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Enhancing the hydration process of common beans by ultrasound and high temperatures: Impact on cooking and thermodynamic properties

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ABSTRACT

Although many technologies have been applied to enhance the hydration process of grains, some combinations and mechanisms still need better description. Consequently, this work studied how the combination of ultrasound and temperature affected the hydration process of one variety of legume grain, as well as described their thermodynamic properties of hydration and the impact on cooking kinetics. White kidney beans were hydrated using ultrasound technology (28 W/L of volumetric power and 45 kHz of frequency) at four different temperatures (25, 35, 45 and 55 °C). In addition, the softening kinetics during cooking at boiling temperature was studied by penetration analysis. Further, the thermodynamic properties, such as activation enthalpy, Gibbs free energy and entropy were determined. It was demonstrated that despite both technologies improve the hydration process individually, hot temperatures hinder the ultrasound effect. Further, the thermodynamic properties of the hydration phenomenon were affected by ultrasound, suggesting how the molecules rearrangement is affected by this technology during hydration. Finally, the use of both technologies did not affect softening kinetics of the bean during cooking process.

1. Introduction

Pulses are an important food source due to their nutritional and agronomic advantages. Besides being a mainly protein, iron and fiber source, pulses are easy to grow and help to fertilize the soils (FAO, 2016). For being consumed and facilitating their digestion, pulses must pass for previous processes such as cooking, germination, fermentation, etc. (Siddiq et al., 2011). However, as they are dried food, a hydration process is needed as a first step. Further, as the grain hydration is a slow and batch process, its study and improvement is desirable.

The hydration kinetics of pulses is a complex phenomenon, involving different mechanisms and presents two possible behaviors: downward concave shape (DCS) and sigmoidal shape. The first behavior is the most common in all kind of grains. Consequently, it is the most studied. The DCS behavior presents a high hydration rate from the beginning of the process due to the water activity difference between the grain and the soaking water. This rate decreases until reaching the equilibrium moisture content e.g. the maximum quantity of water that the grain can hold. In contrast, the second behavior seems to be exclusive for *Fabaceae* family grains and it was still slightly studied. This behavior is caused by the water permeability of the seed coat, which changes widely with the water activity and then limits and defines the water flow. This is represented by a lag phase which ends when the seed coat is hydrated and becomes permeable to water (Miano and Augusto, 2015). Finally, the water uptake continues until reaching the equilibrium moisture content. For both behaviors, some technologies have been studied to accelerate the hydration process, and in each behavior the enhancement mechanisms are different.

The classical way to accelerate the hydration process is to increase the water soaking temperature. This technique has demonstrated satisfactory results for different pulses and cereal grains, such as corn kernels (Verma and Prasad, 1999), lentils (Oroian, 2017), adzuki beans (Oliveira et al., 2013), barley kernels (Montanuci et al., 2015), Andean lupin (Miano et al., 2015), among many others. However, the use of elevated temperatures has as drawbacks the possibility of components degradation as well as the increase of process cost (heating and isolation). Therefore, other technologies have been studied, as ultrasound technology.

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Ultrasound technology has demonstrated excellent results for improving different mass transfer unit operations. This technology consists of using acoustic energy, with frequencies higher than 20 kHz, to cause physicochemical changes on biological products, to increase their quality, safety or to improve the processing (Mason et al., 1996). Regarding hydration process, this technology has improved not only the DCS hydration kinetics behavior (Ghafoor et al., 2014; Miano et al., 2017a; Patero and Augusto, 2015; Ranjbari et al., 2013; Ulloa et al., 2015; Yildirim et al., 2013), but also the sigmoidal one (López et al., 2017; Miano et al., 2016b), reducing the lag phase time and increasing the hydration rate. It should be mentioned that these works represent all the studies using ultrasound to enhance the hydration of beans.

Both, the use of hot soaking water and ultrasound technology has demonstrated their efficiency on enhancing the hydration process of pulses, but isolated. Nonetheless, any work has used the combination of both, especially for grains with sigmoidal behavior of hydration. For that reason, this work evaluated if ultrasound and hot soaking water in combination can accelerate the hydration process of sigmoidal behavior hydration kinetics pulses. Further, the effect of both technologies was evaluated in the cooking kinetics of the beans and in the thermodynamic properties of hydration.

2. Materials and methods

2.1. Raw material

White kidney beans (*Phaseolus vulgaris;* 15.82 ± 0.26% d.b (g water/100 g of dry matter) of moisture content; 16.97 ± 0.74 mm of length, 8.12 ± 0.59 mm of width and 6.46 ± 0.31 mm of thick) were obtained at a local market of Piracicaba - Brazil. This pulse was chosen because it presents the sigmoidal behavior of hydration (Miano et al., 2017c), being frequently consumed all around the world.

