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Influence of ultrasonication during soaking on water absorption and Softness characteristics in the cooking process of cowpea

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ABSTRACT

Owing to the long duration of cooking legumes, which limits their consumption and utilization, soaking has been used to reduce cooking time, save energy consumption, and diminish their hardness. However, limited studies have reported the influence of cooking and soaking treatment along with ultrasonication on hydration, hardness, and cooking time reduction of legumes. Therefore, this study investigated the impact of cooking and soaking treatments on Dr. Saunder cowpea's water absorption, hardness, and cooking time reduction with and without ultrasonication. Samples of Dr. Saunder's cowpea were first soaked at 30 °C and 50 °C for 15 – 90 min (with and without ultrasonication), after which they were cooked at 100 °C and 121 °C for 15 – 120 min. The absorbed water and hardness of the tested samples under these treatments were measured. Hydration and softening behaviors were modeled from the obtained data using Ibarz-Augusto and first-order equations, respectively. Arrhenius equation was used to describe the kinetics of the hydration and softening process. Results showed that ultrasonic treatments accelerated water absorption and reduced the hardness of the samples; consequently, in a shorter time, using less energy will receive the desired hardness as the final product. The Ibartz-Augusto and first-order equations perfectively fit the sigmoidal and decaying exponential behavior of the absorbed water and hardness data with high prediction performance ($R^2 \approx 1$) marked by minimal error values. The deployment of ultrasonication and increased cooking temperature were observed to reduce the kinetic parameter (water absorption) and elevate the softening rates and activation energy (for hydration and softening). A synergy of the trio treatments reduced the total cooking duration from 120 min to 90 min (25 %), thus promoting the benefit of deploying ultrasonication to soften cowpeas and other seeds rapidly.

1. Introduction

Ultrasonics has diverse applications across multiple disciplines. In material synthesis, colloidal nanocrystal synthesis and biomedical applications [1]ultrasonic waves are used to produce nanoparticles and nanocomposites, as cavitation promotes high-energy environments that accelerate chemical reactions and enhance material properties. In environmental science, ultrasonics is employed for wastewater treatment by breaking down organic pollutants and aiding the degradation of harmful compounds [2]. In the food industry, ultrasonics enhances extraction processes, such as isolating bioactive compounds from plant matrices, and improves food emulsification and homogenization [3]. In biomedicine, therapeutic ultrasound has shown promise in drug delivery and the disruption of biological barriers like the blood–brain barrier, enabling precise treatments [4].

Cowpea accounts for over 50 % of the legumes consumed globally [5]. Cowpeas are an inexpensive dietary source of proteins, carbohydrates, fiber, minerals, and vitamins, which have considerably encouraged their cultivation and consumption, mainly in Africa, Latin America, and developing countries of Asia. Cowpeas are not consumed raw but must be cooked or processed before consumption. Cooking cowpeas (legumes) enhances their nutritional and sensory properties by reducing antinutrients (e.g. tannins and phytic acid). It lowers lectin phytohemagglutinin, a toxic compound that causes gastric upsets [6]. Depending on several factors such as cooking method, variety, storage condition, seed characteristics (seed coat color, skin, flatness, etc.), and cooking

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medium, the cooking time of cowpeas ranges from 45 to 230 min [5,6] This relatively long duration is undesirable for economic and environmental reasons, and therefore, the cooking time must be reduced.

As part of the process for reducing cooking time, legumes are often pretreated using several methods prior to further processing. Soaking [7]is one of the pretreatment methods that is applied extensively and it involves hydrating the legume seeds for various time durations.

Soaking grains and seeds is a diffusion-driven process, where water enters the seed through its outer layers and spreads internally, activating critical physiological and enzymatic functions. This hydration kickstarts metabolic activities necessary for germination, such as enzyme activation that breaks down stored nutrients like starch into simpler molecules for energy. The process depends on factors such as water availability, seed structure, and environmental conditionsMuchlisyiyah et al. [8,9]. This allows for water or other soaking media (e.g. NaCl, $CaCl_2$, Na_2CO_3, etc.) to diffuse through the seed coat to the cotyledons due to the difference in medium vapor pressure in the seed and outside the seed until equilibrium is attained [10]. This facilitates even distribution of the soaking medium within the seed, therefore causing uniform softening of the cotyledons.

Several studies have been carried out on the influence of variations in the soaking temperature and duration on the water absorption, nutritional and sensory characteristics of various cultivars of legumes (cowpea) [11–14]. Generally, an increase in soaking duration and temperature was observed to enhance the water absorption characteristics of the studied seeds. The hydrothermal characteristics (at soaking temperatures of 25 – 45 °C and duration of 0 – 620 min) and the development of a model to predict the hydration kinetics of the two cultivars of cowpea and Bambara seeds were carried out [11]. The water absorption behavior of Adzuki beans soaked for 9 h and at a soaking temperature of 35 °C was studied [12]. The influence of a soaking duration of 0 – 390 min and soaking temperature of 23 – 60 °C on the water absorption and morphology of Andean lupin (Lupinus mutabilis Sweet) was investigated by (Miano & Augusto. In addition, the effect of soaking temperatures of 25 – 55 °C and soaking times of 0 – 500 min on the physical properties of moong beans was studied [14]. These studies failed to investigate the influence of the hydrothermal properties on the hardness of legumes. However, the influence of soaking temperature (20 °C, 50 °C, and 85 °C) and duration (0 to 180 min) on the water intake and hardness characteristics of three cultivars of lentils was studied [10]. Increasing the soaking temperature and time was observed to enhance water uptake in the cultivars, but the reverse was noticed for the hardness.

Ultrasonication (UT) has also been used to improve hydration further and reduce the cooking time of legume seeds, in addition to conventional hydration methods of cooking and soaking treatments. Sonication is an environmentally friendly, non-thermal, non-destructive, speedy, flexible, and promising technique that deploys sound waves to homogenize or disrupt materials (biological or chemical medium) utilized in food (drying, salting, osmotic dehydration, etc.) [15,16]and non-food sectors[17]. UT yields high-quality products and achieves reduced processing time at lower temperatures by enhancing heat and mass transfer rates. However studies on its use for the hydration and softening of legumes are lacking [18–24]. The influence of ultrasonication on the hydration and germination of mung beans soaked at 25 °C for 500 min was examined by Miano et al. [21]. Ghafoor et al. studied the effect of ultrasonication on water absorption rate and pasting characteristics of navy beans soaked at 16 °C for 4.5 h min [18]. Yildirim et al. investigated the impact of variation in ultrasonication frequency on the water absorption of chickpeas soaked at 20 – 97 °C for 3.5 h min [23]. UT was studied on chickpeas and mung beans' water absorption and germination characteristics soaked for 4 h [22]. These studies revealed enhanced hydration and germination of the studied legumes as UT was introduced, which further increased with increasing ultrasonication energy density and soaking duration and temperature.

This present study aimed to examine the effect of UT treatment on water absorption and hardness behavior of cowpeas under varying soaking and cooking conditions. It also sought to model the hydration and softening kinetics of the cowpeas subjected to soaking, cooking, and UTs. This study provides an insight into the mass transfer characteristics of cowpea, which influenced its hydration and softening, as this would enable the optimum design of the processing conditions to realize the final products' maximum quality and nutrient content. The possible reduction in soaking and cooking time, which consequently minimizes energy consumption on applying UT, was also investigated.

2. Materials and methods

2.1. Materials

A red cowpea type, [Dr. Sanders (DS)], grown in South Africa and supplied by Agricol, Silverton, South Africa, was used in this study. The cowpeas were manually size-graded by removing split, dented, spoilt, and small samples. All materials used were of analytical grade.

