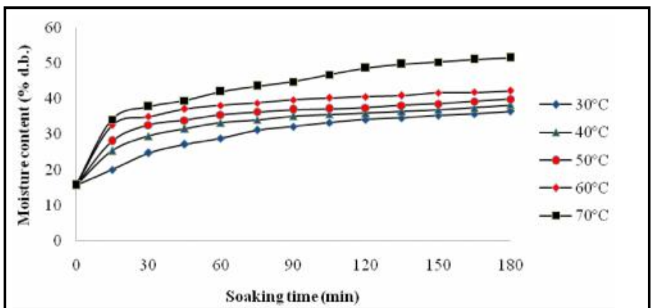

Fig. 3 : Moisture content curve of BPT 5204 rice at different temperatures

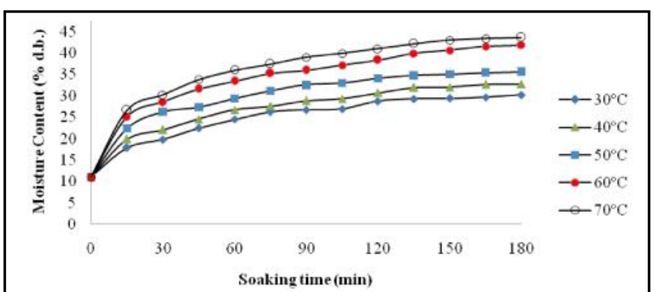

Fig. 1 : Moisture content curve of BPT 5204 paddy at different temperatures

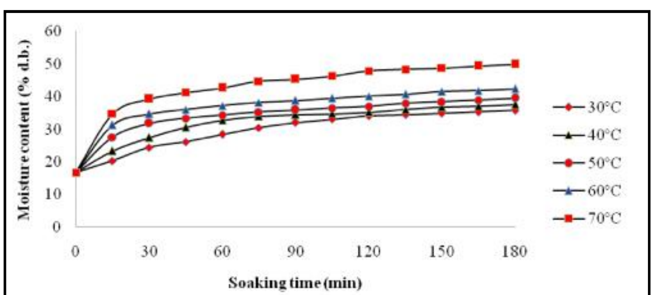

Fig. 4 : Moisture content curve of NLR 92 rice at different temperatures

28.09, 32.55 and 34.14% d.b., and 16.64% d.b. to 20.37, 23.33, 27.6, 31.28 and 34.74% d.b, respectively for the temperatures ranging from 30 to 70^0C. In later stages increment in water absorption observed but at lower rate. The initial rapid water uptake might be due filling of cracks on grain surface and internal fissures, which formed during dehusking (Kashaninejad *et al.,* 2007).

It was observed that BPT 5204 rice absorbed more water than NLR 92 rice. Higher water absorption in milled rice may be due to higher amylopectin content. The major component absorbing water in seeds is protein, although other components such as mucilages, cellulose, starch and pectic substances contribute to the phenomenon (Antwi, 2011).

A regular increase in water absorption was observed as temperature increased from 30 to 60^0C for both the variety of rice but a different behavior was observed at 70^0C *i.e.* more water absorbed compared to 60^0C probably due to starch gelatinization or may be due to effect of high temperature inducing softening of grain. The gelatinization of grain rice gradually increases between 60 and 70^0C, and saturates around 80^0C (Kashaninejad *et al.,* 2007). The behavior of starch in water is temperature and concentration dependent. Grain starches in general show very little uptake of water at room temperature and their swelling power is also small. At higher temperature water uptake increases and starch granules collapse, which lead to solubilisation of amylase and amyl pectin to form a colloidal solution (Antwi, 2011). In this study for both rice soaked at 70^0C absorbed more water than other condition because at this temperature starch gelatinization commences.

It was also observed that both paddy varieties absorbed lower amount of water than that of brown rice. The lower water absorption capacity of paddy could be due to its husk which is a barrier that resists water movement into the kernel. Also the amount of moisture absorbed for both variety of paddy and rice was not the same, this could be as a result of the difference in physiochemical and nutritional composition of the varieties considered, soaking temperature and time. (Karunarathna *et al*., 2010).

