

## ORIGINAL ARTICLE

# Effect of ultrasonication and temperature on hydration process and hardness of two cowpea types

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## Abstract

Ultrasonication deployment provides a green and non-thermal option to traditional hydrothermal treatment. This study presents the impact of ultrasonication and soaking temperatures (30 and 50°C) on the water uptake and hardness of two cowpea types under increasing soaking times (15–240 min). Moisture content and hardness of the studied samples were measured using standard test methods and instruments. An increase in soaking temperature and the use of ultrasonication enhanced water uptake and reduced hardness. Ultrasonication improved mass transfer, which enhanced the diffusion of water uptake. The samples' water uptake and softening characteristics were significantly modeled with high accuracy ( $R^2 = 0.99$ ) using sigmoidal and first-order kinetics equations, respectively. The impact of sonication was found to be more significant at 30°C soaking of the studied cowpeas as the soaking time increased. This work justified using ultrasonication as a green technique to enhance the softening of cowpeas.

## KEYWORDS

cowpea, Dr Saunders, Glenda, hardness, soaking, ultrasonication

## 1 | INTRODUCTION

Cowpea (*Vigna unguiculata* L. Walp) is an important drought- and heat-tolerant crop produced extensively in Africa (95% of global production), with Nigeria being the largest producer and consumer (Amagwula et al., 2022; Mekonnen et al., 2022; Uthpala et al., 2020). Notwithstanding, the widespread consumption of cowpea in Africa, as its energy, nutrients, and amino acid contents are comparable with those of soya beans, seems to be underutilized (Mekonnen et al., 2022; Tshovhote et al., 2003). Cowpea is chiefly utilized in the form of cooked whole seeds. However, with most legumes, cooking of cowpea is accomplished after boiling for close to 2 h and even longer depending on the species, thus leading to high consumption of energy and a long duration of cooking (Kayitesi et al., 2013; Sodedji et al., 2024).

Legumes variety, storage duration, and storage conditions (at high temperature and low humidity) are important factors affecting their varying degrees of hardness (Koriyama & Kasai, 2019; Yildirim, 2021). Hard-to-cook legumes that take more time to soften under typical cooking practices are typical of most stored legumes and some recently harvested seeds (depending on the species), which have limited their acceptance and use (Joshi et al., 2010). To address this challenge concerning legume (cowpea) preparation, it is of the essence to reduce the cooking time and energy consumed, soften tissue, and improve the processing of cowpea. Therefore, the pretreatment of legumes (requiring energy) prior to final processing to alter various properties related to the final products' suitability, such as nutritional, sensory, swelling, water uptake, and hardness, is of great importance (Ding et al., 2022; Sabat et al., 2023). Soaking is a classical, easy, and key process before grain (legumes) processing. This is essential to

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improve hydration, hardness, and other properties of the to-be-processed legumes (Karataş & Arslan, 2022). Conventionally, legumes are hydrated for 12–16 h before cooking to ease cooking and processing, in which water penetrates through the seed coat to the cotyledons and dispenses among protein and starch constituents (Joshi et al., 2010; Yıldırım, 2021). This enables even water distribution within the seed, therefore, causing uniform softening of the cotyledons. However, longer hydration time leads to odor generation, grain discoloration, extreme leaching of soluble solids, fermentation, and propagation of spoilage and pathogenic microorganisms.

Several studies have reported the hydrothermal treatment of different legumes and their influence on physical and chemical processes (Costa et al., 2018; Sharanagat et al., 2018; Turhan & Sagol, 2004). The influence of soaking temperatures (25–45°C) and time (0–620 min) on the moisture content of two cultivars of cowpea and Bambara groundnut seeds was studied along with the hydration kinetics using different models (Kaptso et al., 2008). Increasing the soaking temperature and time increased moisture content until saturation was reached. The effect of soaking temperature (23–60°C) and time (0–390 min) on the moisture content and morphology of Andean lupin (*Lupinus mutabilis* Sweet) was also studied (Miano & Augusto, 2015). The current global trend of industrial food processing is geared toward clean and green technology, which involves the use of techniques such as high pressure, ultrasound, micronization, infrared radiation, ohmic heating, microwave, and plasma to improve conventional hydrothermal processes (Carvalho et al., 2021; Hu et al., 2021; Kayitesi et al., 2013; Zare et al., 2024). These techniques, combined with pre-soaking treatments or not, all require the use of energy. Food processing practices involve energy utilization at different stages of processing and effective and efficient energy management is very important to reduce operational costs, minimize environmental footprints, lower global warming, and ensure sustainable production processes (Hefft & Higgins, 2021; Sabat et al., 2023; Uthpala et al., 2020; Zare et al., 2024).

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) and has been utilized in food (drying, salting, osmotic dehydration, etc.) (Karwasra et al., 2020; Patero & Augusto, 2015) and non-food sectors (Yasmin et al., 2023). Although ultrasonication can produce high-quality products at lower temperatures by enhancing heat and mass transfer rates, not a lot of studies have been conducted in this regard (Ghafoor et al., 2014; Han et al., 2021; Kaur & Gill, 2019; Yıldırım, 2021; Zhang et al., 2021). Minimal studies have been carried out on the combined impact of ultrasonication and hydrothermal treatment on water uptake and/or hardness of legumes, especially underutilized cowpeas.

This observed gap in research prompted the conduct of this work, which investigated the impact of combined hydrothermal and ultrasonication treatments on the water uptake and hardness of two cowpea types. The influence of ultrasonication treatment was investigated to address the time and energy-consuming characteristics of cooking and soaking cowpeas. In addition, this study, for the first time,

provided some insights into the water uptake, softness behavior, and kinetics of the studied cowpea types.

## 2 | MATERIALS AND METHODS

### 2.1 | Materials

Two cowpea types, Glenda (GL) and Dr Saunders (DS), grown in South Africa and supplied by Agricol, Silverton, South Africa, were used in this study. Cowpea samples were cleaned and manually sorted by hand to remove split, dented, spoilt, and small grains.

### 2.2 | Experimental procedure

#### 2.2.1 | Moisture content analysis

In this experiment, the samples of each cowpea type were first hand-picked to ensure that whole and undented samples were used for the study. Then, approximately 20 g of the hand-picked samples were placed in the moisture content analyzer (Radwag, Wagi Electronics, South Africa) for moisture determination. The instrument was set to moisture content analyzer mode and at a drying temperature of 80°C. The result display and acquisition were set at 10-min intervals with a manual stop option. The moisture content (%) was monitored until it converged to a difference of <0.01% for the specified time interval (1000 min for this study) as recommended by the manufacturer and by the literature (Miano et al., 2015). The corresponding results were then analyzed to determine the average moisture content of each sample of the studied cowpea types. A picture of the moisture content analyzer with the studied cowpea samples is shown in Figure 1.