2.2. Experimental procedure

2.2.1. Water absorption measurement for soaked samples

In this study, the water absorption rate of the cowpea samples was examined when soaked in water of constant volume (100 ml) at different soaking durations and temperatures. For the control experiment, the samples were soaked at 30 °C for 15 – 660 mins (without cooking), while the other studied samples were soaked at 30 °C and 50 °C for 15 – 90 min (with cooking). A maximum temperature of 50 °C was chosen as starch gelatinization is not expected to happen. Before each experiment, the cowpea samples were selected, and about 20 g of each sample was measured into an air-tight sample bottle using RADWAG MA 50R. Moisture analyzer/weighing scale with mass readability of 0.001 g and a maximum capacity of 50 g.

Also, the thermal bath was used to prepare water at constant temperatures of 30 °C and 50 °C. Then, 100 ml of water at the predetermined soaking temperature was taken from the thermal bath and added to the sample in the bottle. The sample bottle was then placed in a bath with constant temperature and allowed to soak for the desired time. Then, the sample was filtered, tenderly cleaned from water moisture, and reweighed. The initial and final weight difference was used to determine the absorbed moisture content (%).

$$Waterabsorbed(\%) = \left(\frac{W_f - W_i}{W_i}\right) \times 100 \quad (1)$$

2.2.2. Water absorption measurement for soaked and ultrasonicated samples

With a similar procedure as above (Sub-section 2.2.1), the thermal bath was used to prepare water at constant temperatures of 30 °C and 50 °C, and the ultrasonic bath was set to the desired soaking temperature and 100 % sonication power for 20 min to get steady. Then, 100 ml of water at the predetermined soaking temperature was taken from the thermal bath and added to the sample in the bottle. The sample bottle was after that placed in the ultrasonic bath and allowed to soak for the desired time while being sonicated. After the soaking time elapsed, the sample was filtered and tenderly cleaned from water moisture and reweighed. The initial and final weight difference was used to determine the absorbed moisture content (%).

2.2.3. Cooking of soaked samples

After recording the weight, the soaked cowpeas were put in pre-warmed temperature resistance containers, and 100 cc distilled boiling water was added to the containers. For cooking at 100C, the containers were placed in a pot which contained tap water in boiling condition. The cooking time is set for 15, 30, 45, 90 and 120 min. The same procedure applied for cooking at 121C, except using a pressure cooked. After the cooking time elapsed, the samples were filtered and tenderly cleaned from water moisture and reweighed. The initial and final weight difference was used to determine the absorbed moisture content (%) after cooking.

2.2.4. Hardness test

The hardness of randomly marked samples (soaked without cooking, soaked with cooking, and soaked with cooking and ultrasonication) was measured using a Digital Shore A Durometer (Hardness tester) which has a measuring range of 0 – 100 HA, a resolution of 0.5 degree, and measuring error ± 1 degree, and an indenter tip pressure of 0.55 N – 8.05 N. The hardness was measured to evaluate the moisture content's impact on the tested samples' hardness. These experiments were performed in triplicates using DS cowpeas and the average values of hardness and mass of cowpeas (before and after drying) were reported.

2.3. Hydration kinetics and hardness modeling

The DS cowpea hydration kinetics were modeled using the sigmoidal model described by [25] as expressed in Eq. (2). Appropriate model parameters obtained from the data of water absorption (with and without ultrasonication) for different soaking and cooking conditions (duration and temperatures) were evaluated using Eq. (2) and used to model the hydration characteristics of the studied samples. Similarly, models were developed for the softening characteristics of the studied DS cowpeas based on the first-order kinetics about the hydrothermal parameters (with and without ultrasonication) [18]. The first-order kinetics was expressed in Eq. (3). The prediction accuracy of the models was evaluated using coefficient of determination (R^2), and the associated errors were estimated using average absolute error and mean squared error (MSE).

$$M_t = \frac{M_e}{1 + \frac{M_e - M_o}{M_o} e^{(-k_{wa} M_e t)}} \tag{2}$$

$$\frac{H_o - H_t}{H_o - H_e} = 1 - e^{(-k_s t)} \tag{3}$$

Where M_o and H_o, M_e and H_e, M_t and H_t are the initial absorbed water and hardness, equivalent absorbed water and hardness, and specific absorbed water and hardness at a soaking time, respectively. Also, k_{wa}/k_s and t are the water absorption/softening rate and soaking time respectively.

To obtain k_s, the x (softening rate ratio) evaluated using Eq. (4) was substituted in Eq. (5). In addition, water absorption and hardness rate were evaluated using the Arrhenius equation as expressed in Eq. (6) to describe the temperature dependence of water absorption and softening rate. This equation is widely employed to describe the effect of temperature on the diverse physical and chemical properties of materials involved in a process.

$$x = \frac{H_0 - H_t}{H_0 - H_e} (0 \leq x \leq 1) \tag{4}$$

$$In(1 - x) = -k_s t \tag{5}$$

$$k_s or k_{wa} = Ae^{\left(\frac{-E}{RT}\right)} \tag{6}$$

Where k_s is the softening rate (1/min), k_{wa} is the kinetic parameter (water absorption process) ([% d.b. min]$^{-1}$), E is the activation energy (J/mol), T is the absolute temperature (K), R is the ideal gas constant (8.314 J/mol K), and A is the frequency factor (1/min).

2.4. Data analysis

Data obtained for the hydration and hardness of DS cowpea with and without cooking and UTs were statistically analyzed for the average, coefficient of determination (R^2), and analysis of variance (at 0.05 significance level). The hydration kinetics models developed for the DS cowpea and at different hydrothermal (with and without cooking and ultrasonication) treatments were fitted into the measured water absorption data. Their goodness of fits were analyzed for the R^2 and the root mean squared error. The same was done for the experimental and predicted hardness data obtained via the softening kinetics models.

3. Results and discussion

3.1. Hydration and hardness behavior of soaked samples (without cooking and ultrasonication)

The soaking of DS cowpea samples in distilled water at 30 °C for different durations was marked with water migration into the samples through the seed coat as represented by Fig. 1. Hydration of the samples via diffusion of water was due to the water vapor pressure gradient within and outside the seed coat which acts as a permeable membrane. The mass of the cowpea seeds increased with increasing water absorption. An increase in the soaking duration was noticed to cause a rise in the water absorbed, thereby increasing the mass of the seeds, which consequently reduced their hardness. It can be deduced that the hydration of the DS cowpeas led to a corresponding increase in the mass of samples from 20 g (at 0 min) to 22.8 g (at 15 min) and 41.9 g (at 660 min)) and percent of water absorbed (13.5 %d.b. (at 15 min) to 108.6 % d.b. (at 660 min)) and a reduction in hardness (98.2 %d.b. (at 15 min) to 19.2 % d.b. (at 660 min)). This observation agrees with previous studies on the hydration of different species of legumes [10,26]. A rapid rise in mass and absorbed water was observed immediately after soaking up to 240 min, after which it plateaued with a slow rise from 240 to 660 min. The hydration curve that displayed the sigmoidal behavior is similar to those reported in previous studies for other types of legumes [7,25]. Additionally, the decaying exponential curve of the hardness of the samples with increasing soaking time was similar to those observed in earlier studies [10,26].

The Ibartz and Augusto model was used to predict the sigmoidal hydration behavior of DS cowpeas under increasing soaking time from the experimental data of the absorbed water. A very close fit of the experimental and predicted data (p-value < 0.05) with a prediction performance of $R^2 = 0.9997$ was observed (Fig. 2). The fitted curve has an average absolute error of 2.5415 and a mean squared error of 2.9243 implying minimal error in the prediction of the absorbed water data. This result could be connected to the excellent positive and strong relationship (R = 0.9999) between the mass after soaking and the absorbed water. Notably, a negative and strong correlation existed between the mass after soaking and hardness (R = −0.9814) and water absorbed and hardness (R = −0.9808).

