Ultrasound Assisted Hydration of Navy Beans (Phaseolus Vulgaris)

N. Misra
Technological University Dublin, misra.nrusimhanath@tudublin.ie

Ultrasound assisted hydration of navy beans (*Phaseolus vulgaris*)

M. Ghafoor [a], N.N. Misra [b], K. Mahadevan [a], B.K. Tiwari [a,*]

[a] *Manchester Food Research Centre, Manchester Metropolitan University, Manchester M14 6HR, UK*
[b] *School of Food Science & Environmental Health, Dublin Institute of Technology, Dublin 1, Ireland*

ABSTRACT

The use of ultrasound to enhance the transport phenomena in food processes has been well recognised in recent times. The objective of this study was to evaluate the effect of sonication on hydration rate and pasting profile of navy beans. The hydration kinetics for control and ultrasound assisted soaking was mathematically described using mechanistic (Fickian diffusion) and empirical (Peleg's equation, Weibull model and First Order equation) models. Ultrasound enhanced the rate of hydration which was evident from the plot of kinetic data and model parameters. The effective diffusivities for water transport without and with ultrasound application were estimated to be 1.36×10^{-10} m^2/s and 2.19×10^{-10} m^2/s respectively, considering Fickian diffusion. The Weibull model was concluded to best predict the hydration kinetics of navy beans in an ultrasonic field. Significant increase in peak viscosity of sonicated bean powder was observed compared to control.

1. Introduction

Navy beans (*Phaseolus vulgaris*) are small beans that are creamy white in colour. These are widely used in the preparation of baked beans and are available year-round in pre-packaged containers, bulk bins or as canned navy beans. Similar to other vegetables and fruits, pulses are excellent source of essential nutrients, including proteins, minerals, fibre and phytochemicals. These nutrients are associated with several health-promoting benefits, such as lowering risk for chronic diseases including coronary heart disease (CHD) [1]. Literature reveals that consumption of ca. one cup of navy beans for 3 weeks decreases serum cholesterol concentrations by 19% and low-density lipoprotein cholesterol (LDL-C) by 24% in hypercholesterolemic men [2].

There is a great deal of opportunity to expand value added activities in navy beans [3]. Canned navy bean processors seek beans that lend themselves to ease of preparation, greater processing efficiency, higher processor yield and high water holding capacity [4]. Prior to filling in cans, navy beans are often continuously soaked in high temperature systems for hydration. This leads to considerable loss of texture and soluble solids from the beans. Further, pulse grains are usually cooked before being used in the human diet to improve the nutritional quality and the most common process of pre-soaking usually is not sufficient to decrease overall cooking time of pulses [5].

Bean hydration prior to cooking has been reported to have an important role in determining the cooking time, appearance and the extent of protein denaturation and starch gelatinisation of legumes [6,7]. Hydration is a very complex phenomenon that involves different physical mechanisms such as water imbibition, internal diffusion, convection at the surface and within large open pores, and relaxation of the solid matrix [8]. Literature reveals that several models to represent the hydration characteristics of grains have been developed which can predict the necessary time to obtain the desired moisture content under a given scenario. These models are basically either empirical or mechanistic. Empirical models are generally obtained from simple mathematical correlation of experimental data [6,9–12]. On the other hand, the elementary steps of diffusion and/or convection mass transfer are considered in the case of mechanistic models [5,13–15].

Due to the slowness of the solid–liquid mass transfer processes, several methods have been considered to accelerate the kinetics [16]. Ultrasound is a form of energy generated by sound waves (which are mechanical in nature) of frequencies that are too high to be detected by human ear, i.e. above 16 kHz [17,18]. A series of effects associated with acoustic energy are responsible for increasing the mass transfer rate without heating the material significantly [19]. Power ultrasound has been used to enhance mass transfer in solid/fluid food systems, resulting from cavitation and microstreaming phenomena. Cavitation is a phenomenon that can be either stable or transient. Stable cavitation is associated with small bubbles dissolved in a liquid, while transient cavitation occurs when the bubble size changes quickly and collapses, and as a result locally produces very high pressure (100 MPa) and high

temperature (5000 K) [20–22]. Acoustic streaming can be described as a steady fluid motion created under the influence of high amplitude acoustic waves, when they propagate through a dissipative fluid medium [23]. The applications of power ultrasound in food processing have been reviewed by several authors [24–27].