The experimental moisture content values for blackgram (Fig. 5) during soaking from 0 to 180 min at temperatures of 30, 40, 50, 60 and 70^0C were increased from 7.7% d.b. to 43.02, 64.22, 81.54, 92.13 and 95.02% d.b. The amount of water absorbed at lower temperature (30^0C) was less than higher temperature (40 to 70^0C). Also a linear increment of moisture content was observed with time for all the temperature studied. Almost there was no change moisture absorption rate was observed during soaking up to 3 h at different temperatures from 30 to 70^0C, which indicate that blackgram hydrated slowly with time and temperature. This behavior probably due to fibre content of seed coat which may contain a specific type of hemicelluloses, pentosans and

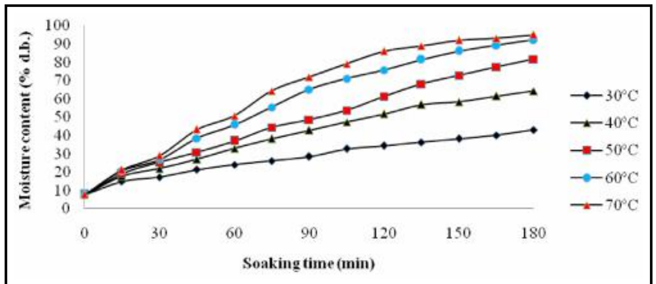

Fig. 5 : Moisture content curve of blackgram at different temperatures

some non-starchy polysaccharides which may hinder hydration up to 3 h and after acquiring some moisture, it may start absorbing to a greater extent (Ferda *et al.,* 2001).

The experimental moisture content values for blackgram dhal (Fig. 6) during soaking from 0 to 180 min at different temperatures 30, 40, 50, 60 and 70^0C were increased from 11.9% d.b. to 130.20, 132.65, 134.4, 134.5 and 135.11% d.b. It was observed that after 3 h soaking moisture content values were very close to each other for all the temperature studied. There was a rapid increment in moisture content for soaking from 0 to 15 min from moisture content 11.9% d.b. to 61.90, 75.65, 96.6, 104.58 and 107.07% d.b. for the temperature ranging from 30 to 70^0C. In legume soaking, the initial rapid water uptake was probably due to filling of capillaries on surface layer of seed. In later stages amount of water absorbed was very less. It may be due to reduced water holding capacity due to higher leaching loss (Ferda *et al.,* 2001). It was observed that the amount of water absorbed by blackgram was lower than that of dhal within experimental condition (Fig. 5 and 6). As dhal is free from seed coat due to which moisture absorption was faster and higher or might be due to the middle lamella in legume without seed coat may absorb moisture faster.

In general, for different grains one can expect an inverse relation between the rate of absorption and seed size, since a larger seed provides a smaller surface area per unit mass for moisture transfer (Resio *et al.,* 2003). Might be due to this rice and dhal absorbed more water than paddy and black gram

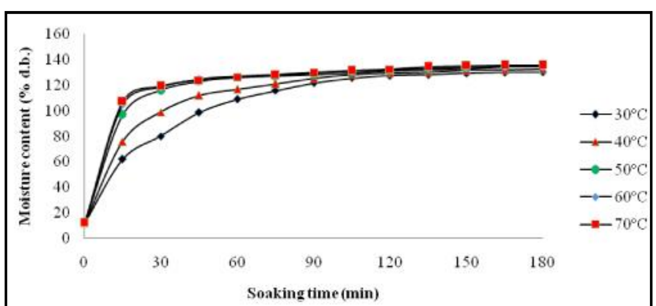

Fig. 6 : Moisture content curve of blackgram dhal at different temperatures

within experimental conditions. It can be seen from the water absorption curve (Fig. 1-6) for all the samples, the time of soaking required for attaining particular amount moisture content was reduced as the temperature was increased. The temperature of the soaking medium was a major factor in reducing the soaking time of gains (Kashaninejad *et al.*, 2007; Kashaninejad and Kashiri, 2007; Engels *et al.*, 1986).

Table 4 shows the equilibrium moisture content of all the samples at different soaking temperatures calculated from extrapolation method for all the samples.

In general one can be say that higher value of slope co-efficient will give higher diffusivity. The K values (Table 2) for BPT 5204 paddy and rice were more than that of NLR paddy and rice. Also it can be seen that for both rice varieties, K was higher than that of paddy. Also it was observed that K value for blackgram dhal was more than that of whole grain. The

Table 1 : Equilibrium moisture content of different samples at different soaking temperature used in Fick's diffusion model

Samples	Equilibrium moisture content (M_e) (% d.b.)				
	30^0C	40^0C	50^0C	60^0C	70^0C
BPT Paddy	34.96	37.86	39.82	47.58	49.15
NLR Paddy	36.18	40.49	44.43	49.86	54.77
BPT Rice	39.42	41.12	44.10	48.04	58.40
NLR Rice	40.84	41.52	44.23	45.87	56.97
Black gram	189.07	167.45	158.72	150.91	119.73
Black gram dhal	150.78	143.47	140.10	138.48	136.9

