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Structural changes caused by ultrasound pretreatment: Direct and indirect demonstration in potato cylinders

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ABSTRACT

This work aimed to demonstrate the internal and external structural changes in potato cylinders caused by different times of ultrasound pretreatment. In addition, the structural changes were associated with the viscoelasticity and mass transfer. For which, potato cylinders were immersed in distilled water and pretreated with and without ultrasound (ultrasonic bath of 91 W/L and 25 kHz) up to 120 min. Then, the microstructure was evaluated by stereoscopic observation as a direct method, and by viscoelasticity and mass transfer evaluation (pigment diffusion and drying) as indirect methods. Both external and internal structure of the material were evaluated. As results, it was demonstrated the formation of microchannels inside the potato tissue as well as the surface erosion caused by ultrasound, especially after 60 min of pretreatment. Further, it was observed that the product viscoelasticity is affected by the ultrasound pretreatment reducing the elasticity. In addition, the mass transfer on the cylinders was improved by ultrasound pretreatment. The pigment transfer was enhanced, demonstrating the acoustic erosion at the sample border. Furthermore, the drying process was accelerated by ultrasound, demonstrating the reduction of the internal resistance to water transfer. Finally, it was observed that high structural changes on the potato cylinders can bring some disadvantages such as changes on the color and severe shrinkage. This work concluded that the structural changes caused by ultrasound can be evidenced directly and indirectly. Furthermore, different structural changes took place, on both inside and outside of the vegetable sample. However, despite ultrasound improves further process, especially those that involve mass transfer, the parameters time and ultrasonic power must be optimized to obtain desirable results without reducing the product quality.

1. Introduction

High power ultrasound has been very useful for improving mass transfer processes, such as extraction [1], drying [2], hydration [3], acidification [4], osmotic dehydration [5], salting [6], desalting [7] and nutrient incorporation [8,9]. The mass transfer improvement was attributed to diverse mechanisms that reduce both internal and external resistances [10].

External resistance is reduced by increasing the convection of the bulk flow by ultrasound mechanisms: ultrasonic streaming, acoustic cavitation and micro jets [11,12]. On the other hand, when the high power acoustic wave passes through food, its internal resistance to mass transfer is reduced due to different mechanisms.

The alternating compression and rarefaction of the acoustic wave causes pressure difference in the structure. The intercellular fluids then flow, improving the exit and entrance of substances [13]. In addition, when food has high water activity (i.e. food at rubbery state), the acoustic wave causes the alternating compression and expansion of the tissues and cells, which behave as sponges that squeeze and release repeatedly. This mechanism, called as "sponge effect" [14], also facilitates the fluid flow and can unblock the pores and spaces inside food [15].

Furthermore, the internal resistance to mass transfer can be improved due to the structural changes caused by the acoustic cavitation, such as structure disruption, cell flattening, intercellular adhesion lost [16], cell membrane rupture, and formation of micro cavities and microchannels [17]. This mechanism is advantageous for further processes, especially mass transfer unit operations [10,18]. However, sometimes this could be disadvantageous, since the food structure is damaged, decreasing for instance the sensory quality or the biochemical stability [19].

In fact, several works used ultrasound technology as a pretreatment for improving many mass transfer processes [19–27]. It means that the sample is treated with ultrasound for a specific time, immersed in water

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or a solution, for then being processed (drying, extraction, frying and so on). In this case, the enhancement of the process is mainly attributed to the structural changes caused by ultrasound. However, despite most of the works mentioned those mechanisms, many of them neither demonstrate the structural changes that caused the mass transfer improvement nor the severity of the pretreatment on the structure. Therefore, the use of ultrasound as pretreatment needs to be better described.

For that reason, this work aimed to describe and demonstrated the structural changes caused by ultrasound pretreatment in a model food, by using both direct (microscopy images) and indirect (viscoelastic properties and mass transfer) approaches.

2. Material and methods

2.1. Sample preparation and ultrasound pretreatment

Potato was used as a model food. Fresh potatoes (*Solanum tuberosum*) var. Monalisa were obtained from local market of Piracicaba-Brazil. Transversal cylinders of 2.0 cm of height and 2.0 cm of diameter were obtained using a stainless-steel corer (perpendicular to plane xy, according to Fig. 1). The effect of ultrasound was evaluated through the changes on the cylinders structure caused by immersing them into water, applying ultrasound for 30 min (US 30), 60 min (US 60), 90 min (US 90) and 120 min (US 120). In addition, as control treatments, cylinders were immersed into water without ultrasound for the same periods of time (W 30, W 60, W 90 and W 120), also cylinders without any kind of treatment (C) were evaluated.

For the ultrasound pretreatment, 25 cylinders were placed in net bags (5 cylinders per bag) at the bottom of an ultrasonic bath (Q13/25, Ultronique Brazil; internal dimensions of 33 × 38 × 15 cm; frequency of 25 kHz, volumetric power of 91 W/L – measured by the calorimetric method [28]) containing 4 L of distilled water. The temperature was maintained at 25 ± 1 °C during the process using a heat exchanger inside the ultrasonic bath and an auxiliary water bath. The location of the samples inside the ultrasonic bath was decided taking into account the good practices described by Vinatoru [29], to assure the highest ultrasonic intensity.