The hardness of randomly marked samples was measured using a Digital Shore A Durometer (Hardness tester), which has a measuring range of 0–100 HA, with an indenter tip pressure of (0.55–8.05 N). The hardness was measured to evaluate the impact of moisture content on the hardness of the samples. These experiments were performed in triplicate, and the average values of moisture content, hardness, and mass of cowpeas (before and after drying) were reported.

#### 2.2.2 | Water uptake rate measurement for soaked samples

The rate of water uptake for each of the cowpea types was determined when soaked in water of constant volume at different soaking times ( $15 \text{ min} < t < 240 \text{ min}$ ) and soaking temperatures of 30 and 50°C. Before each experiment, about 20 g of each cowpea sample was measured into an air-tight sample bottle using RADWAG MA 50. R 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 and 50°C.



**FIGURE 1** Measuring of studied cowpea sample with moisture content analyzer.

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 the constant temperature bath and soaked for the desired time. Then, the sample was filtered, tenderly cleaned from water moisture, and reweighed. The initial and final mass difference was used to determine the absorbed moisture content (%).

### 2.2.3 | Water uptake rate measurement for ultrasonicated and soaked samples

With a similar procedure as above (Section 2.2.2), the thermal bath was used to prepare water at constant temperatures of 30 and 50°C, and the ultrasonic bath was set to the desired soaking temperature along with 100% sonication power for different soaking times. 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 the ultrasonic bath and allowed to soak for the desired time while being sonicated. As the soaking time elapsed, the sample was filtered and tenderly cleaned from water moisture and reweighed. The initial and final mass differences determined the absorbed moisture content (%).

To guarantee that the experimental results were accurate and reliable, an error analysis was carried out as some factors, such as environmental impacts, human factors, and equipment precision, affect experimental measurements. The mass ( $m$ ) of the cowpeas, volume ( $v$ ) of water (for soaking), water uptake ( $wu$ ), and hardness ( $h$ ) were quantities considered for error analysis. The maximum error percentage were as  $m = \pm 0.003\%$ ,  $v = \pm 0.5\%$ ,  $wu = \pm 0.05\%$ , and  $h = \pm 0.3\%$ . Equation (1) is mostly used in the literature (Nwaokocho

et al., 2022) for uncertainty as the result of a combination of errors based on the accuracy of the instrumentation and obtained data from measurements carried out. However, in this study, the measurements of different parameters were down, and no combination of errors was involved.

$$U_R = \pm \left[ (U_{R1})^2 + (U_{R2})^2 + \dots + (U_{Rn})^2 \right]^{1/2}. \quad (1)$$

### 2.3 | Hydration kinetics and hardness modeling

The hydration kinetics of the two cowpea types were modeled using the sigmoidal model described by Ibarz and Augusto (2015) as expressed in Equation (2). Appropriate model parameters obtained from the water intake data (with and without ultrasonication) for different soaking times and temperatures were evaluated using Equation (2) and used to model the hydration characteristics of the studied samples. Similarly, models were developed for the softening characteristics of the two cowpea types based on the first-order kinetics of the hydrothermal parameters (with and without ultrasonication) (Ghafoor et al., 2014). The first-order kinetics was expressed in Equation (3). In addition, water uptake and hardness were evaluated using the Arrhenius equation as expressed in Equation (4) to describe the temperature dependence of water uptake 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.

$$M_t = \frac{M_e}{1 + \frac{M_e - M_o}{M_o} e^{(-k * M_e * t)}}, \quad (2)$$

$$\frac{H_o - H_t}{H_o - H_e} = 1 - e^{(-k * t)}, \quad (3)$$

where  $M_o$  and  $H_o$ ,  $M_e$  and  $H_e$ , and  $M_t$  and  $H_t$  are the initial absorbed water and texture, equivalent absorbed water and texture, and specific absorbed water and hardness at a soaking time, respectively. Also,  $k$  and  $t$  are the water uptake/softening rate and soaking time, respectively.

$$k_s/k_{wu} = A e^{\left(\frac{E}{RT}\right)}, \quad (4)$$

where  $k_s$  is the softening rate constant (1/min),  $k_{wu}$  is the water uptake rate ( $[\% \text{ d. b. min}]^{-1}$ ),  $E$  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 mass of cowpea (before and during drying and soaking), absorbed moisture content, and hardness with and without

ultrasonication treatment 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 each of the cowpea types and at different hydrothermal (with and without ultrasonication) treatments were fitted into the measured water intake data. The goodness of fit between experimental and predicted data was evaluated using the coefficient of determination ( $R^2$ ) and the root mean square error. In addition, regression models were developed for the cowpea types' relationship between hardness and water intake at different hydrothermal treatments (with and without ultrasonication treatments).

## 3 | RESULTS AND DISCUSSION

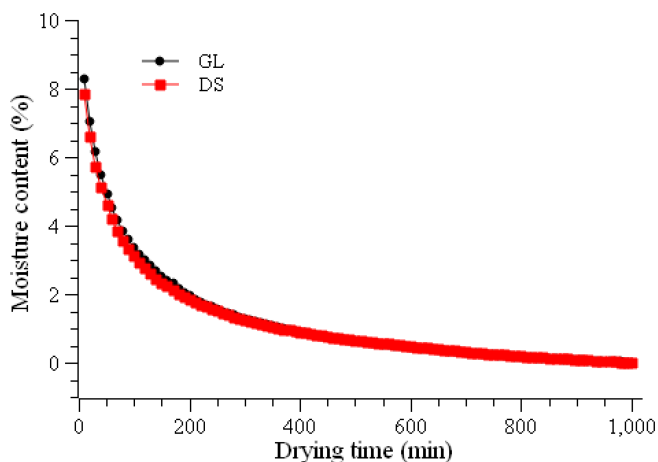
### 3.1 | Drying characteristics of cowpeas

Figure 2 illustrates the drying characteristics of the GL and DS cowpea types. Moisture content loss was observed to decrease as the drying duration increased. For the two cowpea types, similar drying curves (exponential decay) were observed, with GL samples possessing lower moisture content loss after 10 min of drying and higher moisture content loss after 1000 min. Thus, the GL cowpeas have slightly higher moisture content loss than the DS cowpeas.

A fit of the exponential curve for the drying of GL samples was performed. The polynomial expression was developed as described in Equation (5). This expression can predict over 99% of the obtained data.

$$Y = 0.0558 + 0.1378x - 0.001326x^2 + 7.8288x^3 - 2.8418x^4 + 6.4542x^5. \quad (5)$$

Also, a fit of the exponential growth curve for drying DS samples was done. The developed polynomial expression was given in Equation (6) and can fit over 99% of the measured data.