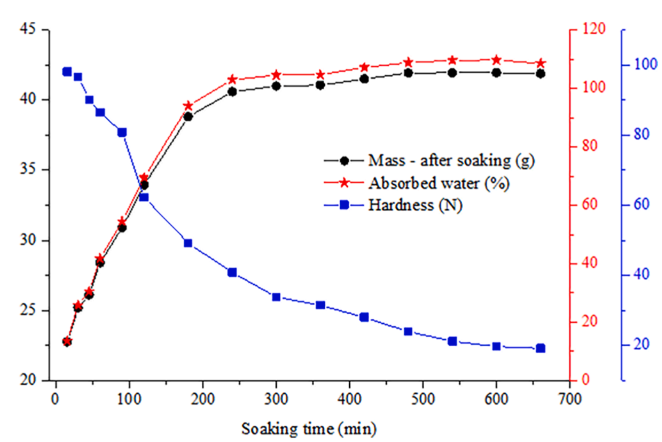

Fig. 1. Effect of soaking time on mass (after soaking), water absorption, and hardness of Dr Saunders cowpea seeds soaked at 30 °C.

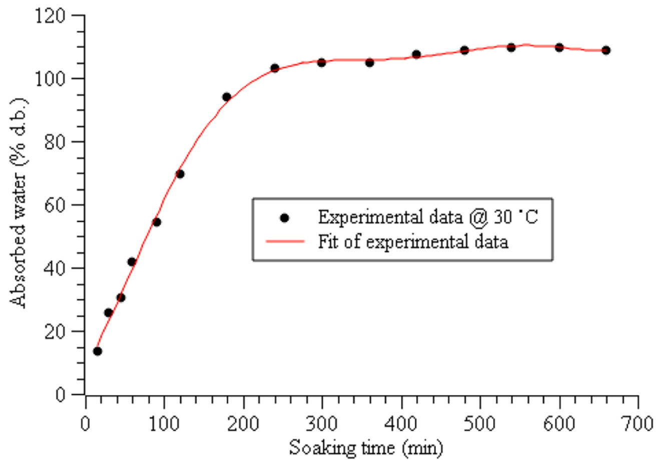

Fig. 2. Hydration kinetics of Dr Saunders cowpea seeds soaked at 30 °C.

3.2. *Water absorption behavior at 30°C (with cooking and ultrasonication)*

Soaking treatment reduces the hardness of legumes or grains, which is time and temperature-dependent. The addition of cooking treatment, such as an increase in cooking time and temperature, is expected to further aid the softening of these materials and also lower both the cooking time and soaking time. In this present study, the DS cowpea samples were soaked at 30 °C for 15 – 90 min and cooked at 100 °C and 121 °C without and with UT. Data obtained and analyzed were found to be statistically similar with a p-value of < 0.05. Fig. 3 shows that the samples' water absorption rate was enhanced with increased soaking time, cooking time, and cooking temperature. This finding aligns with previous studies, which reported a similar effect of increasing cooking and soaking temperature and duration [26,27]. Increasing the cooking temperature from 100 °C and 121 °C was found to elevate water absorption by 1.01 % – 10.81 % as soaking and cooking time increased when the samples were soaked at 30 °C and without ultrasonication. Upon UT and increasing cooking time, water absorption was enhanced by 2.82 % – 10.95 % as cooking and soaking time increased. This shows that increasing the cooking temperature slightly accelerated water absorption whether UT was applied or not. However, the effect of UT was more significant at higher cooking temperatures and durations, particularly at 121 °C (see Fig. 3). This could be connected to the water absorption increase that can possibly result in higher cooking temperature and duration coupled with the deployment of ultrasonication, which has been reported to be more effective at lower soaking temperatures

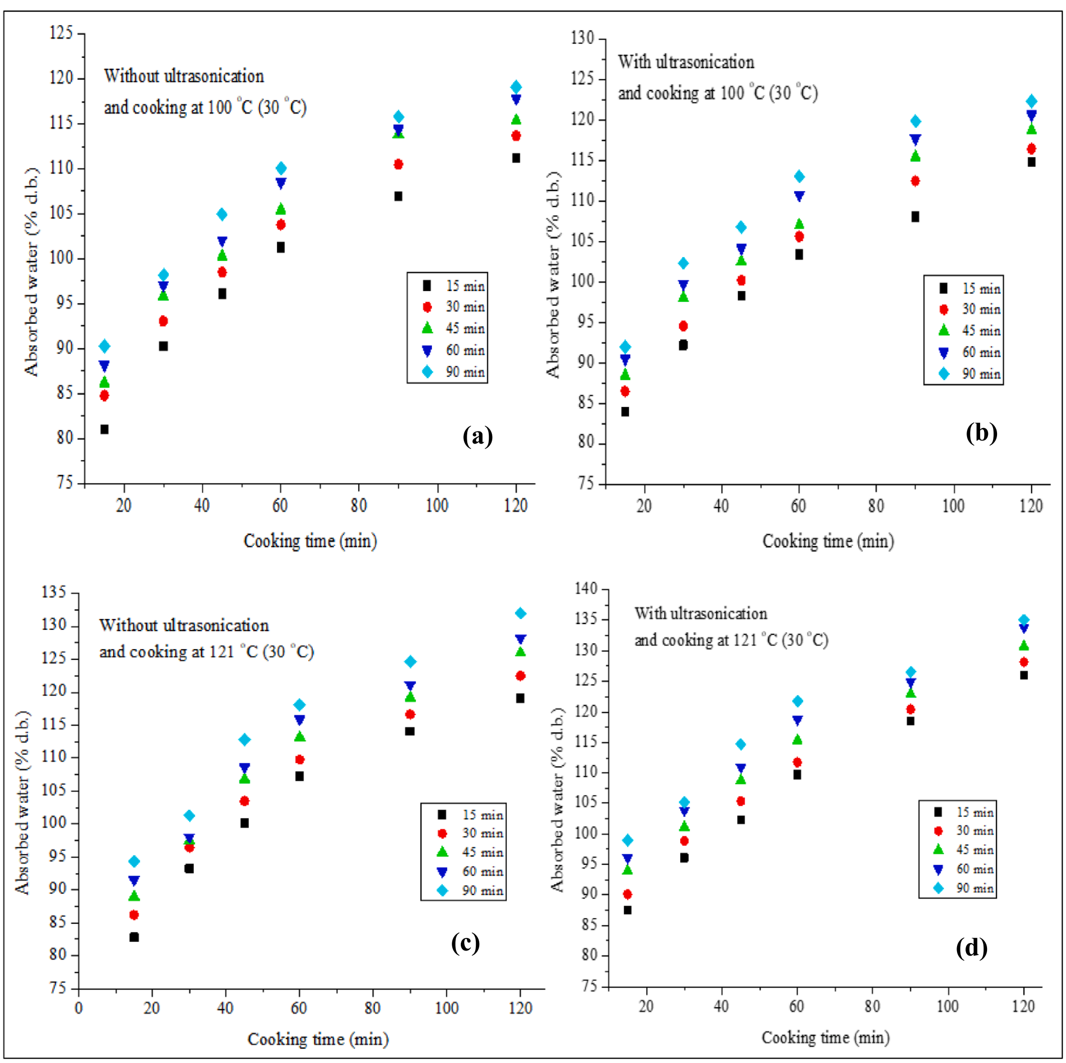

Fig. 3. Water absorbed (at 30 °C soaking temperature for the Dr. Saunders cowpea seeds) with rise in cooking time under increasing soaking time (a) without ultrasonication and cooking at 100 °C, (b) with ultrasonication and cooking at 100 °C, (c) without ultrasonication and cooking at 121 °C, and (d) with ultrasonication and cooking at 121 °C.