The cylinders of each treatment were removed from water and superficially dried with paper towel for them being analyzed.

2.2. Microstructure evaluation

The sample microstructure was evaluated using a microscopy stereoscopy (model XTD-30-LED, NOVA, Brazil) with 152× magnification, coupled to a portable camera of 1.3 megapixels. The external (border) and internal microstructure of the potato cylinder were observed using toluidine blue solution (0.1% in water) to stain the cell walls. The border was observed directly (top view focusing on the border), and the internal structure was observed by performing a transversal cut in the middle of the cylinder.

2.3. Viscoelastic evaluation

For evaluating the effect of ultrasound on the mechanical properties of the potato cylinders, the stress relaxation analysis was performed. This assay was performed using a Texture Analyzer (TA.XT Plus, Stable Micro Systems Ltd., Surrey, UK) with a load cell of 50 kg-f (490.3 N) and a 35 mm cylindrical probe (P/35).

The potato cylinders were firstly compressed until 3 mm of deformation at 0.2 mm·s^{-1}. Then, the deformation was maintained constant for 30 s, being the data of force (N) versus time (s) recorded to plot and to analyze the relaxation curves.

The data was fitted using the model proposed by Guo and Campanella [30] (Eq. (1)), due to the simplicity of interpreting its parameters and its suitable adjustment on many kind of food [31].

$$\sigma(t) = k \bullet \frac{\varepsilon_0}{\Gamma(1-\alpha)} \bullet t^{-\alpha} \quad (1)$$

where, $\sigma(t)$ is the compression stress over the compression time, k is a parameter that represents the viscoelastic modulus, ε_0 is the strain (whose value was 0.15 and was constant in the stress relaxation test), t is the compression time, α is the fractional order (whose value is from 0 to 1: values closer to 0 means that the samples behave more like a Newtonian viscous fluid, and values closer to 1 means that the samples behave more like a Hookean elastic solid) and Γ is the gamma function.

2.4. Mass transfer evaluation

Based on microstructure results, some treatments were selected to evaluate the mass transfer through the potato cylinders pretreated with and without ultrasound. It was evaluated in two ways.

The first way consists of immersing the cylinders after 90 min of ultrasound pretreatment in a pigment solution (toluidine blue solution 0.1% in water). After 15 min of immersion, the cylinders were cut longitudinally to qualitatively see how deep the pigment enter. This was performed using four cylinders of each treatment.

The second way to study the mass transfer was evaluating the

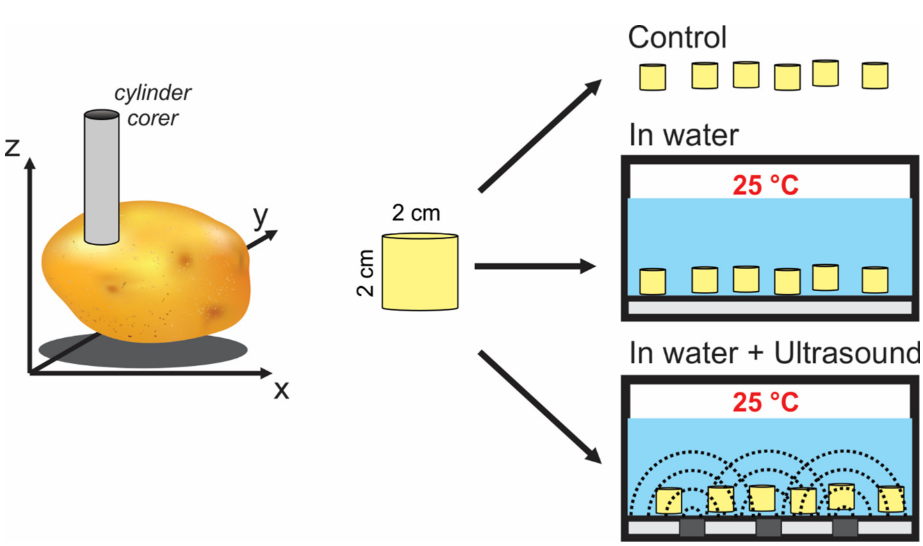

Fig. 1. Sample preparation for evaluating the effect of ultrasound pretreatment time on the structure. Without scale.

drying kinetics of the samples. For that, convective drying was performed at 60 °C using an air stream with velocity of 0.8 ± 0.1 $m \cdot s^{-1}$, in an oven with circulation and air renewal (MA 035, Marconi, São Paulo, Brazil). The potato cylinders were placed on a metal net to allow the free movement of warm air over the entire surface of the samples. The samples were dried until constant mass. The sample mass was recorded every 30 min using a precision scale (Mark 2200, TECNAL, Piracicaba, Brazil) coupled to the oven. Three replicates of the process were performed, each one using 12 cylinders.