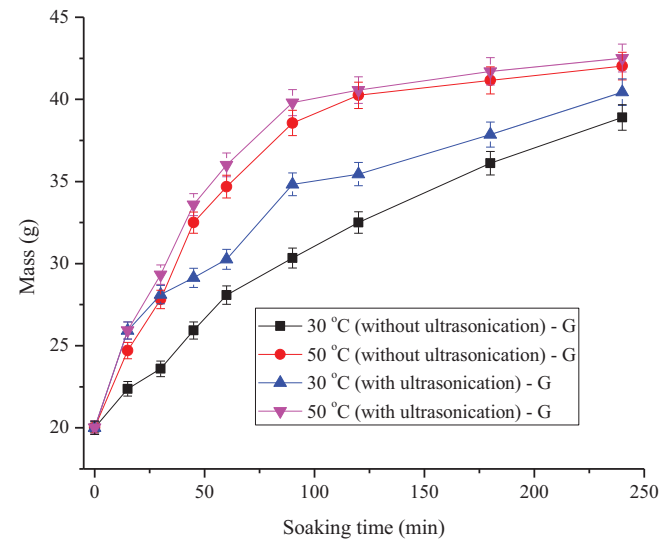
**FIGURE 2** Drying curve for studied samples (Glenda and Dr Saunders).

$$Y = 0.2138 + 0.1322x - 0.00126x^2 + 7.2909x^3 - 2.5934x^4 + 5.7891x^5. \quad (6)$$

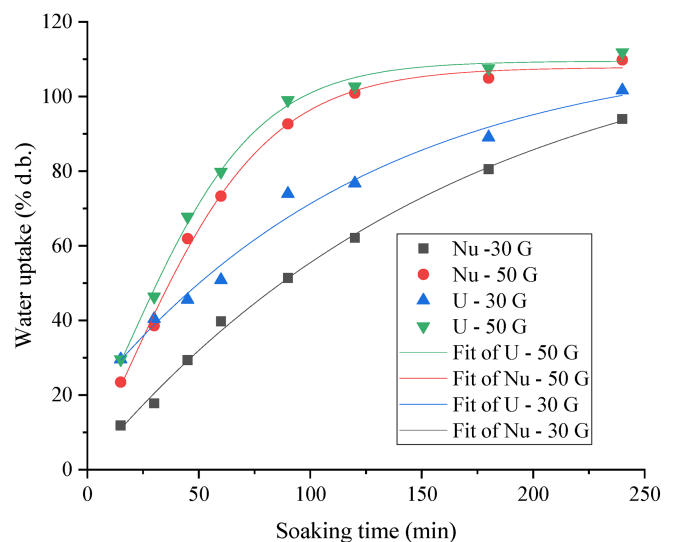
### 3.2 | Water uptake characteristics

#### 3.2.1 | GL samples

The impact of variation in soaking time (15–240 min) and temperature (30 and 50°C) on the mass and water uptake of GL cowpeas without and with ultrasonication treatment is presented in Figures 3 and 4. With an initial average mass of 20 g, the mass increased to 22.38 g after 15 min of soaking and rose further to 42.03 g after 240 min of soaking without ultrasonication treatment (Figure 3). The mass gain



**FIGURE 3** Effect of ultrasonication on the mass of GL samples as soaking time and temperature increased.



**FIGURE 4** Effect of soaking time and temperature on water uptake for GL samples, with and without ultrasonication.

recorded in this present study agreed with the literature, where over twofold of the initial mass was reported for soaking chickpeas for 1500 min at 25–75°C (Costa et al., 2018). This increase in mass was due to water uptake via diffusion through the cowpea coat. After 15 min of soaking and without ultrasonication, a water uptake of 11.86% was observed, which increased gradually as the soaking time increased, with 93.97% water uptake after 240 min of soaking.

From Figure 3, it can be observed that an increase in the soaking temperature caused a rise in the mass of cowpeas owing to increased water uptake. With a temperature difference of 20°C, the mass of the cowpea rose from 22.38 to 24.71 g (10.41%) when soaked for 15 min and 38.89 to 42.03 g (8.07%) with a soaking time of 240 min. This was due to a corresponding rise in water uptake from 11.86% to 23.43% (97.55% increase) for 15 min of soaking time and 93.97% to 109.80% (16.85% increase) for 240 min soaking time (Figure 4). This revealed a higher rate of water uptake at the commencement of the soaking process as water migrated from the soaking medium to the cowpea grains due to diffusion and capillarity, which was enhanced as the soaking temperature increased reduced water viscosity, thereby opening the pore size and coat cell structures of the cowpea to facilitate greater and more rapid water uptake (Miano et al., 2015). The observed effect of soaking temperature and time is found to agree with the work of Hu et al. (2021).

The impact of adding ultrasonication treatment alongside temperature and soaking time on GL cowpeas' mass and water uptake was investigated and presented in Figures 3 and 4. It can be seen from Figure 3 that as the soaking time increased, the mass of the cowpea increased, which was independent of the soaking temperature. However, higher values were obtained at a lower soaking temperature of 30°C. At a soaking temperature of 30°C, the mass of the cowpea increased from 20.01 to 25.93 g after soaking for 15 min and then rose to 40.44 g after soaking for 240 min. Also, the mass of the cowpea rose from around 20.02 to 25.93 g after soaking for 15 min and then increased to 42.51 g after soaking for 240 min at 50°C. An increase in temperature from 30 to 50°C was observed to enhance the mass of cowpea samples slightly.

Figure 4 provides the water uptake characteristics as ultrasonication treatment was introduced. For both soaking temperatures, an increase in water uptake leading to an elevated mass of cowpea was observed as the soaking time rose from 15 to 240 min. At 30°C, higher water uptake values were noticed compared to water uptake in the absence of ultrasonication under increasing soaking time. Water uptake increased from 29.57% to 101.65% (at soaking temperature of 30°C) and rose from 29.55% to 111.84% (at 50°C soaking temperature) when soaking time varied from 15 to 240 min. This demonstrated the influence of temperature in enhancing water uptake via the mass transfer phenomenon into the cowpea, which led to its increased mass and water uptake. The water uptake behavior of GL cowpea is found to agree with previous studies (Costa et al., 2018; Joshi et al., 2010). The water uptake characteristics agreed with previous studies that engaged ultrasonication to improve water uptake of navy beans at 16°C (Ghafoor et al., 2014) and sorghum grains at room temperature

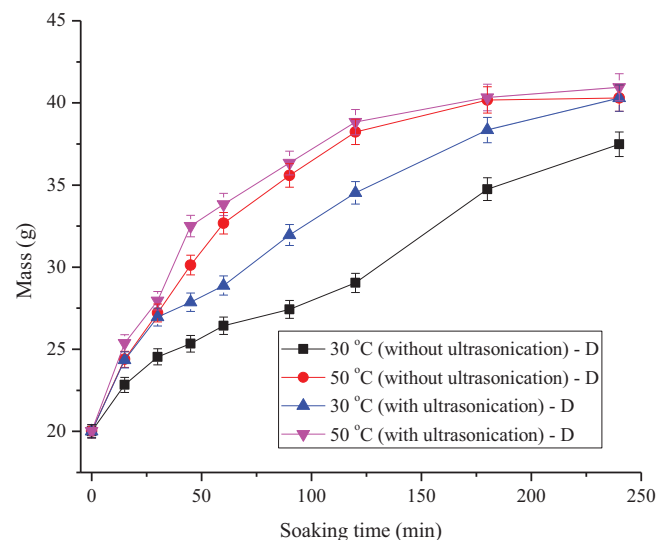
(Patero & Augusto, 2015). Thus, ultrasonication has more effect on water uptake than soaking temperature and time.