In this study, ultrasound was employed as a method to enhance the rate of water absorption in navy beans while soaking. The main objectives were: (a) to evaluate the effect of ultrasound on rate of hydration while soaking navy beans; (b) to examine the capability of selected mechanistic and empirical mathematical models for their suitability to predict the water absorption with ultrasound application; (c) to investigate the effect of ultrasound assisted soaking on the viscosity characteristics of bean powder.

2. Materials and methods

2.1. Physical properties of beans

Navy beans (*P. vulgaris*) with initial moisture content of 10.32 ± 0.25% (d.b.) were obtained from Heinz, UK. This initial moisture content was determined by drying the samples in an oven at 103 °C for 72 h. The dimensions of the bean were determined using a vernier calliper and average values of five observations were recorded. Fig. 1 shows the different geometrical dimensions of navy beans. The beans were considered as ellipsoidal bodies. Average weight of five beans was determined using a precision balance and found to be 0.215 ± 0.014 g.

In order to take into account the non-sphericity of the grains, the radius of an equivalent sphere was used in the calculations. The arithmetic mean diameter (A_m) and geometric mean diameter (G_m) were calculated based on the three dimensions using Eqs. (1) and (2) given by Mohsenin [28] while the equivalent radius (r) was calculated using the mathematical expression for ellipsoidal bodies [29,30], given by Eq. (3)

$$G_m = (lwd)^{1/3} \tag{1}$$

$$A_m = \frac{l + w + d}{3} \tag{2}$$

$$r = \frac{1}{2}\left\{\frac{G_m + A_m + S_m}{3}\right\} \tag{3}$$

where A_m is the arithmetic mean diameter (mm), G_m is the geometric mean diameter (mm) and S_m is the square mean diameter (mm), given by Eq. (4)

$$S_m = \left(\frac{lw + wd + ld}{3}\right)^{1/3} \tag{4}$$

2.2. Soaking procedure

Bean samples with a fresh mass-equivalent of 20 g total solids were placed inside a very thin cotton perforated cloth and soaked in 100 mL water in beakers. Two sets of beakers were placed in a water bath at a temperature of 16 °C, which served as control in duplicate. For ultrasound assisted soaking two sets of beakers were placed inside a sonication bath (Model FS 200B, Decon Laboratories, England) and operated continuously at 47 kHz and 750 W power levels. The weight of hydrated beans was determined at regular intervals using a precision balance. The successive differences in weights were used to calculate the moisture content for these intervals.

During hydration, water moves inside the food material and significant soluble solids are lost. The kinetics of solid loss depends on the immersion medium [31] and state of system variables. To check for any significant loss of solids from the beans, the total soluble solids (TSS) in the soaking water was measured at regular intervals using a Abbe refractometer. In this study, the effect of loss of soluble solids from navy beans was not taken into account in calculating the moisture content because maximum loss of soluble solids from navy beans at temperatures of 16 °C after 4.5 h soaking with ultrasound was negligible in comparison with the water gain. The sonication assisted soaking produced well-hydrated beans with minimum damage, similar to control beans soaked without sonication.

2.3. Pasting characteristics of bean powder

The pasting profile of the beans was determined using a Rapid Visco Analyser (RVA-TecMaster, Pertan, United Kingdom) equipped with Thermocline for Windows (TCW) software for viscometric data acquisition and analysis. Raw grains, sonicated and water soaked bean samples were dried at 40 °C to a moisture level of 12 ± 0.5% and milled according to the manufacturer's guidelines and subjected to the standard 1 profile. Sample (2.5 g) and distilled water (25 mL) were added within a standard RVA container. The test container was held at 50 °C for 1 min and then heated from 50 to 95 °C at a uniform rate of 12.16 °C/min. The sample was held at 95 °C for 2.5 min, then cooled off to 50 °C at a rate of 11.84 °C/min and held for 2 min. The total cycle lasted 13 min. The stirring was constant at 160 rpm. The data from the RVA curve was analysed using a Thermocline for Windows version 22 (Newport Scientific Pty. Ltd.) to determine the peak viscosity (maximum viscosity during heating and holding at 95 °C) and final viscosity (viscosity at the end of the test profile). Gelatinisation or pasting curves of sonicated, raw and water soaked samples were obtained and viscosity was expressed in units of centipoise (cP). All samples were analysed in triplicates.