The initial (*in-natura* samples) moisture content was measured by completely drying crushed samples at 105 °C using a moisture analyzer (MX-50, A&D Company, Tokyo, Japan). By mass balance, using the initial moisture and the sample mass, all the moisture data over drying time was calculated. Drying curves were plotted as a function of the moisture content and as a function of the dimensionless moisture ratio (MR) over the processing time. The MR was computed according to Eq. (2), where M_t is the moisture content during the drying process time (t), M_e is the equilibrium moisture and M_0 is the initial moisture of *in-natura* sample.

$$MR(t) = \frac{M_t - M_e}{M_0 - M_e} \quad (2)$$

The drying data was fitted using the Page Model (Eq. (3)) [32], where MR(t) is the dimensionless moisture at drying time (t), k is the drying rate constant and n the dimensionless drying constant. Although the Page Model is an empirical model, it was successfully applied to drying process of different products, such as mint leaves [33], green beans [34], okra [35] and pumpkin [36,37]. Furthermore, Simpson, Ramírez, Nuñez, Jaques and Almonacid [38] recently demonstrated that the anomalous diffusion approach, based on fractional calculus, can attribute phenomenological meanings to the model parameters: the drying rate constant (k) is associated with the diffusion coefficient and the geometry of the sample, while the dimensionless drying constant (n) describes the "type of diffusion", related to the food microstructure ($n > 1$ super-diffusion and $n < 1$ sub-diffusion). Our interpretation is that when $n \neq 1$, other mechanisms than diffusion are important. For example, the "super-diffusional process" ($n > 1$) may indicate the importance of capillarity [37].

$$\mathrm{MR(t)} = \exp(-k.\ t^n) \quad (3)$$

2.5. Statistical analysis

All the processes and analyses were performed at least 3 times. The analysis of variance (ANOVA) was carried out with a significance level of 5%. To determine differences among means of pre-treatments, Tukey test was used. Statistical analyses were performed using IBM SPSS Statistics 23 software (IBM SPSS, USA).

3. Results and discussion

Ultrasound pretreatment in water is usually used prior to many mass transfer processes, enhancing them. Most of the published works have attributed the improvement to structural changes on the products. For instance, ultrasound pretreatment was used for improving drying process on carrots [25], apple [39], strawberry [40] and melon [16]; improving osmotic dehydration of kiwifruit [20]; and improving frying of sweet potatoes [41]. However, this mechanism is mostly mentioned without proving it. Below, some direct and indirect evidence are presented about the structural changes that ultrasound causes when it is used as a pretreatment.

3.1. Direct demonstration of structural changes

Fig. 2 directly shows the structural changes caused by ultrasound pretreatment on the potato cylinders. In fact, it was reported that ultrasound application causes tissue disruption by acoustic cavitation. However, this mechanism takes place randomly. Therefore, the micro cavities and microchannels that are formed have different shapes and tortuosity, which can have connectivity or not with the exterior medium [17]. As demonstrated (Fig. 2), ultrasound resulted in different changes on the internal and external structure of potato cylinders depending on the pretreatment time. Each one can enhance differently the mass transfer processes.

Fig. 2 proves the microchannels formation in potato tissue by ultrasound. In fact, few of the works that used ultrasound as pretreatment have proved by microscopy the formation of microchannels on papaya and pineapple tissue [42], melon tissue [4,16], apple tissue [43] and kiwifruit tissue [20] – in special considering different processing times. As control pretreatment, the cylinders were immersed in water, which did not cause any structural change on the potato tissue. When the cylinders were immersed in water with ultrasound, there was microchannels formation after 60 min of pretreatment. This demonstrates that the microchannels need time to be formed and to get broader [16,17]. The microchannels can improve the mass transfer since this would facilitate the entrance or exit of fluids. Consequently, the ultrasound pretreatment time needs to be enough to form this microchannels and improve further mass transfer processes. It is important to highlight that this also depend on the ultrasonic power, and the food properties as the water activity and rigidity [17].

Most of the works only shows the structural changes caused by ultrasound of the internal tissues (inside food) of vegetables. However, there is not any work showing how the food boundaries are erode by acoustic waves. Therefore, Fig. 2 also shows the effect of ultrasound pretreatment on the border structure of the potato cylinders. The exterior of a product is eroded by ultrasound due to acoustic cavitation and micro jets [10]. This structural modification also increases the superficial area, which improves mass transfer. After 90 min of ultrasound pretreatment, the cylinder surface was very damaged since cells are not distinguished at all. The surface damage take place even in short pretreatment times, in contrast to internal microchannel formation. Therefore, this mechanism could be the main cause of mass transfer improvement in processes when ultrasound is used for short times as a pretreatment.

It is important to be mentioned that despite these structural changes improve the mass transfer, they can also cause undesirable effects. For instance, textural changes, loss of biomolecules as nutrients or enzymes (that can be activated or inactivated with ultrasound processing [44,45]), differences on sensorial perception, bad rehydration quality after a drying process, and so on. Consequently, the pretreatment time, depending on ultrasound power, is an important parameter to be controlled depending on the final product that is required. In fact, important differences on the product quality are reported as follows.

3.2. Indirect demonstration of structural changes

3.2.1. Mechanical properties change

The mechanical properties of the potato cylinders were evaluated to study how viscoelasticity is affected by ultrasound pretreatment. Fig. 3 shows how the relaxation curves of potato cylinders were affect by ultrasound pretreatment. Those curves were adjusted ($0.87 < R^2 < 0.99$) using the model proposed by Guo and Campanella [30] and the parameters k and α were obtained.