### 3.2.2 | DS samples

Figures 5 and 6 present the mass and water uptake of DS cowpea samples at different soaking temperatures and times without and with the application of ultrasonication treatment. As the soaking time increased when soaked at 30°C, the mass of the studied samples rose from the initial mass of 20–22.83 g after 15 min of soaking and increased gradually to 37.48 g after 240 min of soaking, translating to an increment of 87.31%, all without ultrasonication (Figure 5).

Similarly, the mass of the samples was elevated by 101.4% when the samples were soaked at 50°C and as the soaking time increased from 15 min (24.39 g) to 240 min (40.3 g). The rise in the soaking temperature was noticed to elevate the mass of the samples as water uptake into them via diffusion through the skin increased with an increase in soaking time. In addition, water uptake into the studied samples increased as soaking temperature and time increased (without ultrasonication). When the samples were soaked at 30 and 50°C, water uptake was improved by 531.47% and 370.45% with 13.79% and 87.08%, and 21.66% and 101.9% water uptake at soaking time of 15 and 240 min, respectively (Figure 6).

By comparing the mass (after soaking) and water uptake obtained from both cowpea types (without ultrasonication), it can be observed that the mass and water uptake of GL at a soaking time of 240 min and temperature of 30°C were slightly higher than those of DS (see Figures 3–6). This demonstrated that the GL samples exhibited a better water permeation through their skins than the DS samples, resulting in improved water uptake and increased mass. However, at a soaking time of 240 min and temperature of 50°C, relatively similar mass and water uptake results were achieved for both cowpea types.



**FIGURE 5** Effect of ultrasonication on the mass of DS samples as soaking time and temperature increased.

In addition, soaking temperature and time increase were observed to improve water uptake and mass for both cowpea types under no ultrasonication treatment.

Mass and water uptake behaviors obtained for the ultrasonication treatment of DS cowpea samples soaked at different times and temperatures are presented in Figures 5 and 6, respectively. The mass of the samples after soaking was observed to increase as both the soaking duration and temperature rose (Figure 5). At 30°C soaking temperature, the mass increased from 20 to 24.35 g after soaking for 15 min, and after 240 min of soaking, a mass of 40.3 g was recorded. This translated to a 101.3% increment as the soaking time increased to 240 min. With a mass of 25.38 g after 15 min of soaking from the initial 20 g, the mass was further increased to 40.95 g after 240 min of soaking, when the soaking was carried out at 50°C. A mass increment of 104.65% was observed after soaking for 240 min. This indicates an accelerated movement of water via the skins of the cowpeas in the samples due to a high mass concentration gradient and slight temperature rise.

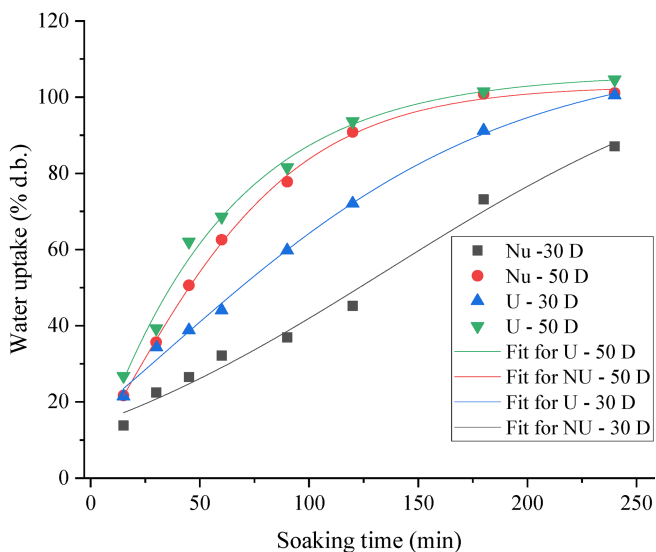
Without ultrasonication, the DS cowpea samples' mass (after soaking) was lower than those of the same samples under ultrasonication at the studied soaking times and temperatures (see Figure 5), thus revealing the impact of ultrasonication on the mass of the samples. An increment of 1.52–5.48 g (at 30°C) and 0.154–2.37 g (at 50°C), translating to 15.41%–61.7% and 0.38%–7.88%, respectively, for different soaking temperatures was recorded when ultrasonication was introduced. Water uptake characteristics of DS samples at different soaking temperatures and varying soaking times are provided in Figure 6. As observed earlier, an increase in soaking temperature and time resulted in a corresponding rise in water uptake. When soaking was carried out at 30°C, water uptake rose from 21.47% (after 15 min) to 100.5% (after 240 min), corresponding to an increase of 386.1%. Also, a water uptake increment of 290.41% (from 26.8% (for 15 min of soaking) to 104.63% (for 240 min of soaking)) was recorded when the

samples were soaked at 50°C. It can be deduced that the rate of water uptake was higher at the beginning of soaking and reduced toward the end of the studied soaking time as the mass (water) concentration gradient of the cowpea samples significantly declined. Under similar ultrasonication treatment, an increase in soaking temperature was observed to improve water uptake for these samples of cowpea for each soaking time (see Figure 6). Both cowpea types' water uptake behaviors are similar to those of other beans and grains whether with or without ultrasonication treatment (Costa et al., 2018; Joshi et al., 2010; Patero & Augusto, 2015).

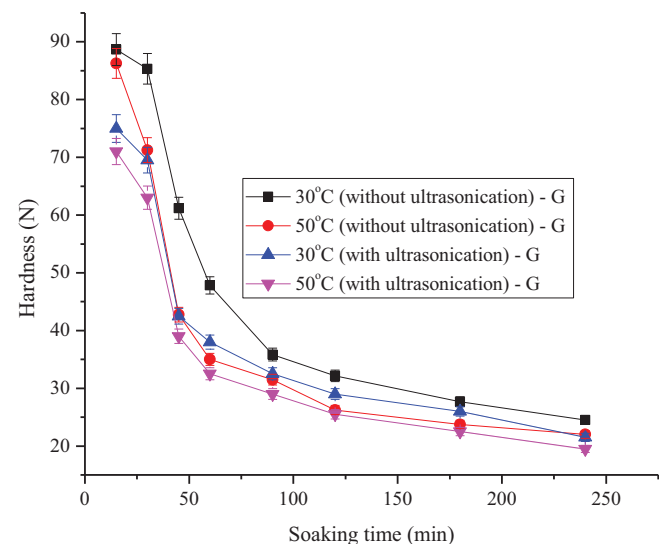
### 3.3 | Hardness characteristics

#### 3.3.1 | GL samples

Figure 7 illustrates the softening and change in hardness characteristics of the GL cowpea with and without ultrasonication treatment. Soaking this cowpea type at 30°C and varying the soaking time without ultrasonication showed a corresponding increase in mass and water uptake of the cowpeas leading to a reduction in hardness. With an initial average hardness of  $99.1 \pm 0.167$  N (after 15 min of soaking), the cowpea hardness reduced to 88.67 N, and after 240 min of soaking, the hardness was decreased drastically to 24.50 N (Figure 7). Evidently, increasing the soaking time reduced the hardness of the cowpea. However, at an elevated temperature (50°C), the hardness was slightly reduced from 86.25 to 22.00 N (292.05% decrease). Temperature rise was observed to reduce the cowpea hardness as values of 88.67 and 86.25 N and 24.50 and 22.00 N were recorded for soaking time of 15 min at 30°C and 240 min at 50°C, respectively. The hardness of 22 N after 240 min (without ultrasonication) was observed to be similar to that reported for soybeans (after 6 h of soaking at 10–50°C) and lower than the 26 N for red kidney beans