2.4. Modelling of water absorption kinetics

Kinetic models were fitted to the experimental data obtained from soaking experiments. Nonlinear regression was carried out in Minitab software package (Minitab® ver. 16, Minitab Ltd.) using Gauss–Newton algorithm. The models considered in the present
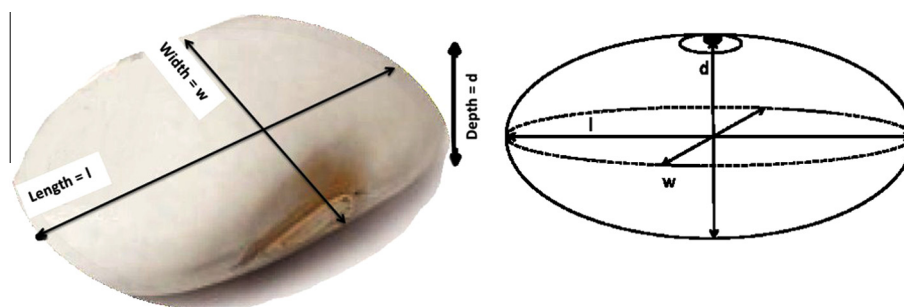

Fig. 1. Schematic of different dimensions of a navy bean. The shape of navy bean can be approximated to an ellipsoid.

study are Fickian diffusion model, Peleg model, Weibull model and first order kinetics model.

2.4.1. Fick's diffusion model

Fick's laws of diffusion and its derived equations account for the vast majority of the models utilised in food science [32]. Assuming that water diffuses through the kernel, that the water diffusivity is constant and the effect of volume change negligible, and that the surface concentration reaches saturation instantaneously upon water immersion, Fick's second law of diffusion for a spherical body in terms of average moisture content, m, is given by Eq. (6) [33]:

$$\frac{M_t - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \sum_{k=1}^{\infty} \frac{1}{k^2} \exp\left(-\frac{k^2 \pi^2 D_{ef} t}{r^2}\right) \tag{5}$$

where M_t, M_0 and M_e are moisture content at any time, initial, and equilibrium (or saturation) moisture contents (kg/kg, dry basis), t is the time (s), r (m) the equivalent radius (radius of the sphere having the same volume as the grain) and D_{ef} the effective diffusivity (m²/s). When time becomes large, the diffusion coefficients can be estimated taking into account only the first term of the infinite Fourier series solution and the limiting form of Eq. (5) can be approximated to [34] Eq. (6) (also known as the Henderson and Pabis model):

$$\frac{M_t - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \exp\left(-\frac{D_{ef} \pi^2 t}{r^2}\right) \tag{6}$$

For situations where the left hand side of Eq. (6) becomes ⩾0.5, the total error is usually below 0.1%. Eq. (6) can be rearranged to obtain Eq. (7) [5], as is used in this study:

$$M_t = M_e + (M_0 - M_e)\frac{6}{\pi^2} \exp\left(-\frac{D_{ef} \pi^2 t}{r^2}\right) \tag{7}$$

2.4.2. Peleg model

A quite simple non-exponential empirical equation proposed to model water absorption and desorption by food materials (that asymptotically approach equilibrium) is the well-known Peleg equation, given by Eq. (8) [9]:

$$M_t = M_0 + \left[\frac{t}{k_1 + k_2 t}\right] \tag{8}$$

where k_1 (s), Peleg rate constant relates to sorption rate at the very beginning, while the capacity constant, k_2 relates to maximum (or minimum) attainable moisture content.

2.4.3. Weibull model

Typically, the Weibull distribution is described by two parameters: the scale parameter, α, is the reciprocal of the process rate constant, and the shape parameter, β represented in Eq. (9):

$$\frac{M_0 - M_t}{M_0 - M_e} = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^\beta\right] \tag{9}$$

The scale parameter, α, defines the rate and different values of α lead to very different curves; for instance, the higher its value, the slower the process at short times [32].

2.4.4. First order kinetics

First-order kinetics is often assumed based on an empirical approach that the rate of hydration is proportional to a temporary driving force (Eq. (10)). When $\beta = 1$ in the Weibull distribution model, it reduces to a first order. The parameter k is the rate constant:

$$\frac{M_0 - M_t}{M_0 - M_e} = 1 - \exp(-kt) \tag{10}$$

2.5. Statistical analysis

For the evaluation of the fitting capacity of the models the statistical criterion of the adjusted coefficient of multiple determinations (R_{adj}^2) and the root mean squared error RMSE have been used:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n_t}(y_{\exp}(t_i) - y(t_i, p_{ls}))^2}{n_t - n_p}}$$

where $y_{\exp}(t_i)$ denotes the experimental observations, $y(t_i, P_{ls})$ the predicted values, n_t the total number of data points, n_p the number of estimated model parameters:

$$R_{adj}^2 = 1 - \left(\frac{n_t - 1}{n_t - n_p}\right) \cdot \frac{SSE}{SSTO}$$

Herein, SSTO is the total sum of squared errors $\sum (y_i - \bar{y})^2$ and SSE the sum of squared errors $\sum(y_{\exp}(t_i) - y(t_i, p_{ls}))$.