Ultrasound reduces the maximum stress and the elasticity of the potato cylinders as the pretreatment is longer (Fig. 3A). It should be mentioned that the relaxation curves of the cylinders that were immersed in distilled water without ultrasound (control treatment) were not affected ($p > 0.05$). Fig. 3B and C show that the maximum stress and the value of the parameter k were not affected when the cylinders were immersed in distilled water without ultrasound. Despite that the potato cylinders were in a hypotonic medium, there was not significant gain of water that can change the osmotic pressure of the potato cells

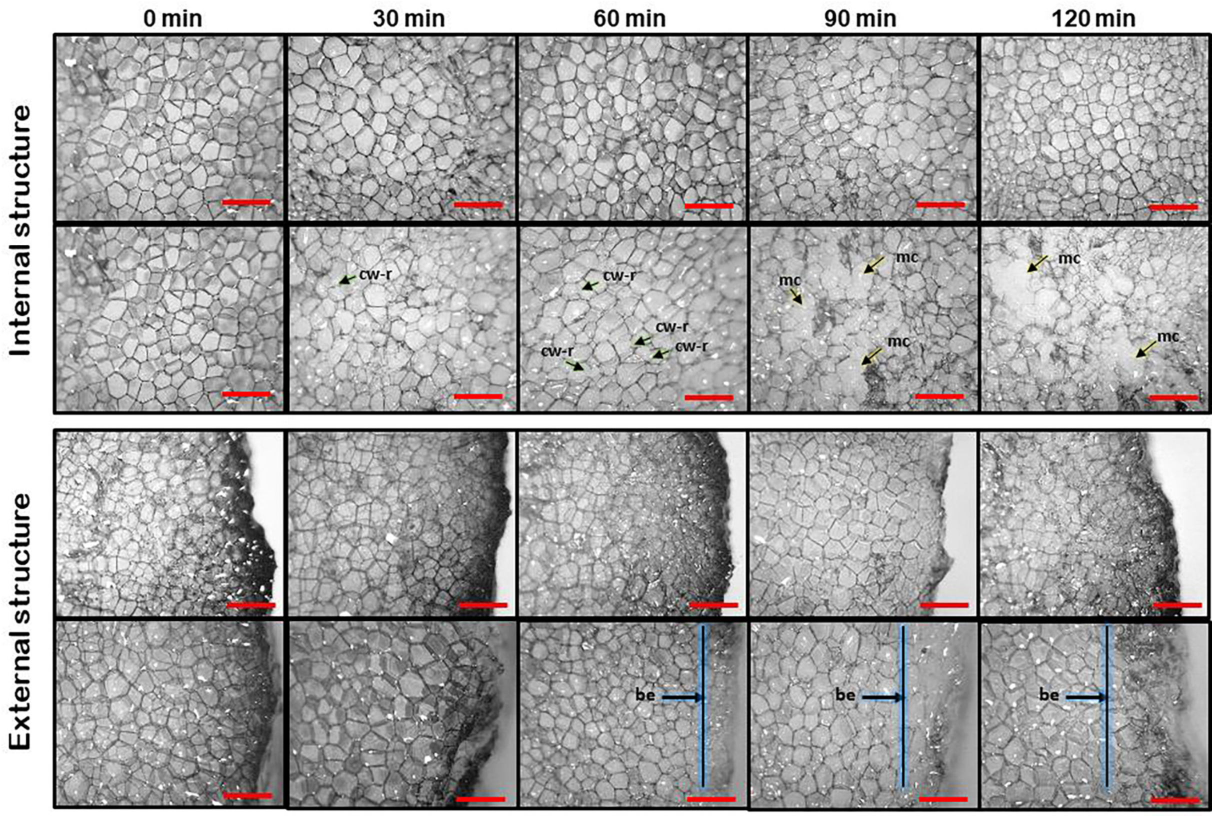

Fig. 2. Left: Potato cylinder internal structure. Images obtained using a microscopy stereoscopy of the cross section (transversal cut) of the potato cylinder at different pretreatments conditions. The red horizontal bar represents 0.5 mm. cw-r: cell wall rupture; mc: microchannels (which were highlighted). Right: Potato cylinder external (border) structure. Images obtained using a microscopy stereoscopy of the external surface (cylinder base) of the potato cylinder at different pretreatments conditions. The red horizontal bar represents 0.5 mm. be: border erosion.

and thus, changing their viscoelasticity. In contrast, the maximum stress and the parameter k were reduced when ultrasound was used. In fact, until 30 min of pretreatment, these values were not significantly affected. However, after 60 min these values were significantly reduced. This is in accordance with the microscopy images, which demonstrate significant cell rupture inside the cylinders from 60 min of pretreatment (Fig. 2) causing the structure to weaken. In fact, some works demonstrate that ultrasound increase the pectin solubility specially after 30 min of pretreatment on apple [43]. On the other hand, the structure weaken was significantly kept almost the same until 2 h of ultrasound pretreatment, despite there is a tendency to be more reduced.