[16,27].

A comparison of the hydration of samples under increasing soaking time (at 30 °C) and those with increasing cooking time and temperature and soaking time (without and with UT) was carried out. It was observed that the water absorbed into the studied samples soaked at 30 °C was enhanced by 32.73 – 100.68 (when cooked at 100 °C without UT), 39.47 – 98.3 (when cooked at 100 °C with UT), 39.79 – 112.42 (when cooked at 121 °C without UT), and 38.44 – 105.59 (when cooked at 121 °C with UT). It is apparent that adding cooking conditions (temperature and time) increased water absorption while UT enhanced it at a cooking temperature of 100 °C.

3.3. Water absorption behavior at 50°C (with cooking and ultrasonication)

Fig. 4 presents the influence of increasing cooking temperature (100 and 121 °C), time (15 – 120 min), and soaking duration (15 – 90 min) on the hydration of cowpea samples soaked at 50 °C with and without UT. As earlier mentioned, increasing cooking temperature and time caused an improvement in water absorption as soaking time rose from 15 min to 90 min irrespective of UT or not. Hydration of the samples improved by 0.60 % – 9.34 % (without ultrasonication) and 3.07 % – 10.78 % (with ultrasonication) as the cooking temperature rose from 100 °C to 121 °C under increasing soaking and cooking time. An increase in cooking temperature is noticed to enhance water absorption into the samples. Fig. 4 shows that UT application slightly increased water absorption by 0.1 % – 3.17 % (for cooking at 100 °C) and 0.76 % – 5.63 % (for cooking at 121 °C) as soaking and cooking time increased. Thus, UT deployment contributed positively to the absorption of water by the studied sample, which could be related to the high cooking temperature under its application.

3.4. Hydration kinetics and model

Mass transfer of water into the skin coat of DS cowpeas leads to their hydration as a function of cooking temperature and duration and UT under increasing soaking time. The hydration behaviors of the samples cooked at 100 °C and 121 °C after soaking for 15 min and 90 min under increasing cooking time with and without UT were illustrated in Figs. 5 and 6 respectively. Both figures (5a, 5b, 6a, and 6b) demonstrated an increasing exponential curve as cooking time increased for cooking temperatures of 100 °C and 121 °C with and without UT. Increased soaking time (15 min to 90 min) resulted in a rise in the water absorbed irrespective of the soaking temperature, cooking time and temperature,

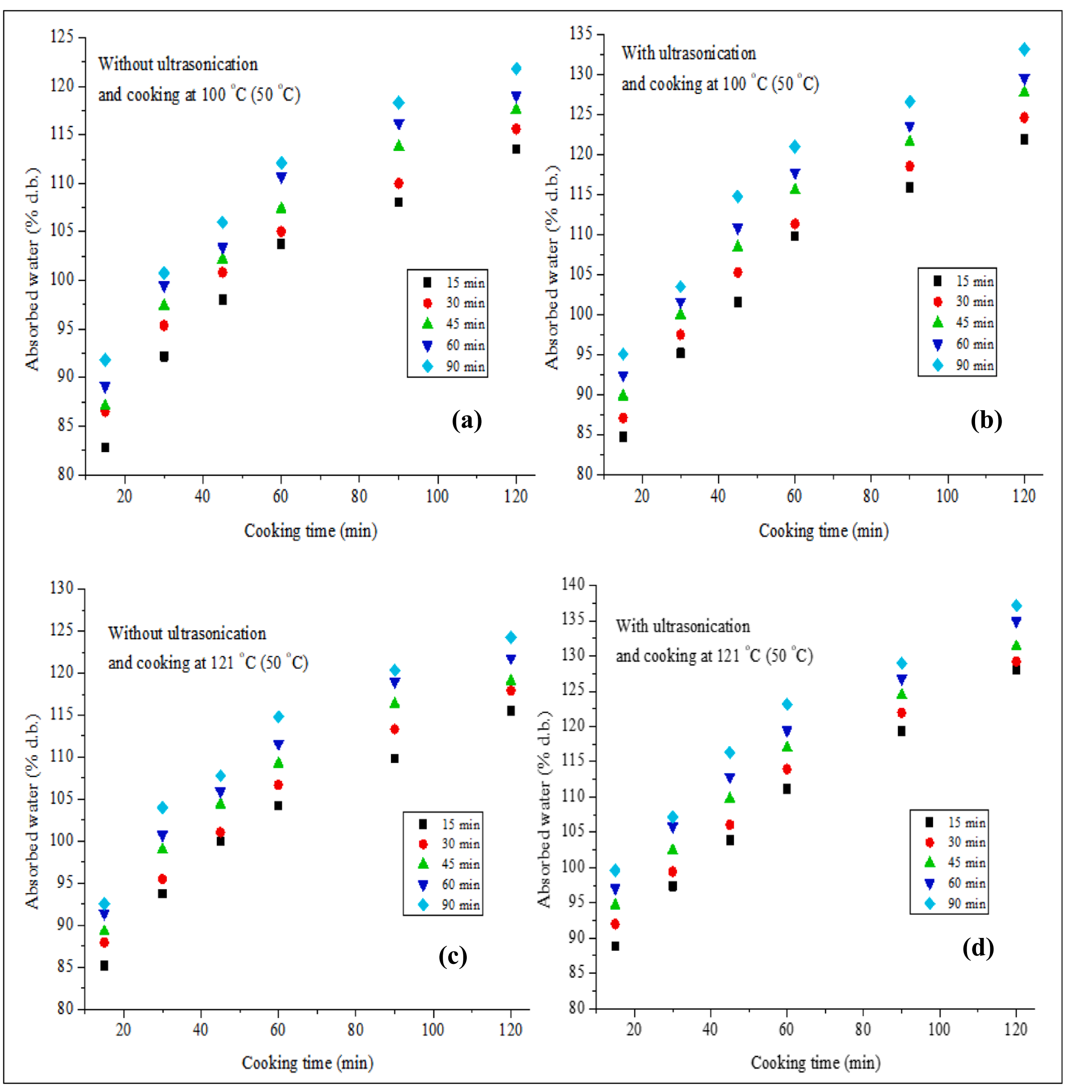

Fig. 4. Water absorbed (at 50 °C soaking temperature for the Dr. Saunders cowpea seeds) with rise in cooking time under increasing soaking time (a) without ultrasonication and cooking at 100 °C, (b) with ultrasonication and cooking at 100 °C, (c) without ultrasonication and cooking at 121 °C, and (d) with ultrasonication and cooking at 121 °C.