**FIGURE 6** Effect of soaking time and temperature on water uptake for DS samples, with and without ultrasonication.



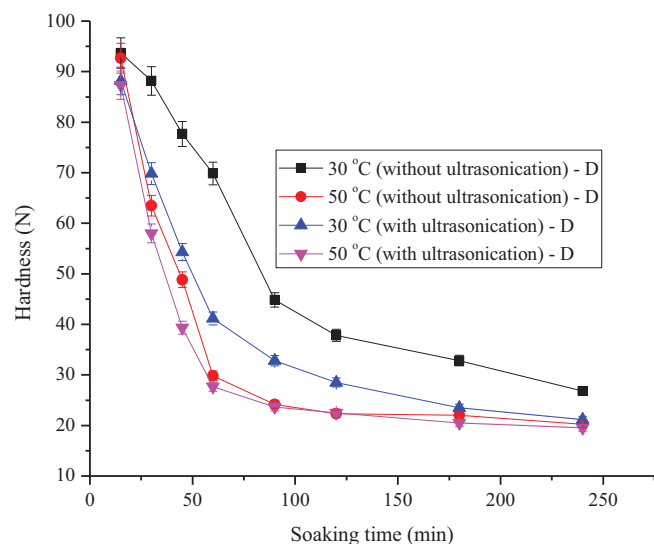
**FIGURE 7** Effect of soaking time and temperature on the hardness of GL samples, with and without ultrasonication.

(after 6 h of soaking at 10–50°C) (Koriyama & Kasai, 2019). Penetration of more water into the cowpea via the coat at the elevated temperature was observed to reduce its hardness as temperature rise enhanced capillary flow and diffusion as the cowpeas' composition, cell wall structure, and compactness were altered. Temperature has more impact than soaking time on the hardness of the cowpeas as the temperature elevation improved water uptake and reduced hardness.

Characteristics of the hardness of the studied cowpea samples are given in Figure 7, which are subject to ultrasonication treatment in addition to increasing soaking temperature and time. For soaking temperatures of 30 and 50°C, the hardness decreased as soaking time increased, with slightly higher hardness values recorded when soaking was carried out at 30°C. The hardness of GL cowpea samples was found to reduce by 248.84% (from 75 to 21.50 N) for soaking at 30°C, whereas a decrease of 264.10% (71 to 21.50 N) was observed for soaking at 50°C. The lowest hardness (21.5 N) was slightly less than what was reported for soybean and red kidney beans (Koriyama & Kasai, 2019). Hardness at an elevated soaking temperature of 50°C was observed to be lower than that at 30°C as increased temperature and ultrasonication permitted the permeation of more water into the samples via the cowpea coat. A comparison of the hardness of these samples, as given in Figure 7, showed that applying ultrasonication treatment slightly caused a reduction in the hardness at different soaking temperatures and as the soaking time increased.

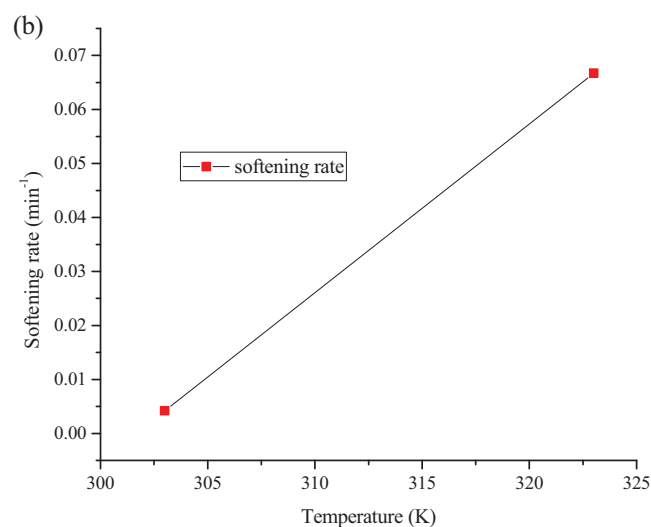
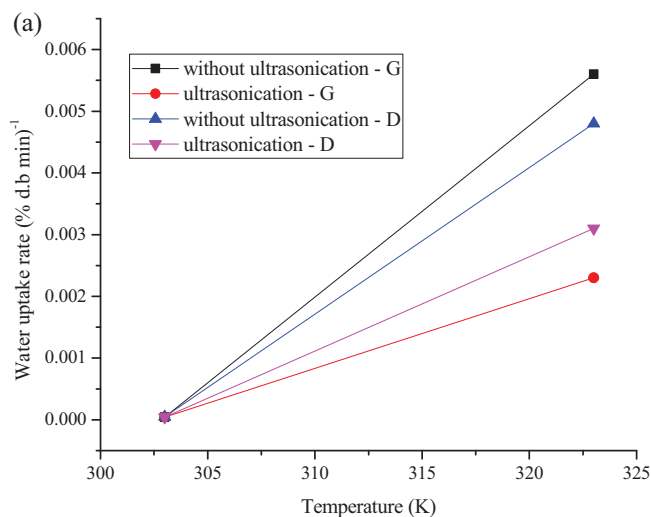
### 3.3.2 | DS samples

Figure 8 illustrates the softening and change in hardness characteristics of the DS samples under varying hydrothermal conditions with and without ultrasonication. Hardness was found to reduce as soaking time and temperature appreciated. At a soaking temperature of 30°C and without ultrasonication, hardness decreased from an initial



**FIGURE 8** Effect of soaking time and temperature on the hardness of DS samples, with and without ultrasonication.

average hardness of  $98.4 \pm 0.456$  N to 93.67 N (15 min of soaking) and 26.83 N (240 min of soaking), thus accounting for a 71.35% reduction in hardness (Figure 8). Also, the hardness reduced (78.15%) from 92.67 N (15 min of soaking) to 20.25 N (240 min of soaking) when the samples were soaked at 50°C. By comparing the mass (after soaking) and water uptake obtained from both species of cowpea (GL and DS), it can be observed that the mass and water uptake of GL at a soaking time of 240 min and temperature of 30°C were slightly higher than those of DS while the hardness was slightly lower (Figures 3–8). This demonstrated that the GL samples exhibited better water permeation through their coats than the DS samples, resulting in improved water uptake, leading to lower hardness and increased mass. However, at a soaking time of 240 min and temperature of 50°C, relatively similar mass and water uptake results were achieved for both species but with slightly higher hardness for the GL samples. For both species and under no ultrasonication treatment, soaking temperature and time increase were observed to improve water uptake and mass, but with reduced hardness. Generally, without



**FIGURE 9** Effect of temperature on (a) water uptake (kinetic) rate and (b) softening rate.

ultrasonication, the hardness of GL samples was moderately lower than that of DS samples at corresponding soaking time and temperature (see Figures 7 and 8).