In addition, the value of α was not significantly affected by immersing the cylinders in water without ultrasound, but it was significantly increased when ultrasound was applied ($p < 0.05$) (Fig. 3D). The parameter α gives an idea of how elastic or viscous is the behaviour of the sample [30]. Therefore, the increment of this parameter value means that the sample had a more viscous behaviour after 30 min of ultrasound. In fact, the progressive rupture of the cell walls and cell membranes improve the exit of the cell fluids. Moreover, the ultrasound can change the integrity of the cell walls and membrane, facilitating the fluid flow through it during compression. Consequently, increasing in the viscous behaviour during the compression of the cylinders can be a result of fluid flow. The parameter α was increased ~4 times until 60 min of pre-treatment and then it was kept constant. In fact, after this pretreatment time, the cellular damage was big enough (Fig. 2) to cause the elastic behaviour reduction significantly. Further damages until 120 min of pretreatment did not significantly affect the viscoelastic behaviour. Therefore, regarding this property, ultrasound could be used for 60, 90 or 120 min for improving mass transfer without an additional change on viscoelasticity.

It is also important to highlight that the samples that were processed using ultrasound presented higher values of standard deviation on their parameter values. This indicates a higher difference among the treated cylinders. This can be explained by the idea that the ultrasound destroys the structure of the cylinders randomly, obtaining some cylinders with more structural changes than others.

Consequently, ultrasound changes the mechanical properties significantly after 60 min of treatment, being the treatments at 90 min and 120 min no significantly different to this. The mechanical properties can be changed by the cell disruption, cell separation and tissue destabilization, as observed in Fig. 2.

Further, the samples can gain water and lose solid as starch during the pre-treatment. It should be mentioned that most of the works that used ultrasound as pretreatment reported that the product gains water [20,25,41]. This depend on the moisture content of the product. In fact, the evaluated potato samples had 84.35 ± 2.22%w.b. of moisture content. The variation of the sample mass after processing was ~3% when they were immersed in distilled water and ~0% when ultrasound was used. The increment of the mass of the cylinders immersed in water was mainly because the gain of water. In contrast, in the case of the cylinders immersed in water with ultrasound application, there could be both gain of water and loss of solids from the disrupted cells. Thereby, this caused any variation of the cylinder mass.

3.2.2. Mass transfer improvement

Now, the mass transfer was evaluated to and through the cylinders.

Firstly, a pigment transfer was qualitatively evaluated on cylinders that were immersed in distilled water with and without ultrasound for 90 min. This ultrasound pretreatment time was selected since, when microstructure was evaluated, greater structure changes were observed at 90 min (Fig. 2). Fig. 4 shows that the pigment entered more in the cylinders that were pretreated with ultrasound. This also demonstrate