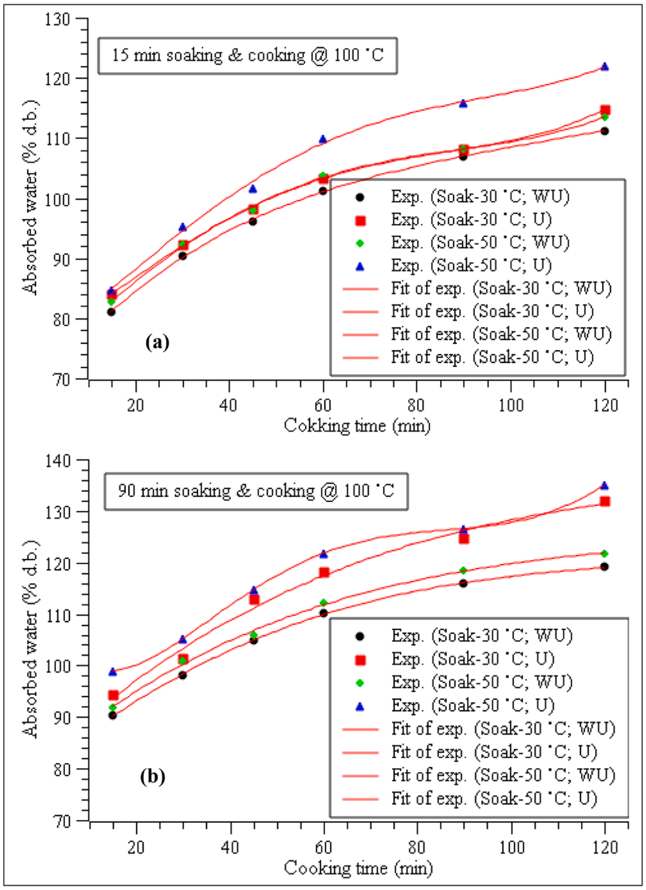

Fig. 5. Hydration kinetics of Dr. Saunders cowpea seeds cooked at 100 °C after soaking for (a) 15 min and (b) 90 min.

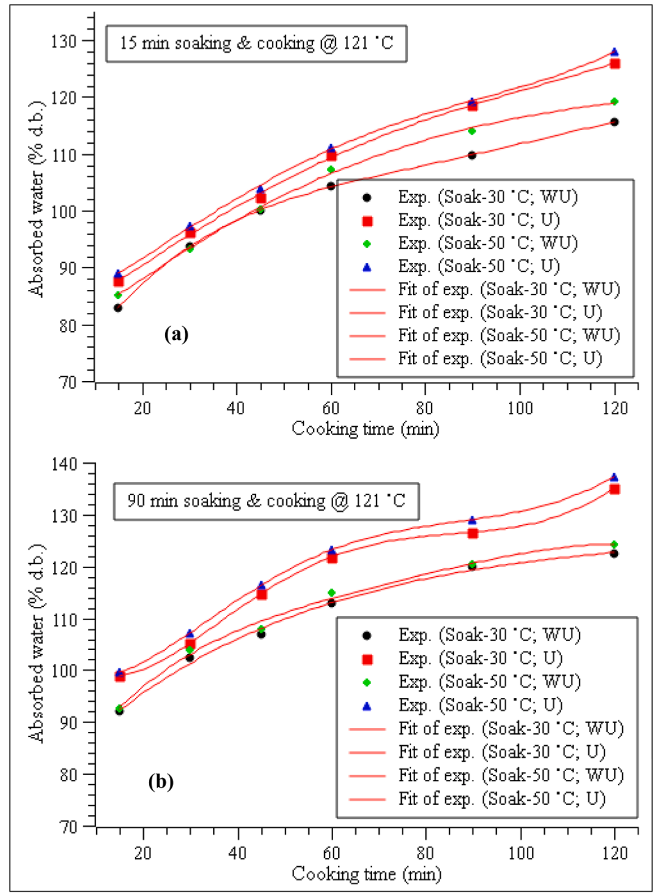

Fig. 6. Hydration kinetics of Dr. Saunders cowpea seeds cooked at 121 °C after soaking for (a) 15 min and (b) 90 min.

and UT (with and without). Additionally, the UT was found to be significant to the hydration of the studied samples, especially as soaking and cooking temperatures were elevated. The Ibartz and Augusto model used to describe the hydration kinetics behavior of the experimental data (90 min of soaking leading to maximum water absorption) was found to fit these data very well. Excellent prediction performances of $R^2 = 0.9997 – 0.9999$ and $0.9998 – 0.9999$ and minimal errors of AAE = 0.4275 – 0.6577 and 0.3269 – 0.5899, and MSE = 0.2397 – 0.3615 and 0.1892 – 0.3354 were estimated for cooking performed at 100 °C and 121 °C respectively, with and without UT. The prediction performance values were close to unity, which revealed excellent accuracy of the prediction of the experimental data using the Ibartz and Augusto model, which agreed with previous studies that engaged the same model [12,25]. Error values were low, showing a small deviation between the experimental and predicted data.

$$k_{wa} = 2.9919e^{\left(\frac{-31638.47}{RT}\right)} (\text{without UT (at } 100\,^{\circ}\text{C)}) \tag{7}$$

$$k_{wa} = 3.2018e^{\left(\frac{-32426.18}{RT}\right)} (\text{with UT (at } 100\,^{\circ}\text{C)}) \tag{8}$$

$$k_{wa} = 3.5282e^{\left(\frac{-35239.26}{RT}\right)} (\text{without UT (at } 121\,^{\circ}\text{C)}) \tag{9}$$

$$k_{wa} = 3.5718e^{\left(\frac{-35621.49}{RT}\right)} (\text{with UT (at } 121\,^{\circ}\text{C)}) \tag{10}$$

The Arrhenius equations describing the hydration kinetics behaviors at various cooking and ultrasonication treatments were expressed using Eqs. (7) – (10). The kinetic parameter (k_{wa}) was estimated to be 7.39 x 10^{-4} (without UT) and 7.07 x 10^{-4} (with UT), and 7.25 x 10^{-4} (without UT) and 6.74 x 10^{-4} (with UT) for samples soaked at 30 °C and with cooking performed at 100 °C and 121 °C, respectively. Also, k_{wu} of 7.26 x 10^{-4} (without UT) and 6.74 x 10^{-4} (with UT), and 7.2 x 10^{-4} (without UT) and 6.7 x 10^{-4} (with UT) was evaluated for samples soaked at 50 °C and with cooking performed at 100 °C and 121 °C, respectively. The deployment of UT and increased cooking temperature were observed to lower the kinetic parameters. The effect of UT on k_{wu} recorded in this study is consistent with the work of Ghafoor et al. [18]. The values obtained in this study were within the range of values published by Ibarz & Augusto [25] (3.6 x 10^{-5} – 4.63 x 10^{-4} (%db min)$^{-1}$) and Miano et al. [12] (7.7 x 10^{-5} (%db min)$^{-1}$). The activation energy of 31.64 and 32.42 and 35.24 and 35.62 kJ/mol were evaluated without and with UT and at 100 °C and 121 °C cooking temperatures, respectively. A slightly higher activation energy was recorded with UT and increased cooking temperature. These results were observed to be within the range of values (19.50 – 48 kJ/mol) reported in the literature [23]but for soaking treatment only.

3.5. Hardness behavior at 30°C (with cooking and ultrasonication)

The influence of soaking, cooking, and UTs on the hydration of legumes is scarcely studied, and this present work has investigated the effects of these treatments on the hydration behavior of DS cowpea samples, which consequently reduce their hardness. Fig. 7 presents the softening characteristics of the studied samples soaked at 30 °C as a dependent on soaking time, and cooking temperature and time with or without UT. It is observed in Fig. 7 (a – d) that increasing the cooking temperature and time and soaking time reduced the hardness of the