One-way analysis of variance (ANOVA) and Tukey tests were performed using SPSS statistical package (Ver. 19) to test for significant differences between treatments. Significance level were tested at $p < 0.05$.

3. Results and discussion

3.1. Equivalent radius of navy bean

The average length (l), width (w) and depth (d) of the navy beans was found to be 8.9 ± 0.493 mm, 5.9 ± 0.245 mm and 5.04 ± 0.171 mm respectively. The radius of the equivalent sphere was estimated to be 3.0095 ± 0.071 mm.

3.2. Mathematical modelling

3.2.1. Fick's diffusion model

The parameters of the Fick's diffusion model, D_{ef} and M_e, were estimated by using the non-linear regression analysis and found to be 1.36×10^{-10} m²/s and 114.37% d.b. for soaking without ultrasound, and 2.19×10^{-10} m²/s and 119.21% d.b. with ultrasound respectively. The experimental and predicted values are shown in Fig. 2, which clearly depict that application of ultrasound increased the diffusivity of water into the beans. Moisture diffusivity is an important transport property necessary for the design and optimisation of all the processes that involve internal moisture movement [5].

When high intensity acoustic energy travels through a solid medium, the sound wave causes a series of rapid and successive compressions and rarefactions, with rates depending on its frequency. In turn, the material is subjected to a rapid series of alternating contractions and expansions, much like when a sponge is squeezed and released repeatedly (sponge effect). This mechanism, known as "*rectified diffusion*", is very important in mass transfer operations [18,35,36]. The sponge effect caused by ultrasound application may be responsible for the creation of microscopic channels in beans, which reduce the internal resistance to the mass transfer [37]. The alternating pressures and microstreaming phenomenon at the interfaces disturb the diffusion boundary layer, whence decreasing the resistance to convective mass transfer.

To the best of our knowledge, this is the first study attempting at enhancement of hydration rates of navy beans using high frequency acoustics. Similar to the results obtained in this study, Yildirim et al. [5] have also reported an increase in magnitude of diffusion coefficient from 1.40×10^{-10} m²/s to 2.01×10^{-10} m²/s at 20 °C for chickpeas soaked with ultrasound irradiation at 25 kHz, 300 W respectively. We wish to highlight the difficulty that we encountered in comparing diffusivities reported in literature. This problem stems from the different estimation methods and
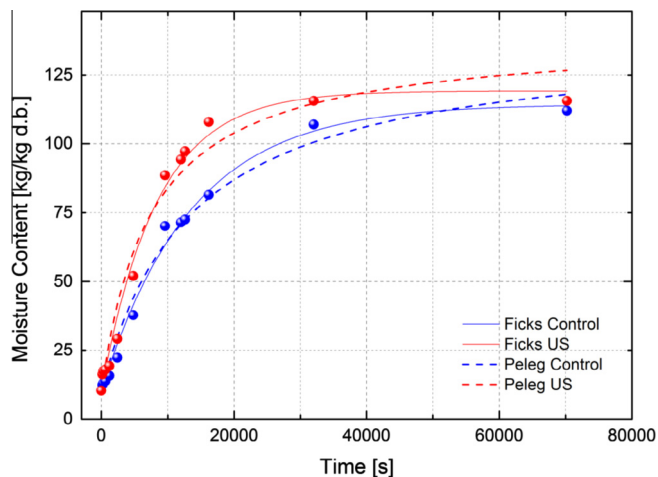
Fig. 2. Experimental and predicted values of moisture content without (blue) and with (red) ultrasound treatment. Solid Lines represent corresponding Fick's diffusion model fitted to the data; dashed lines represent corresponding Peleg's model fitted to the data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
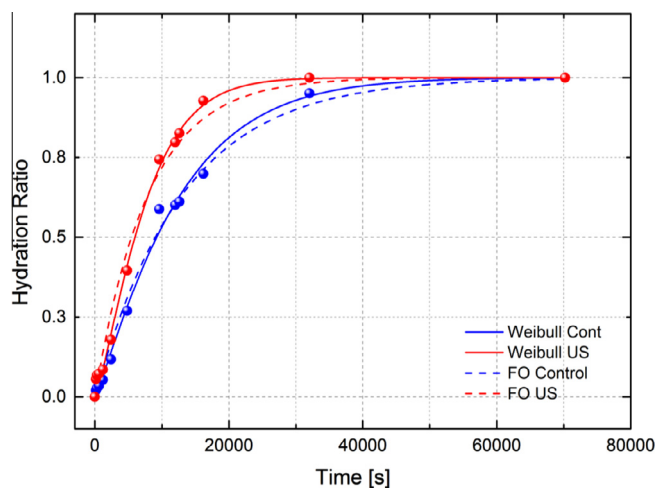