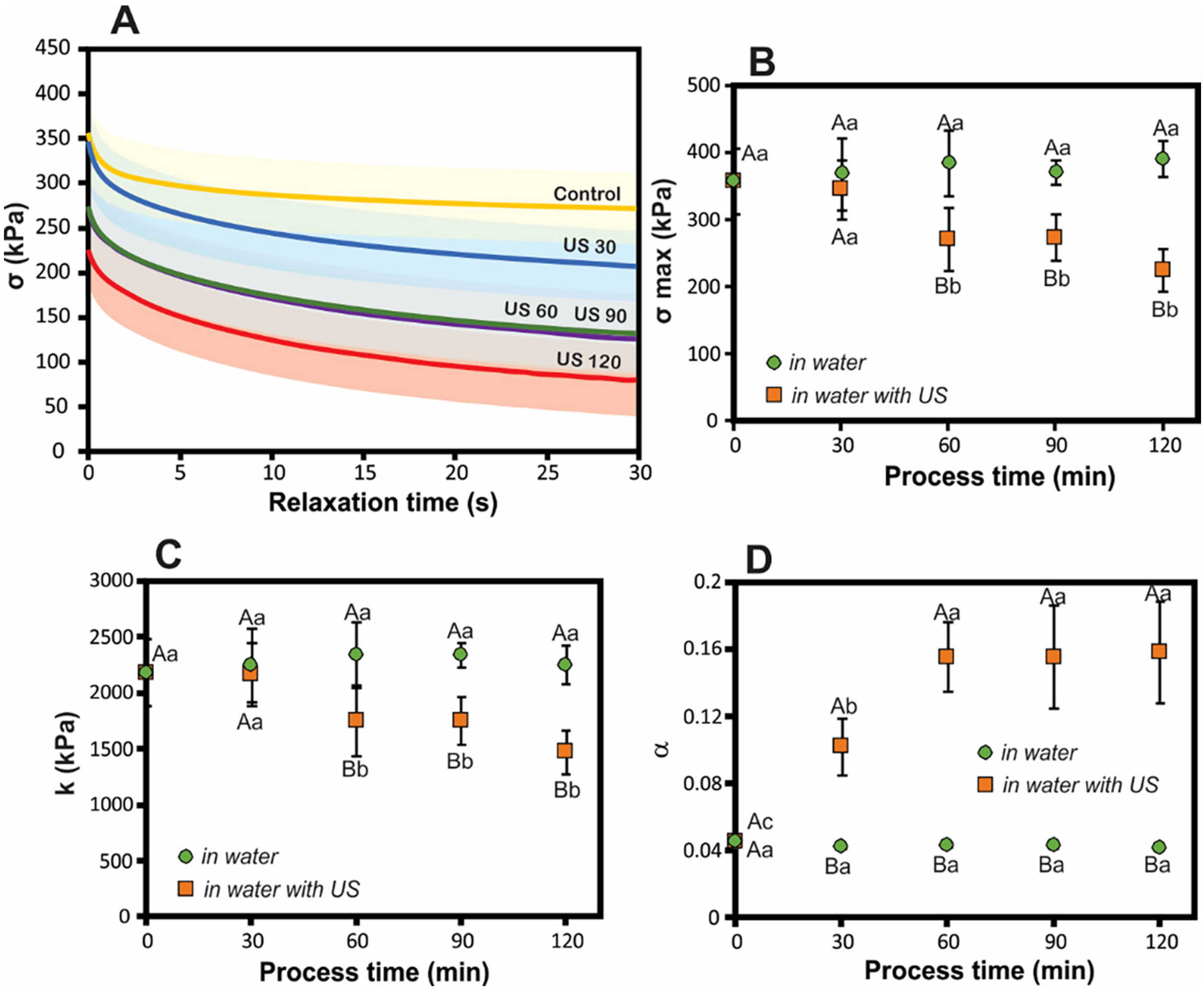

Fig. 3. A. Relaxation curves of potato cylinders pretreated for different times with ultrasound. The continuous lines represent the experimental data and the shade region represent the confidence bands with 95% of confidence B. Effect of ultrasound pretreatment time on the maximum stress that the potato cylinders can support. C. Effect of ultrasound pretreatment time on the viscoelastic modulus parameter (k) from the model proposed by Guo and Campanella (2017) (Eq. (1)) of potato cylinders. D. Effect of ultrasound pretreatment time on the fractional order parameter (α) from the model proposed by Guo and Campanella (2017) (Eq. (1)) of potato cylinders. In B., C. and D., dots represent the experimental data and vertical bars the standard deviation. Upper-case letters indicate the mean comparison (Tukeý́s test $p < 0.05$) between the pretreatment with and without ultrasound and lower-case letters indicate the mean comparison among pretreatment times.

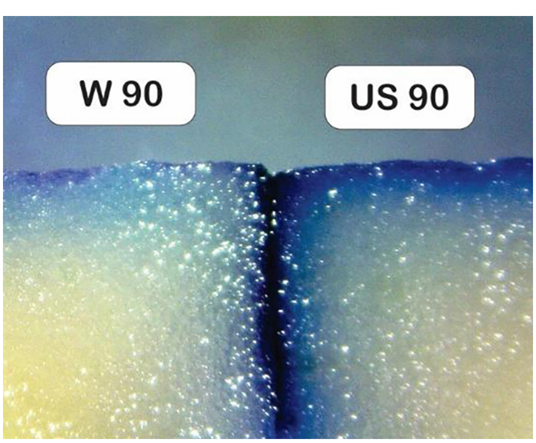

Fig. 4. Photography of the pigment transfer into the potato cylinders of a sample pretreated for 90 min without (W 90) and with ultrasound (US 90).

the cylinder erosion by ultrasound as shown in Fig. 2. Furthermore, it is suggested that there was not any significant microchannel connected to the exterior, since the pigment did not penetrate to the inner of the cylinder. This supports the idea that microchannel are randomly formed, most of them without connection with exterior, and that the process need time to form microchannels with connectivity to the medium, allowing the mass transfer through them.

In addition, for evaluating how the structure changes influence the drying process, the control and pretreated samples were convective dried. For this, an intermediate (60 min (US 60) and the final conditions (120 min (US 120)) of ultrasound pretreatments were evaluated. Additionally, one treatment by immersion in water for 120 min (W 120) was selected to comparison purpose.

Fig. 5(A) shows the moisture content reduction (% w.b.) as a function of the convective drying time. As expected, it was observed that all the US treatments dried the samples faster than the control treatment. Additionally, the horizontal line represents a moisture content of 25% w.b. According to Jay, Loessner and Golden [46], a moisture less than 25% w.b. are necessary for dried (or low-moisture) foods. Compared to control samples, the time needed to reach this moisture content was reduced about 10.7% for US 60, 28% for US 120 and 4.5% for W 120 treatments. Similar results were found for other products as apple, where drying time was reduced 13–17% when 30 min of ultrasound pre-treatment was applied [39]; basil drying time was reduced almost 20% using 30 min of pre-treatment [47]; melon drying time was reduced almost 28% applying 30 min of pre-treatment [16]. In addition, many other works have demonstrated that ultrasound