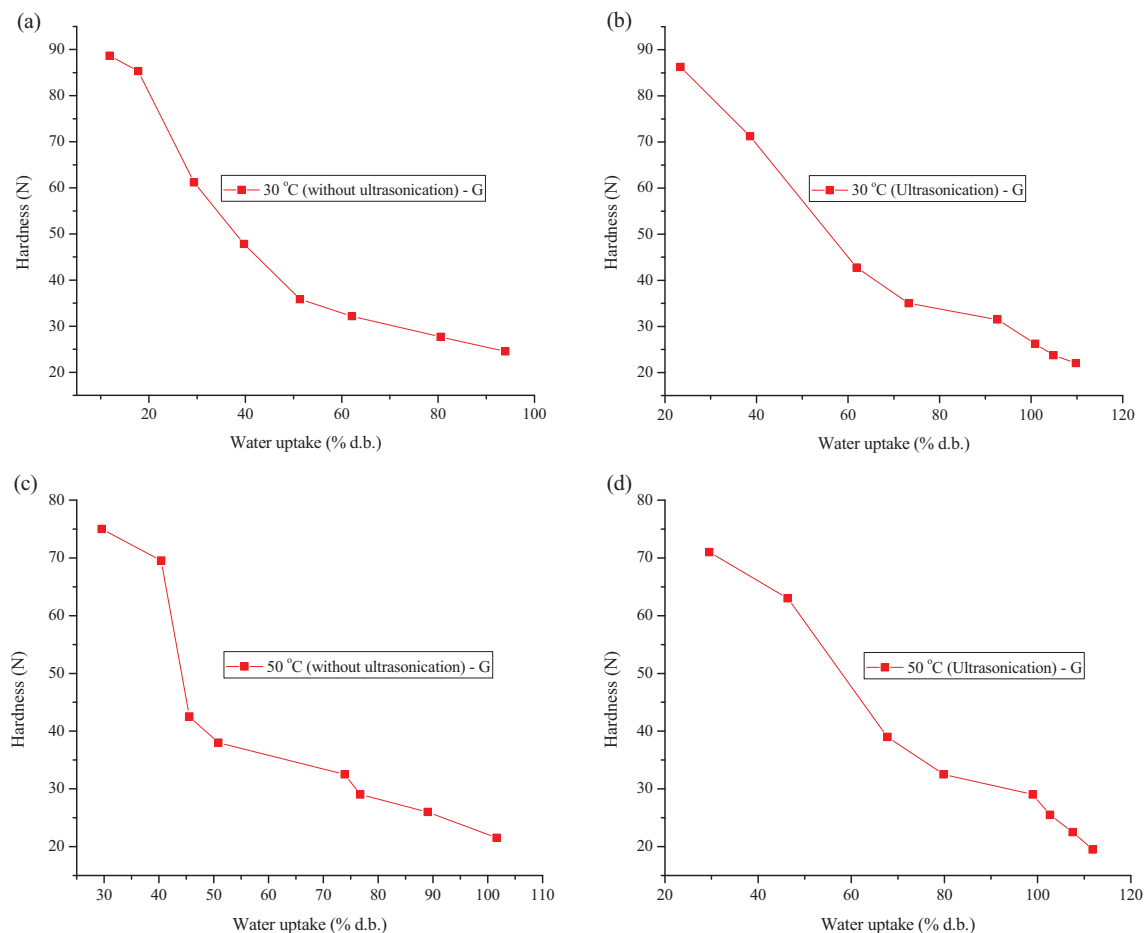
The hardness of the samples after soaking at different temperatures and soaking times subject to ultrasonication treatment is given in Figure 8. As observed for GL cowpeas, the hardness of the DS cowpea samples reduced as soaking time and temperature increased. At 30 and 50°C, the samples' hardness was decreased by 75.99% and 77.67%, respectively, as soaking time increased. The impact of the ultrasonication treatment on the hardness of the samples was observed to be higher (26.83–93.7 N at a soaking temperature of 30°C and 20.25–92.67 N at soaking temperature of 50°C) without the treatment compared with those of 21.17–88.17 N (soaked at 30°C) and 19.50–87.33 N (soaked at 50°C) under ultrasonication treatment (Figure 8). This reduction in hardness can be attributed to the use of ultrasonication.

### 3.4 | Development of models for hydration and softening kinetics

The values of water uptake obtained in this work for both the GL and DS samples at different soaking temperatures and times without

and using ultrasonication treatment were modeled using the Ibartz and Augusto equation. With the water uptake rates of 0.0056, 0.0023, 0.0048, and 0.0031 1/% d. b. min for the GL (without ultrasonication), GL (ultrasonication), DS (without ultrasonication), and DS (with ultrasonication), respectively and other parameters in the equation, the fit of the obtained water uptake data into the equation were performed as illustrated in Figures 4 and 5 (GL samples and DS samples, respectively). At different conditions and for the two cowpea types, good fits of the measured data of water uptake were achieved with high accuracy (over  $R^2 = 0.99$  and  $p$  value  $<0.0001$ ) and minimal error. Generally, the fits described the water uptake characteristics of the GL and DS samples under increasing hydrothermal conditions with and without ultrasonication treatment. As the water uptake increased exponentially (from the beginning of soaking at a high-water uptake rate), the mass of the samples increased, and the hardness decreased over the soaking duration and at different soaking temperatures subject to whether ultrasonication was applied or not.

Similarly, the softening characteristics of the studied samples (GL and DS) were modeled using the first-order kinetics equation. The softening rate ( $k_s$ ) of  $0.0667 \text{ min}^{-1}$  and other measured hardness data were used in the equation to model the softening characteristics, as illustrated in Figures 7 and 8. The models fitted well for different



**FIGURE 10** (a) Influence of water uptake on hardness for GL samples at soaking temperature of 30°C (a) without and (b) with ultrasonication and at 50°C (c) without and (d) with ultrasonication.

ultrasonication conditions and all the studied samples with high prediction performance (over  $R^2 = 0.99$  and  $p$  value  $<0.0001$ ) and small error. In addition, the Arrhenius equation was used to describe the impact of temperature on the water uptake and softening characteristics of all the studied samples. The kinetics parameters of  $k_s$  (softening rate) and  $k_{wu}$  (water uptake rate) were effectively modeled using the Arrhenius model expressed in Equation (4). As a function of temperature, the  $k_s$  and  $k_{wu}$  were used to describe the water uptake and hardness behavior of the samples as expressed in Equations (7–11). These mathematical expressions revealed the exponential increase in  $k_s$  and  $k_{wu}$  as temperature rises (see Figure 9).