Fig. 3. Experimental and predicted values of moisture content without (▲) and with (■) ultrasound treatment. Solid lines represent corresponding Weibull model fitted to the data; dashed lines represent corresponding first order kinetics model fitted to the data.

models employed together with the variation in food composition and physical structure. A compilation of effective diffusivities for some agricultural seed materials is provided in [38] and a comparison of data from this study is in agreement with reported diffusivities for water absorption in grains.
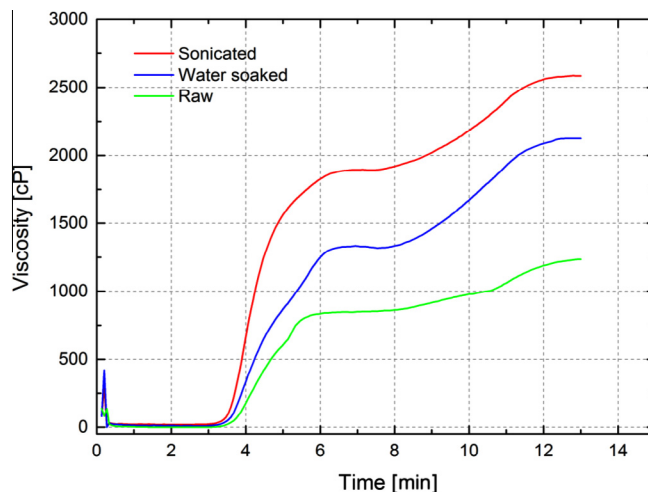

Fig. 4. RVA viscosity (cP) as function of pasting time (min) for raw, sonicated and water soaked beans.

Although, vast majority of the studies for mathematically describing liquid water transport in agricultural products rely on Fick's law, it should be noted that the liquid water transport cannot be solely described as a diffusion process. This aspect has been highlighted in the work of Khazaei and Mohammadi [39]. It is also worthwhile noting that an effective diffusivity (D_e) is used due to limited information on the mechanism of moisture movement during soaking process. Therefore, it is necessary to evaluate empirical models for accurately predicting the hydration kinetics. The higher RMSE value of the Fick's model also forms a motivation for empirical modelling approaches. It also suggests the non-Fickian nature of navy bean hydration, which is explained by the fact that it is not completely diffusion controlled, but also involves swelling and structural changes.

3.2.2. Peleg model

The parameters in this model k_1 (s) and k_2 as estimated by nonlinear regression fitting were found to be 105.21 s and 0.0077 for soaking without ultrasound while 58.3275 s and 0.0077 with ultrasound respectively (Fig. 2). Ultrasound soaking significantly affected k_1 parameter than k_2. It should be noted that a higher value of k_1 (s) in Eq. (9) implies slower rate of the process. Abu-Ghannam and McKenna [10] studied sorption behaviour of soybean, cow pea and peanuts at low, room and high temperatures and reported that Peleg's constant k_1 varied with temperature while constant k_2 was not affected. This can be justified based on the fact that the equilibrium moisture content of the grains are unlikely to increase by a significant amount, given the fact that k_2 provides information regarding the maximum value at which the rate curve plateaus [26]. A comparison of the model errors (RMSE) revealed

Table 1
Regression coefficients and coefficient of determination (r^2) for the models fitted to hydration kinetics data.

Model	Soaking condition	Regression coefficients	R^2_{adj}	RMSE
Fick's diffusion	Control	$D_{ef} = 1.36 \times 10^{-10}$ m^2/s; M_e = 114.37% d.b.	0.992	3.18
	Sonicated	$D_{ef} = 2.19 \times 10^{-10}$ m^2/s; M_e = 119.21% d.b.	0.989	4.43
Peleg	Control	k_1 = 105.21 s; k_2 = 0.0077	0.985	4.70
	Sonicated	k_1 = 58.32 s; k_2 = 0.0077	0.969	7.61
Weibull	Control	α = 12719.87; β = 1.13	0.994	0.03
	Sonicated	α = 7964.79; β = 1.26	0.995	0.03
First order	Control	$k = 7.70 \times 10^{-5}$	0.993	0.03
	Sonicated	$k = 12.69 \times 10^{-5}$	0.989	0.04

Table 2
Peak viscosity and final viscosity of samples.