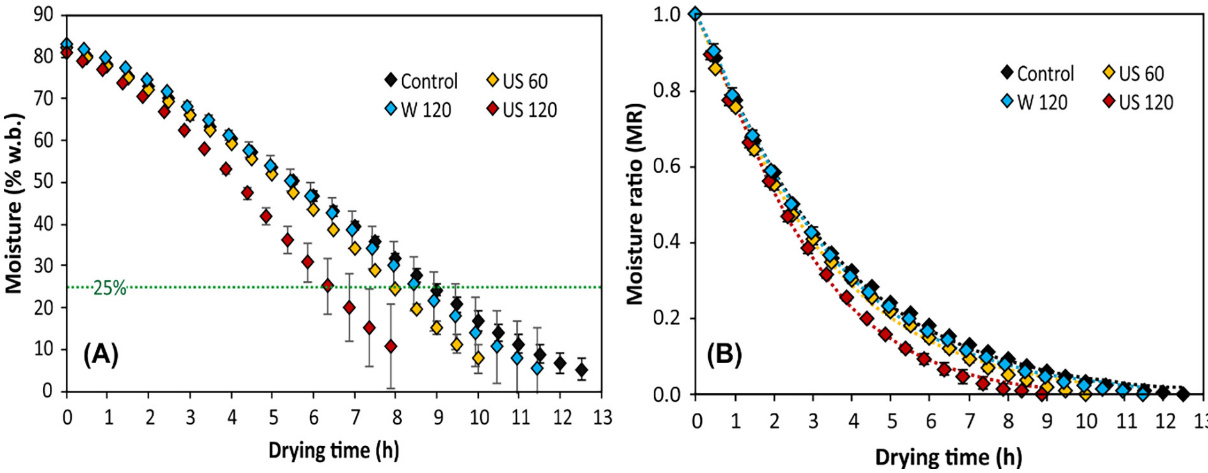

Fig. 5. (A) Moisture on wet basis % as a function of drying time; the horizontal line represents a moisture of 25%. (B) Moisture ratio (MR) as a function of drying time. Dots are experimental data, vertical bars are the standard deviation, and doted lines are the modelled data using the Page Model (Eq. (3)).

pre-treatment accelerated drying process [21,23,25,27,40,48–50].

Fig. 5(B) shows the normalized moisture or moisture ratio (MR), which data were modelled using the Page Model ($R^2 > 0.99$). The Page Model (Eq. (3)) parameters (n and k) can be used to describe the drying process (Table 1). As observed, for all samples the n value was > 1, being the n value for control samples slightly lower than those of the other samples. According to Simpson, Ramírez, Nuñez, Jaques and Almonacid [38], the parameter n on Page Model is related to the type of diffusion ($n > 1$ super-diffusion and $n < 1$ sub-diffusion). Therefore, all pre-treatments showed a super-diffusive behaviour ($n > 1$) during drying, which increased with ultrasound pretreatment. This could be attributed to the microchannel formation that contributes to capillary flow. As shown in Table 1, a small variation was observed for the parameter$k$, which is associated with the drying rate. Although statistically there was no significant differences ($p > 0.05$), it can be evidenced a tendency to increase the k value with longer time of applied ultrasound.

As described and evidenced on microstructure (Section 3.1), at short times of ultrasound pretreatment, the structure was not significantly affected – in this case, lower than 60 min. In fact, pre-treatments shorter than 30 min has shown being not enough to change significantly the structure [43,51]. By using short pre-treatment times, the water of the medium enters to the sample, the solids from the surface leave towards the liquid medium and the intercellular compounds, such as starch granules, could be redistributed with low cell wall damages. At this level of modification, the evidenced effects on drying process are generally low or not evidenced. For example, the drying curves of the treatment US 60 seemed like the Control treatment (Fig. 5). Even so, there was a slight reduction on drying time.

As the ultrasound pretreatment time is increased, there was an increase of the changes on the sample structure (Fig. 2). According to Halder, Datta and Spanswick [52], any change in the cell and intercellular structure will affect the water exit pathway during drying. Consequently, the structure changes, as consequence of ultrasound pretreatment, highly impacted the water mobility. It also allowed the water experiences less resistances to flow, as in the case of the US 120, accelerating the drying process.

Additionally, it was observed that at the beginning of the drying process (when samples have high moisture content) all treatments showed similar behaviour (Fig. 5). In fact, it indicated that at this drying stage, the water was easily removed from the surface part. Consequently, the drying rate was similar for all samples. However, at the end of process, when the samples had lower than ~2 g H_2O/g d.b., the US 120 treated samples showed higher differences compared to others. It suggests that effectively the ultrasound pretreatment above 60 min highly reduced the internal resistance (which is more important in the last stage of drying) to water transfer during drying process. Consequently, ultrasound pretreatment above 60 min favoured the last stage of drying by creating routes to water flow from the interior of the samples to the surface. This coincides with the higher changes observed on viscoelasticity of potato cylinders, which were significantly affected after ultrasound pretreatment for 60 min (Fig. 3).

For comparison, a treatment by immersing the samples in water for 2 h (W 120) was performed. After treatment, the moisture of potato cylinders was ~0.4 g H_2O/g d.b, which is higher when compared to *in-natura* samples. This moisture increment could be considered negligible during drying since it was eliminated during the first minutes of drying. However, at the end of process a slight reduction of drying time was observed with this treatment (Fig. 5), probably because of superficial "cleaning" of the sample and the consequent unblocking of pores. Anyway, the effect during drying of (W 120) was different to both cases of ultrasound pretreatment (US 60 and US 120).

Therefore, higher structural modifications are necessary to show significant effects on drying kinetics, which was obtained at long ultrasound pretreatment time.

Fig. 6 shows dried potato cylinders pretreated with the four conditions. Despite the application of ultrasound for 120 min accelerated

Table 1
Page Model (Eq. (3)) parameters. Results expressed as mean ± standard deviation. Differences among letters indicate significant differences ($p < 0.05$) among treatments.