In Equation (7), the softening of the samples as the temperature rises with corresponding  $k_s$  increase was modeled and illustrated in Figure 9a. In addition, the effect of temperature elevation on the water uptake and  $k_{wu}$  was expressed in Equations (7–11) and provided in Figure 9b.

$$k_s = 39.29e^{\left(\frac{-112800.397}{RT}\right)}, \quad (7)$$

$$k_{wu}(T) = 68.1768e^{\left(\frac{-196997.73}{RT}\right)} \text{ (GL – without ultrasonication),} \quad (8)$$

$$k_{wu}(T) = 54.6152e^{\left(\frac{-163032.09}{RT}\right)} \text{ (GL – with ultrasonication),} \quad (9)$$

$$k_{wu}(T) = 64.25877e^{\left(\frac{-187764.84}{RT}\right)} \text{ (DS – without ultrasonication),} \quad (10)$$

$$k_{wu}(T) = 59.6172e^{\left(\frac{-175604.40}{RT}\right)} \text{ (DS – with ultrasonication).} \quad (11)$$

### 3.5 | Hardness and water uptake relationship

An attempt was made to establish the relationship between hardness and water uptake at the different conditions for the studied samples. These relations are illustrated in Figures 10 and 11 for GL and DS samples, respectively. Generally, an exponential reduction in hardness was observed as the water uptake increased. This demonstrated an inverse relationship between these parameters, which agreed with a previous study (Lux et al., 2021). At higher temperature (50°C), the softening of the samples was slightly increased as the coat pores expanded and water viscosity reduction improved water uptake rate and content. In addition, the use of ultrasonication slightly improved the softening of the samples as agitation and mass transfer increased

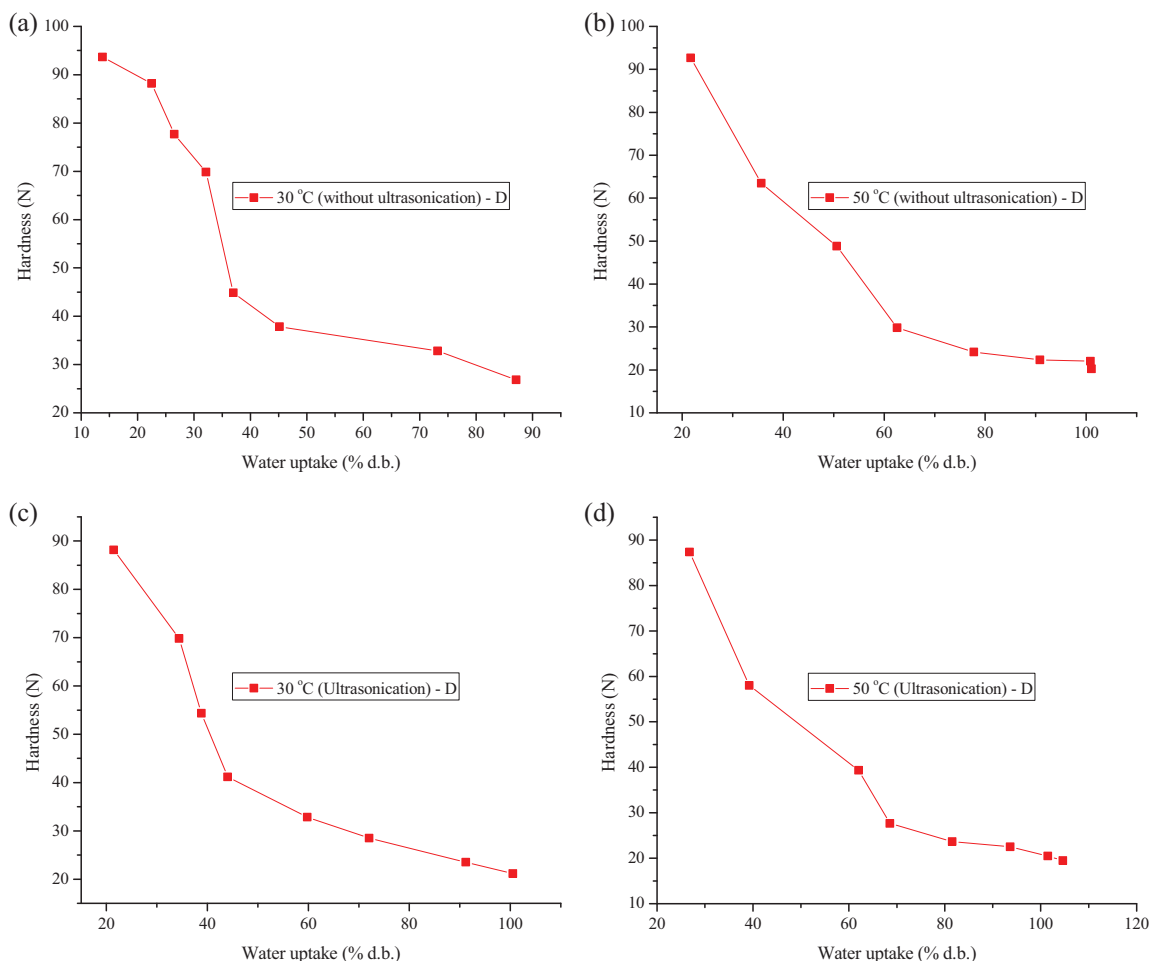


FIGURE 11 (a) Influence of water uptake on hardness for DS samples at soaking temperature of 30°C (a) without and (b) with ultrasonication and at 50°C (c) without and (d) with ultrasonication.

and caused an accelerated reduction in hardness as the water uptake rate was enhanced, especially from the start to around 60 min of soaking. Relatively softer samples were obtained after 240 min of soaking using ultrasonication at a higher soaking temperature, with GL samples exhibiting lower hardness. The goodness of fit of the regression of hardness and water uptake is provided in Table 1. A relatively high  $R^2$  and  $p$  value were observed between these parameters for soaking temperature and ultrasonication effects.

### 3.6 | Statistical analysis of data

The analysis of variance (ANOVA) for the obtained data (soaking time and temperature, mass before and after soaking, water uptake, and hardness) for the cowpea types investigated in this work with and without ultrasonication was carried out. For the GL samples, Table 2 shows that the data obtained with and without ultrasonication treatment were found to be statistically similar to  $F_{obs} > F_{cri}$  with a

**TABLE 1** Statistical performance of water uptake and hardness modeling and regression analysis of hardness and water uptake.