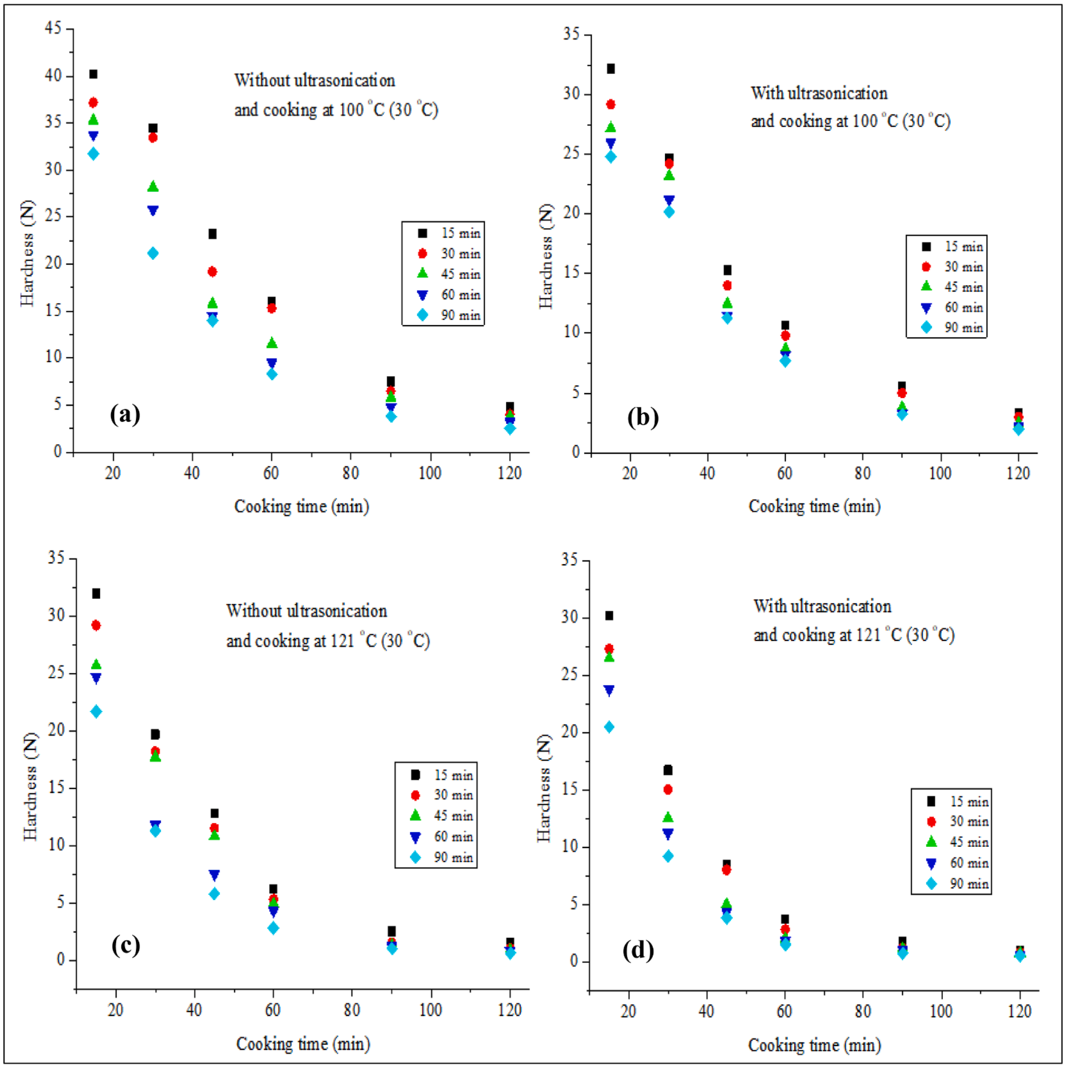

Fig. 7. Hardness (at 30 °C soaking temperature for the Dr. Saunders cowpea seeds) with rise in cooking time under increasing soaking time (a) without ultrasonication and cooking at 100 °C, (b) with ultrasonication and cooking at 100 °C, (c) without ultrasonication and cooking at 121 °C, and (d) with ultrasonication and cooking at 121 °C.

samples. The use of UT showed a significant (P-value < 0.5) reduction in hardness in Fig. 7a and 7b (for cooking temperature of 100 °C) and Fig. 7c and 7d (for cooking temperature of 121 °C). As the cooking temperature rose from 100 °C to 121 °C (under increasing soaking and cooking time), the hardness of samples reduced by 17.34 % – 76.92 % (without UT for Fig. 7a and 7c) and 6.51 % – 80.52 % (with UT for Fig. 7b and 7d). Higher cooking temperature is therefore observed to further soften the studied DS samples despite the reduction caused by increasing cooking, soaking time, and UT.

From hardness of 62.3 N (for 90 min soaking) and 98.17 N (for 15 min soaking) to hardness ranges of 2 – 40.2 N (soaking at 30 °C; cooking at 100 °C and with and without UT), and 0.5 – 32 N (soaking at 30 °C; cooking at 121 °C and with and without UT), all obtained under increasing soaking duration. These results showed the influence of soaking temperature, cooking temperature, and UT on the hardness of the DS samples[18,28]. The reduction in hardness due to soaking and cooking treatments observed in this study is in agreement with those of Koriyama & Kasai [28] and Koriyama et al. [26] for soaked beans and unsoaked and soaked red kidney beans and soybean softening respectively, where hardness as low as 7 – 10 N was recorded after soaking for 24 h at 20 °C and cooking for 120 min at 99.5 °C.

3.6. Hardness behavior at 50°C (with cooking and ultrasonication)

The effect of cooking and UTs on the hardness of the studied samples soaked at 50 °C under rising soaking time is illustrated in Fig. 8. A decaying exponential curve indicating the decrease in hardness as cooking and soaking time increased was observed with and without UT. Comparing Fig. 8a and 8b and 8c and 8d shows the positive impact of UT on hardness as this was significantly (P-value < 0.5) reduced. Also, a comparison of Fig. 8a and 8c and 8b and 8d shows that increasing the cooking time caused a reduction in the hardness of DS cowpea samples. With a rise in cooking temperature from 100 °C to 121 °C (under increasing soaking and cooking time), the hardness was diminished by 16.16 % – 75 % (without UT for Fig. 8a and 8c) and 20.95 % – 80 % (with UT for Fig. 8b and 8d). Furthermore, Figs. 6 and 8 show that the samples softened as the soaking time increased at both 30 °C and 50 °C, regardless of the other treatment parameters. These results agreed with similar studies in the literature [18,28,29].

Comparing the case in Fig. 1 (soaking at 30 °C for 15 to 90 min) and Fig. 8 (cooking and UT plus soaking at 50 °C for 15 to 90 min), shows a significant reduction in hardness (P value < 0.05) was observed which highlights the impact of cooking and UT on this property of DS cowpea. Hardness ranges of 0.8 – 28.5 N (soaking at 50 °C; cooking at 100 °C and with and without UT) and 0.2 – 21 N (soaking at 50 °C; cooking at 121 °C