2.2. Hydration process

For the hydration process, 10 g of pre-selected grains were placed into net bags and soaked in 2 L of distilled water at 25, 35, 45 and 55 °C. The excess of water avoids water be a process limitation. During the hydration process, the samples were periodically drained, superficially dried with towel paper and their moisture content was obtained by mass balance (after verifying the possibility to neglect the solid loss to the water). The sampling was carried out every 15 min for the first hour, every 30 min for the latter two hours and every hour from then on. The hydration process was performed at constant temperature and in triplicate.

Further, to describe the water flow pathway, the permeability of the seed coat was evaluated by covering the hilum and micropyle of the beans using nail polish (Miano et al., 2016b; Ramos et al., 2004) and then comparing the hydration kinetics of the covered beans with the uncovered beans.

2.3. Ultrasound assisted hydration

During the experiments, an ultrasonic bath (USC-1400, Unique Brazil) with a frequency of 40 kHz and a volumetric power of 28 W/L (determined following the calorimetric method described by Kimura et al. (2007)) was used for the ultrasound assisted hydration. As in the conventional hydration process, 10 g of pre-selected grains (placed into net bags) were placed at the bottom of the ultrasonic bath in order to be subjected by the waves with the highest and more homogeneous intensity. This process was performed with 2 L of water at 25, 35, 45 and 55 °C. The data were obtained in the same way as in the conventional hydration process. It should be mentioned that the ultrasonic waves distribution in the water bath was determined by the method of the aluminum foil (Mason, 1991; Vinatoru, 2015).

2.4. Hydration data description

The white kidney beans hydration kinetics data was fitted using the sigmoidal equation proposed by Kaptso et al. (Equation (1) (Kaptso et al., 2008);). For that purpose, the grain moisture content (M, in dry basis, % d.b.) versus the hydration time (min) was tabulated for each treatment. Each replication data was fitted using a generalized reduced gradient algorithm, which is implemented in the 'Solver' tool of software Excel 2016 (Microsoft, USA). Different initial guesses of the three parameters were assessed to detect possible local convergence.

$$M_t = \frac{M_\infty}{1 + exp[-k\cdot(t-\tau)]} \tag{1}$$

Furthermore, the individual effect of the temperature on the Kaptso model parameter was evaluated by fitting the parameter value as a function of the temperature (Kelvin) on a suitable equation. For the parameter k and τ the Arrhenius equation was used (Equation (2)), due to its exponential behavior. Thus, the activation energy (E_a) was obtained for the conventional and the ultrasound assisted hydration process.

$$P_T = A\cdot\exp\left(\frac{-E_a}{R\cdot T}\right) \tag{2}$$

For the equilibrium moisture content, the effect of temperature was explained by an empirical equation due to its specific behavior (Equation (3)).

$$M_{\infty\ T} = M_{\infty\ 25^\circ C} - b\cdot exp(c\cdot T) \tag{3}$$

2.5. Thermodynamics properties

The activation enthalpy ($\Delta H^{\#}$), the activation Gibbs free energy ($\Delta G^{\#}$) and the activation entropy ($\Delta S^{\#}$) were obtained for both the hydration rate (k) and time lag parameters (τ), using the following equations (Sánchez et al., 1992; Silva et al., 2017):

$$\Delta H^{\#} = E_a - R\cdot T \tag{4}$$

$$\Delta G^{\#} = -R\cdot T\cdot ln\left(\frac{P_T\cdot h}{k_B\cdot T}\right) \tag{5}$$

$$\Delta S^{\#} = \frac{\Delta H^{\#} - \Delta G^{\#}}{T} \tag{6}$$

The activation enthalpy ($\Delta H^{\#}$) is related to the necessary energy to form the activated complex before the reactants form the products. The free energy ($\Delta G^{\#}$) is related to the spontaneity of the transition state formation and the activation entropy ($\Delta S^{\#}$) is related to this activated molecule complexity (Al-Zubaidy and Khalil, 2007; Vikram et al., 2005).

2.6. Cooking kinetics

Approximately 80 g of beans were cooked in a Becker with 1.6 L of boiling distilled water (98 °C). Each 10 min, a sample of 10 beans were removed, stored in a closed container to avoid dehydration and cooled until reaching room temperature (~25 °C) before performing the penetration test. The penetration force profile (force