Table 2 : Values of coefficient (K) of Fick's diffusion equation at different soaking temperatures

Samples	Coefficient, K									
	30°C	R^2	40°C	R^2	50°C	R^2	60°C	R^2	70°C	R^2
BPT Paddy	0.00745	0.9617	0.00765	0.9797	0.0083	0.976	0.01015	0.9926	0.01062	0.9927
NLR paddy	0.0052	0.9567	0.00732	0.9948	0.00775	0.9937	0.0793	0.9891	0.0872	0.9899
BPT Rice	0.01025	0.9928	0.01035	0.9783	0.01086	0.9575	0.01182	0.9918	0.01544	0.9851
NLR Rice	0.00941	0.9783	0.00954	0.973	0.01059	0.9857	0.01162	0.9836	0.01343	0.9825
Black gram	0.00105	0.9929	0.00234	0.9925	0.00375	0.9959	0.00507	0.9902	0.00908	0.9756
Dhal	0.00786	0.8779	0.00905	0.9303	0.0094	0.9715	0.01119	0.9725	0.01871	0.9798

Table 3 : Effective diffusivity of different samples at different soaking temperatures

Samples	Effective diffusivity (m^2/s)				
	30°C	40°C	50°C	60°C	70°C
BPT 5204 Paddy	2.63×10^{-11}	2.7×10^{-11}	2.93×10^{-11}	3.58×10^{-11}	3.75×10^{-11}
NLR 92 paddy	1.99×10^{-11}	2.79×10^{-11}	2.95×10^{-11}	3.02×10^{-11}	3.33×10^{-11}
BPT 5204 Rice	3.21×10^{-11}	3.24×10^{-11}	3.4×10^{-11}	3.7×10^{-11}	4.84×10^{-11}
NLR 92 Rice	3.2×10^{-11}	3.25×10^{-11}	3.6×10^{-11}	3.96×10^{-11}	4.57×10^{-11}
Blackgram	1.16×10^{-11}	2.58×10^{-11}	4.15×10^{-11}	5.61×10^{-11}	1.0×10^{-10}
Blackgram dhal	3.06×10^{-11}	3.52×10^{-11}	3.66×10^{-11}	4.36×10^{-11}	7.28×10^{-11}

Table 4 : Effective diffusivity for different grains reported in literature

Sample	Temperature (^{0}C)	Effective diffusivity (m^2/s)	References
Wheat	25 to 65	2.8×10^{-12} to 1.36×10^{-11}	
Rough rice	40 to 50	6.67×10^{-9} to 9.03×10^{-9}	
Brown rice	45 to 65	7.9×10^{-11} to 8.82×10^{-11}	Authors cited in Kashaninejad and Kashiri,
White rice	45 to 65	2.33×10^{-11} to 4.7×10^{-11}	(2007)
Soybean	40 to 60	1.08×10^{-10} to 2.00×10^{-10}	
Sorghum	10 to 50	2.22×10^{-12} to 8.37×10^{-12}	Kashiri *et al.*, 2010
Amaranth	40 to 60	3.84×10^{-11} to 8.25×10^{-11}	Resio *et al.*, 2003
Chickpea	15 to 40	9.71×10^{-11} to 4.9×10^{-10}	Ferda *et al.*, 2001

difference in physicochemical and nutrient composition of different varieties might be responsible for this observation. The higher co-efficients of determination ($R^2 > 0.87$) indicating a very good fit to the experimental data. The effective diffusivity during soaking of BPT paddy, NLR paddy, BPT rice, NLR rice, blackgram and blackgram dhal from 30 to 70^0C is shown in Table 3. It was observed that effective diffusivity was increased as temperature increased from 30 to 70^0C.

The comparison of effective diffusivity for water soaking with those reported in the literature for other grains is shown in Table 4. From Table 3 and 4, it can be concluded that effective diffusivity for this research was very similar to other grains.

Conclusion:

The moisture content of BPT 5204 paddy, NLR 92 paddy, BPT 5204 rice, NLR 92 rice, blackgram and blackgram dhal increased with increasing soaking time and temperature. Higher soaking temperature resulted in a shorter soaking time. The effective diffusivity was increased as soaking temperature increased from 30 to 70^0C for BPT 5204 paddy, NLR 92 paddy, BPT 5204 rice, NLR 92 rice, blackgram and blackgram dhal.

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