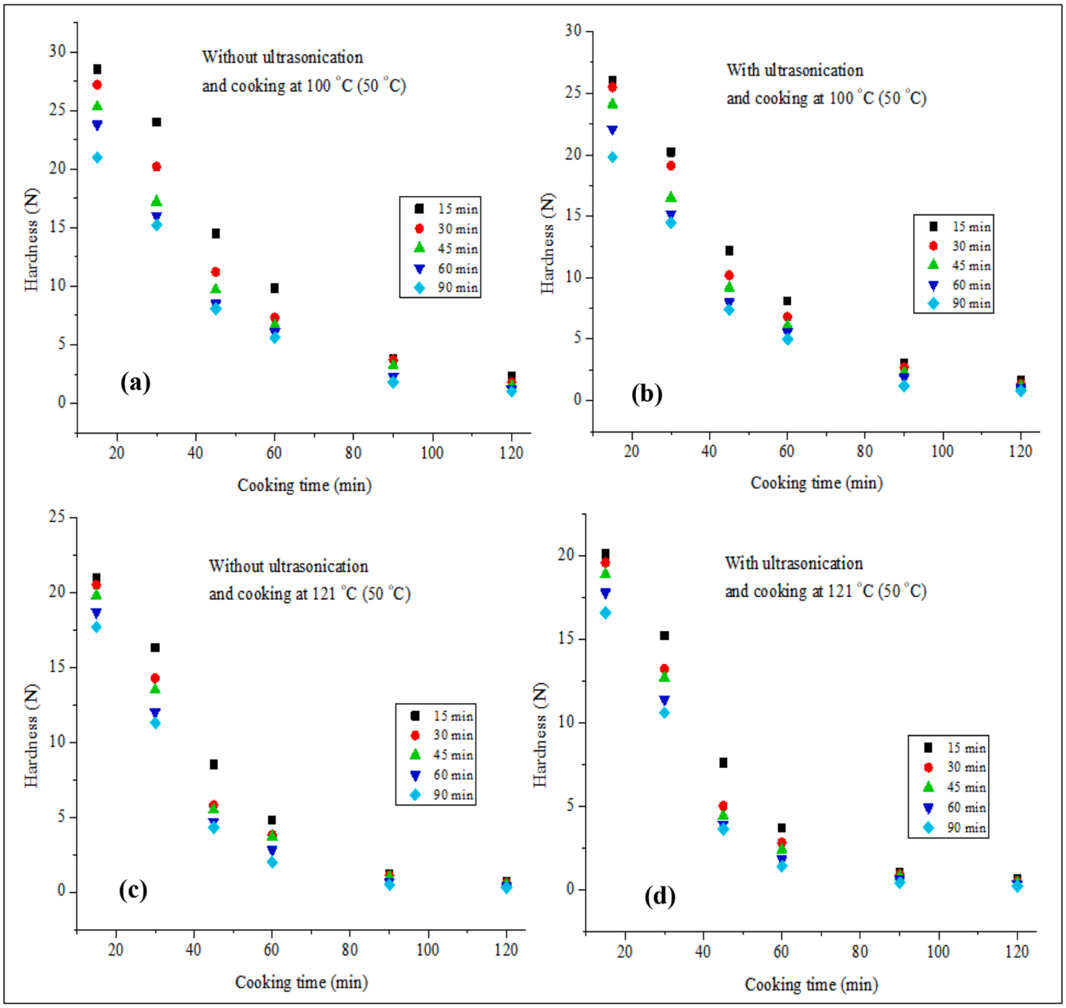

Fig. 8. Hardness (at 50 °C soaking temperature for the Dr. Saunders cowpea seeds) with rise in cooking time under increasing soaking time (a) without ultrasonication and cooking at 100 °C, (b) with ultrasonication and cooking at 100 °C, (c) without ultrasonication and cooking at 121 °C, and (d) with ultrasonication and cooking at 121 °C.

and with and without UT) were recorded for the case in Fig. 8 compared with hardness of 62.3 N (for 90 min soaking) and 98.17 N (for 15 min soaking) obtained in the case in Fig. 1. Apparently, the cooking and ultrasonic treatment contribute significantly (p-value < 0.05) to the softening of DS cowpea samples.

3.7. Softening kinetics and model

The water migration into the soaked DS samples enhanced the softening of the samples. For this study, case 1 reported in sub-section 3.1 involved softening via soaking (at 30 °C) due to hydration of the samples while the latter case involved softening of the studied samples through heating (cooking at 100 °C and 121 °C) and UT. The kinetic analysis of the softening characteristics of the DS cowpea was conducted for the latter case with soaking at 30 °C and 50 °C. Softening due to cooking is accompanied by β-elimination of pectin and other reactions[26]. The modeling of the experimental data of hardness of the samples subjected to cooking (at 100 °C and 121 °C) and UTs after soaking for 15 min is shown in Fig. 9 and in Fig. 10 for 90 min. Increasing the soaking duration and cooking temperature under increasing cooking duration was observed to reduce the hardness of the studied samples with and without UT (Fig. 9a, 9b, 10a, and 10b). First-order kinetics was used to describe the softening behavior of the samples studied. The cooking-induced softening of the DS cowpeas was demonstrated to decay exponentially with increasing cooking duration, which agreed with previous studies on the hardness of legumes [28]. Also, the cooking temperature rise and the introduction of UT were noticed to improve softening as shown in Fig. 9a and 9b and 10a and 10b.

In Fig. 9b and 10b (maximum reduction in hardness), the predicted data were observed to fit into experimental data with very good prediction performances of $R^2 = 0.9954 – 0.9984$ and $R^2 = 0.9908 – 0.999$ coupled with a minimal average absolute error of 2.343 – 5.353 and 1.838 – 8.88 and mean squared error of 1.233 – 2.499 and 0.931 – 4.182 for cooking performed at 100 °C and 121 °C respectively, with and without UT. The near unity value of the prediction performance revealed the high accuracy of the prediction of the experimental data using the first-order kinetics equation. Also, the low values of error evaluators showed that the prediction was carried out with slight differences between the experimental and predicted data. In addition, the Arrhenius equations describing the softening behaviors at various cooking and ultrasonics treatments were expressed using Eqs. (11) – (14). The softening rate (k_s) and activation energy were estimated to be 0.0754, 0.1011, 0.0921, and 0.1049 min^{-1}, and 51.25, 46.02, 59.20, and 45.22 $kJmol^{-1}$, for the cases of without UT (at 100 °C), UT (at 100 °C), without UT (at 121 °C), and UT (at 121 °C), respectively. It can be observed that higher softening rates were recorded with the deployment of UT and elevated cooking temperature as their use improved the hardness reduction of the studied samples. Also, a decrease in the activation energy of the cooking-induced softening process during the UT was observed, which was due to the provision of

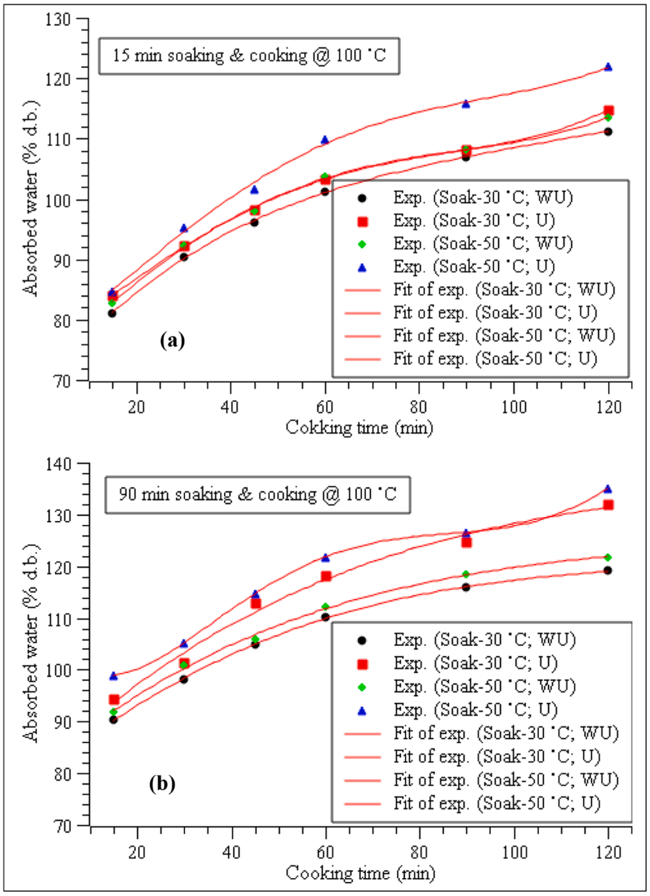

Fig. 9. Model fit of hardness with increasing cooking time for Dr. Saunders cowpea seeds cooked at 100 °C after soaking for (a) 15 min and (b) 90 min.