Parameters	Model equations	Conditions	AAD	$R^2$	R	SE	p value
$M_t$ (% d. b.)	$M_t = \frac{M_e}{1 + \frac{M_e - M_0}{M_0} e^{(-k_t M_e t)}}$	Nu-GL	0.76	0.9991	0.9996	0.9854	<0.0001
		U-GL	0.97	0.9983	0.9991	1.2717	<0.0001
		Nu-DS	1.62	0.9991	0.9996	0.9232	<0.0001
		U-DS	1.59	0.9998	0.9999	0.4904	<0.0001
$H_t$ (N)	$\frac{H_0 - H_t}{H_0 - H_e} = 1 - e^{(-k_t t)}$	Nu-GL	1.36	0.9999	0.9999	0.2083	<0.0001
		U-GL	2.52	0.9991	0.9995	0.8134	<0.0001
		Nu-DS	0.99	0.9966	0.9983	1.3382	<0.0001
		U-DS	1.61	0.9985	0.9992	1.1280	<0.0001
H-WU	-	Nu-GL (30)	-	0.8629	0.9289	10.1863	<0.0001
		Nu-GL (50)	-	0.9375	0.9683	6.4161	<0.0001
		U-GL (30)	-	0.7907	0.8892	9.8778	<0.0001
		U-GL (50)	-	0.9575	0.9785	4.2612	<0.0001
		Nu-DS (30)	-	0.7947	0.8915	12.9308	<0.0001
		Nu-DS (50)	-	0.8613	0.9280	10.5163	<0.0001
		U-DS (30)	-	0.8123	0.9013	11.2314	<0.0001
		U-DS (50)	-	0.8599	0.9273	9.7047	<0.0001

Abbreviations: GL, Glenda samples; DS, Dr. Saunders; Nu, no ultrasonication; U, ultrasonication; 30 and 50, temperature in °C; AAD, average absolute deviation; SE, standard error;  $R^2$ , coefficient of determination; R, coefficient of correlation; WU, water uptake.

Source of variation	SS	Df	MS	$F_{obs}$	p value	$F_{cri}$
GL						
Without ultrasonication						
Between groups	59487.96	5	11897.59	9.42	3.01E-07	2.32
Within groups	113660.3	90	1262.89			
Total	173148.3	95				
With ultrasonication						
Between groups	65330.53	5	13066.11	11.08	2.47E-08	2.32
Within groups	106117.7	90	1179.09			
Total	171448.2	95				
DS						
Without ultrasonication						
Between groups	12646.00	3	4215.33	10.10	1.77E-05	2.76
Within groups	25045.94	60	417.43			
Total	37691.94	63				
With ultrasonication						
Between groups	17168.65	3	5722.88	16.42	6.61E-08	2.76
Within groups	20902.81	60	348.38			
Total	38071.46	63				

**TABLE 2** ANOVA of data for GL and DS cowpea samples.

**TABLE 3** *t*-test analysis of data for Glenda and Dr Saunders cowpea samples.

Variables	Hardness		Water uptake (%)		Hardness		Water uptake (%)	
	GL		DS		DS		DS	
Mean	46.37	39.75	62.01	72.02	41.13	49.70	65.02	54.90
Variance	583.49	361.67	1083.67	813.33	553.18	735.97	807.92	897.78
Observations	16	16	16	16	16	16	16	16
Pearson correlation	0.9888		0.9857		0.9547		0.9682	
Hypothesized mean difference	0		0		0		0	
Df	15		15		15		15	
$t_{obs}$	4.3731		5.8862		4.0773		5.3869	
$p(T \leq t)$ one-tail	0.00027		1.5E-05		0.0005		3.78E-05	
$t_{cri}$ (one-tail)	1.7531		1.7531		1.7531		1.75305	
$p(T \leq t)$ two-tail	0.00055		2.99E-05		0.00099		7.55E-05	
$t_{cri}$ (two-tail)	2.1315		2.1315		2.1315		2.1315	

P-value of <0.05. Due to the application of ultrasonication, a *t*-test of water uptake and hardness data with and without ultrasonication was also carried out, and the result is given in Table 2. With  $t_{obs} > t_{cri}$  for water uptake and hardness data, it showed that their mean values were statistically identical and significant as *p* values are <0.05. Thus, the effect of ultrasonication did not lead to a difference in the mean of these parameters (uptake and hardness). From Table 3, a correlation coefficient of 0.9857 existed between the water uptake (with ultrasonication) and water uptake (without ultrasonication).

In addition, a correlation coefficient of 0.9888 was evaluated to exist between hardness (with ultrasonication) and hardness (without ultrasonication). This indicated a positive and strong relationship between these parameters. Similarly, the ANOVA results for data analysis for the DS samples show that the data were statistically the same and significant as  $F_{obs} > F_{cri}$ , and the *p* value is <0.05 (Table 2). In addition, the *t*-test analysis revealed that the mean of hardness and water uptake data was statistically similar as  $t_{obs} > t_{cri}$  and significant as the *p* value was <0.05 (Table 3). The mean of the data was not significantly and statistically affected by the impact of ultrasonication. The relationship between water uptake (with ultrasonication) and water uptake (without ultrasonication) was observed to be strong and positive, with a correlation coefficient of 0.9682 for the DS samples. A similar result was obtained for the hardness data with a correlation coefficient of 0.9547.

## 4 | CONCLUSION

A study of the influence of combined ultrasonication and hydrothermal treatment on the water uptake and hardness characteristics of GL and DS cowpea samples at different soaking temperatures and times was carried out. The water uptake behavior of all the samples demonstrated an exponential growth curve with soaking time and

temperature increase irrespective of the use of ultrasonication. An increase in soaking temperature from 30 to 50°C was observed to improve the water uptake of cowpea samples, which consequently increased the mass and reduced hardness as the soaking time surged for all the studied samples. This was connected to the expansion of coat pores and reduced water viscosity, which permitted increased water uptake via diffusion and capillary flow. However, the utilization of ultrasonication treatment boosted the mass and water uptake of the samples owing to the agitation of water and samples, leading to increased mass transfer of water. Water uptake and softening behaviors were modeled with high accuracy and significance using sigmoidal and first-order kinetics equations, respectively. In addition, the water uptake and hardness relationships for all samples exhibited reducing exponential curves with relatively strong and negative correlations. The impact of sonication was found to be more significant at lower soaking temperatures as the soaking time increased. GL samples also demonstrated higher water uptake and lower hardness than DS samples. Explicitly, the enhanced water uptake leading to reduced hardness for the two types of cowpeas revealed reduction in soaking and cooking time and saving cooking energy. Applying ultrasonication as a green technique to promote the rapid softening of cowpeas and other grains is recommended.

## AUTHOR CONTRIBUTIONS

**Sholeh Rostamirad:** Conceptualization; investigation; data capturing; data formal analysis; writing—original manuscript. **K. G. Duodu:** Material; methodology; writing—review and editing; supervision. **J. P. Meyer:** Methodology; writing—review and editing; supervision; funding. **M. Sharifpur:** Methodology; mathematical corrections; review and editing.

## CONFLICT OF INTEREST STATEMENT

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 article.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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