Treatment	n	k (min^{-1})
Control	1.098 ± 0.012^b	0.248 ± 0.006^a
W 120	1.124 ± 0.036^{ab}	0.250 ± 0.014^a
US 60	1.105 ± 0.004^b	0.271 ± 0.009^a
US 120	1.214 ± 0.072^a	0.274 ± 0.026^a

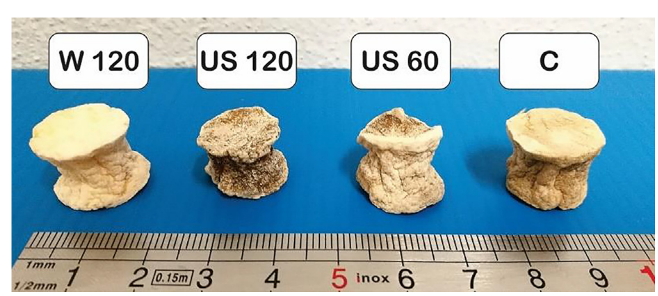

Fig. 6. Potato cylinder pretreated with different conditions after drying process.

the drying process, the cylinders presented higher level of shrinkage than the others pretreatment. In addition, these cylinders become darker. This also demonstrates the cell damage caused by ultrasound cavitation, which avoided the cylinder to maintain their dimensions after drying. In addition, the broken cells released enzyme as Polyphenoloxidase, which when in contact with oxygen and phenols caused browning reactions (furthermore, the Polyphenoloxidase activity can also be increased by ultrasound [45,53]). In fact, the cylinders pretreated with 60 min of ultrasound did not become too dark than the sample pretreated for 120 min. This would corroborate that the longer the ultrasonic pretreatment is, the more severe the structure damage of the food will be, being a problem for the color stability of a dried food [54].

Furthermore, it is interesting to notice that the dried cylinders that were immersed in distilled water for 120 min without ultrasound (W 120) did not reduce its size significantly and presented a lighter color. In this case, the water could wash the enzyme and substrate released by cells from the surface, avoiding further browning reactions during drying. It indicates that the conditions of ultrasound pretreatment to drying should be defined by taking into account an adequate balance between benefits obtained for the drying process with the quality of the obtained product.

3.3. General discussion

Ultrasound pretreatment causes structural changes due to tissue and cell disruption caused by acoustic cavitation. As shown in the results, depending on the ultrasound pretreatment time, the severity of the structure damage is changed. This result is in accordance with other works where ultrasound was also used as pretreatment before a mass transfer unit operation [10,16,41,48]. It should be mentioned that not only pretreatment time can affect the structure of food, but also power, frequency and so on [54,55]. Furthermore, the effect of ultrasound depends on the food characteristics as water activity and porosity [17].

According to the results for potato cylinders, the microstructural changes on the borders (external surface) and in the internal tissue can be significantly evidenced from 60 min of pretreatments using ultrasound with 90 W/L of volumetric power (this can be considered a high power compared to other ultrasonic bath reported in other works). The probability of observing microchannels formation in the structure increases with pretreatment time being still more probable evidenced in the borders (external structure). Further, the samples become less elastic as the ultrasound pretreatment time increases, evidencing the cell and tissue disruption inside the sample. However, despite the viscoelasticity of the samples changed significantly with ultrasound pretreatments for 60 min, these changes kept similar using longer times (90 and 120 min) of pretreatment. This means that despite more damage is observed at 90 and 120 min, the viscoelasticity keeps almost constant, maybe due to the interaction among the cell disruption, gain of water and solid loss effect. Further, this could be since when the sample is intact (control) any small structural change can be evidenced by the relaxation analysis; after reaching a certain limit of structural damage any additional structural alteration may not be sufficiently evidenced in the relaxation curves.

In addition, the use of ultrasound pretreatment enhanced the mass transfer due to the structure change, which was evidenced by pigment transfer and drying process.

The transfer of a pigment corroborates the damage of the cylinders surface by acoustic erosion. The drying process demonstrated that the effect is higher as the pretreatment time is longer since more structural changes took place inside the cylinders. In fact, drying was no significantly enhanced at 60 min of ultrasound pretreatment, since at this time the internal microstructure showed lower microchannel formation. In contrast, by pretreating the potato cylinders for 120 with ultrasound, the formed microchannels reduce the internal resistance to water transfer during drying, which was evidenced in the drying curve. However, the dried potato cylinders obtained after the drying process showed that the longer the ultrasound pretreatment is, the more severe the shrinkage of the cylinders will be. This means that the high quantity of microchannels avoided to keep the original structure, which collapses. In addition, when the ultrasound pretreatment is long, different compounds are released from the cells [56], which is desirable for extraction processes [18]. For instance, enzymes (such as polyphenoloxidase) and their substrate, causing browning reaction and darkening of the potato cylinders. Therefore, although ultrasound pretreatment enhances the mass transfer processes, the intensity of this process must be optimized to avoid obtaining undesirable results on food quality.

4. Conclusions

The structural changes on food caused by ultrasound pretreatment could be evidenced by direct and indirect approaches. This work proved that ultrasound caused the cell disruption, microchannel formation and surface erosion of potato cylinders by direct observation of the tissues. In addition, these mechanisms caused the elasticity reduction of the cylinders and the mass transfer improvement, showing indirectly the ultrasound effect. In fact, the structural changes are depended on the pretreatment time. The longer the ultrasound pretreatment is, the more severe the structural changes, the faster the mass transfer and the lowest quality of the potato cylinders will be. Consequently, it is desirable optimize the time-ultrasound power conditions to improve further process with minimum effects on the product quality.

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