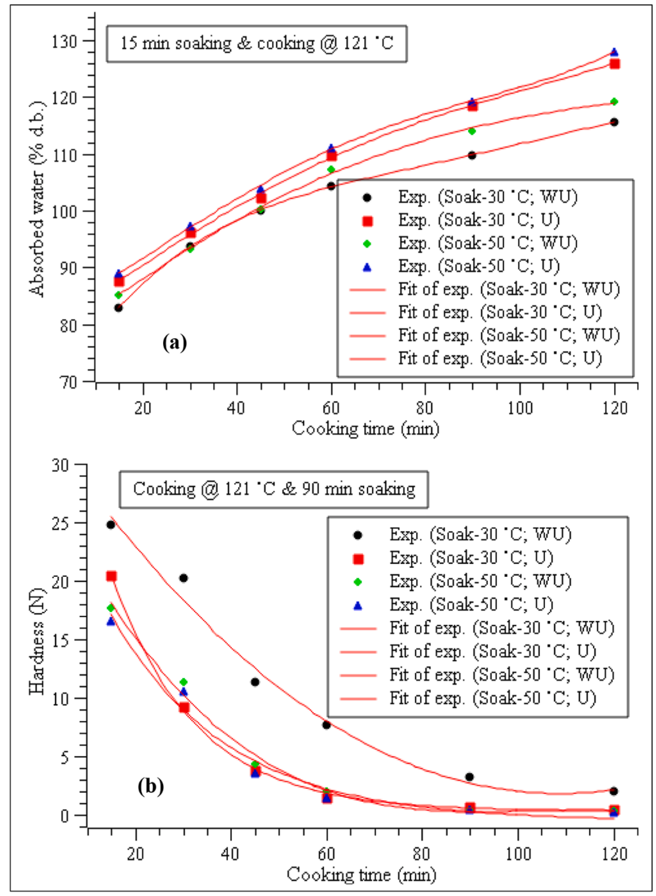

Fig. 10. Model fit of hardness with increasing cooking time for Dr. Saunders cowpea seeds cooked at 121 °C after soaking for (a) 15 min and (b) 90 min.

ultrasonic energy to augment the required activation energy of the process. In addition, an elevation in the cooking temperature was observed to increase the activation energy with and without UT. The softening rates obtained in this work were found to be slightly higher than the values 0.019 – 0.053 min^{-1} (soybean) and 0.013 – 0.052 min^{-1} (red kidney beans) reported in previous studies [28,30]for softening of beans cooked at 99.5 °C and soaked for 8 h at 20 °C. Furthermore, the activation energy evaluated in this study was lower than those reported by Koriyama & Kasai [28] and well in range with those published by Gowen et al. [30].

$$k_s = 13.0596e^{\left(\frac{-51245.60}{RT}\right)} \quad (\text{without UT (at } 100\,^{\circ}\text{C)}) \tag{11}$$

$$k_s = 11.7580e^{\left(\frac{-46022.54}{RT}\right)} \quad (\text{with UT (at } 100\,^{\circ}\text{C)}) \tag{12}$$

$$k_s = 15.6864e^{\left(\frac{-59195.28}{RT}\right)} \quad (\text{without UT (at } 121\,^{\circ}\text{C)}) \tag{13}$$

$$k_s = 11.9499e^{\left(\frac{-47219.27}{RT}\right)} \quad (\text{with UT (at } 121\,^{\circ}\text{C)}) \tag{14}$$

3.8. *Cooking time reduction via softening of samples*

Table 1 presents the soaking and cooking time used to soften the DS samples to an edible state with a hardness of 3 N under increasing soaking and cooking temperatures with and without UT. The time taken to cook edible DS cowpeas was considered to be the total period used to soak and cook. With a maximum soaking time of 90 min and cooking time of 120 min, the total and maximum cooking time of 120 min was used in this work to cook the studied samples. Table 1 shows that the total cooking time was not reduced when cooking was performed at 100 °C (without UT) for samples soaked for 90 min at 30 °C and cooked for 120 min (total cooking time of 120 min). However, the deployment of UT led to total cooking time reduction by 28.6 % due to the soaking time being lowered by 60 min. At this soaking temperature, increasing the cooking temperature to 121 °C reduced the total cooking duration by 28.6 % (without UT) and 50 % (with UT) when cooking was carried out for 60 min after soaking for 90 min (or 90 min after soaking for 15 min) and 60 min after soaking for 30 min, respectively. Elevating the cooking temperature and using UT were observed to either lower the cooking time or soaking and cooking duration. An increase in the soaking temperature (50 °C) for cooking performed at 100 °C decreased total cooking time by 28.6 % or 35.7 % via either 90 min of cooking and soaking for 60 min or 120 min of cooking and 15 of soaking. Using UT, total cooking time was reduced by 50 % by cooking for 90 min at 100 °C and soaking for 15 min. By increasing the cooking temperature to 121 °C, the total cooking time was decreased by 42.9 % (cooking time of 60 min and after soaking for 60 min) and 57.1 % (cooking time of 60 min and after soaking for 30 min). Again, it is demonstrated that the use of UT and increased cooking temperature contributed to both the softening of the DS samples and the lowering of the cooking time. It can be observed in Table 1 that the soaking temperature was insignificant in reducing the total cooking duration when cooking was done at 121 °C for 60 min after soaking for 30 min. Therefore, the optimum total cooking time for DS cowpea was 90 min as opposed to 120 min when soaking, cooking, and UT were synergized in this study.

Table 1
Hardness of Dr. Saunders cowpea seeds via soaking, cooking and ultrasonication conditions.

Soaking temperature	Cooking temperature	Ultrasonication condition	Hardness (3 N)		Total time	% cooking time reduction
			CT (min)	ST (min)		
30 °C	100 °C	Excluded	120	90	210	0
30 °C	100 °C	Included	120	30	150	28.57
30 °C	121 °C	Excluded	60	90	150	28.57
30 °C	121 °C	Excluded	90	15	105	50.0
30 °C	121 °C	Included	60	30	90	57.14
50 °C	100 °C	Excluded	90	60	150	28.57
50 °C	100 °C	Excluded	120	15	135	35.71
50 °C	100 °C	Included	90	15	105	50.0
50 °C	121 °C	Excluded	60	60	120	42.86
50 °C	121 °C	Included	60	30	90	57.14

where: CT = cooking time and ST = soaking time.

4. Conclusion

This work examined the combined effect of soaking (for 15 – 90 min and at 30 and 50 °C), cooking (for 15 – 120 min and at 100 and 121 °C), and ultrasonication (UT) on the hydration, hardness and cooking time reduction of DS cultivar of cowpea. Increasing soaking time and temperature, cooking temperature and duration, and UT were observed to enhance water absorption. As per the hardness, rising cooking and soaking temperatures and duration caused a reduction with the application of UT, further decreasing the hardness. The Ibartz and Augusto model was found to excellently describe the sigmoidal behavior of the absorbed water experimental data with high prediction performance ($R^2 \approx 1$) marked by minimal error values. The utilization of UT and increased cooking temperature were observed to reduce kinetic parameters and enhance softening rates and activation energy (hydration and softening). To achieve edible DS cowpeas with a hardness of 3 N, the synergy of cooking, soaking, and UTs reduced the total cooking duration from 120 min to 90 min (25 %). This was attainable when cooking was carried out at 121 °C for 60 min after soaking for 30 min at 30 °C with UT. The application of ultrasonication as a green technique to promote the rapid softening of cowpeas and other grains is recommended.

CRediT authorship contribution statement

Sholeh Rostamirad: Writing – original draft, Software, Investigation, Data curation. **K.G. Duodu:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **J.P. Meyer:** Writing – review & editing, Supervision, Resources, Funding acquisition. **M. Sharifpur:** Writing – review & editing, Validation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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