Samples	Peak viscosity (cP)	Final viscosity (cP)	Pasting temperature (°C)	Breakdown (cP)	Setback (cP)
Sonicated beans	1935.33 ± 45.24[a]	2663.33 ± 78.50[a]	79.63 ± 0.51[a]	66.67 ± 9.29[a]	794.67 ± 42.16[a]
Water soaked	1339.33 ± 25.42[b]	2152.00 ± 38.43[b]	80.73 ± 0.03[b]	84.00 ± 22.61[a]	896.67 ± 36.61[b]
Raw beans	857.33 ± 9.71[c]	1251.00 ± 14.42[c]	82.58 ± 0.53[c]	10.67 ± 0.57[c]	404.33 ± 7.64[c]

*Columns that do not share the same letter (a or b or c) are significantly different at $p < 0.05$.

that Peleg's model could not satisfactorily explain the dynamic moisture levels of grain during hydration, as compared to Fick's model. Therefore, Weibull and First order models were also evaluated for the purpose of prediction of hydration levels.

3.2.3. Weibull model

The values of α and β were estimated to be 12,719.87 and 1.13 for control, while 7964.79 and 1.26 for hydration with sonication respectively. The lower value of α for ultrasound assisted hydration compared to control implies a faster process rate for former. The Weibull model exhibited a strong fit to predict the hydration ratio as indicated by the lowest RMSE value among all models (Fig. 3).

3.2.4. First order kinetics

The value of k was estimated to be 7.70×10^{-5} and 12.69×10^{-5} for control and sonication assisted hydration respectively (Fig. 3). These values are in agreement with the parameter α obtained from fitting Weibull model. The inverse of α (i.e. $1/\alpha$) for control and ultrasound assisted soaking processes are $(1/12,719.8=)$ 7.8×10^{-5} and $(1/7964.8=)$ 12.7×10^{-5} respectively. Thus, it emphasises upon the relatively robust nature of Weibull model compared to the first-order exponential decay type model.

The regression coefficients, goodness of fit expressed in terms of coefficient of determination (R^2) and mean relative error (%) have been summarised in Table 1. The best fitting for water transport experimental data was obtained using Weibull's distribution model as evident from the lowest RMSE values.

3.3. Pasting characteristics

Classification of viscosity pattern is important to categorise the starch for end product recommendation. Fig. 4 shows the pasting profile of sonicated, water soaked and raw bean samples. Sonicated samples showed significantly higher peak viscosity (1935.33 ± 45.24 cP) compared to water soaked (1339.33 ± 25.42 cP) and raw samples (857.33 ± 9.71 cP). Similar trend was observed for final viscosity and setback viscosity (Table 2). The higher viscosity observed in the case of water soaked only and sonicated samples may be due to stronger interaction between starch granules. Similar increase in viscosities was reported by Anton et al. [40] for navy and pinto bean samples which were soaked and subsequently dried. It is likely that ultrasound treatment during soaking modifies the microstructure of navy beans. This may cause the amylose granules of starch to be packed more compactly in bean powder, thereby hindering the accessibility of water molecules to the binding sites on the amylose chains of the correspondent starches. It should be noted that most published work report a decrease in viscosity of starch solutions post ultrasound treatment [41,42]. However, all reported studies were conducted for pure starch in solution and not on whole grain flour. The higher viscosity of sonicated bean powder could especially be beneficial for food industries, considering that most navy bean based products demand higher viscosity (except for beverage based products, where a low viscosity is desirable) [40,43].

4. Conclusions

Ultrasound was found to enhance the mass transfer kinetics in the soaking process of navy beans. Diffusion coefficients of water for control and sonication process were estimated using Fick's second law of diffusion. This study suggests that the effective diffusivities for water transport in beans are enhanced due to sonication, resulting in quick hydration of beans. It also demonstrates the potential of sonication treatment in reducing the soaking time of beans. Significant changes in viscosity characteristics of sonicated beans have been observed, which needs more investigation for a sound explanation. Further studies are required to evaluate the effect of ultrasound assisted soaking on the nutritional properties of navy beans and changes in microstructure.

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