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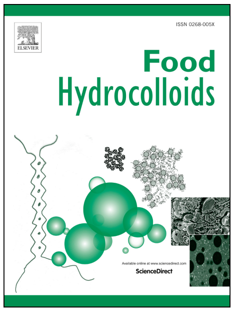

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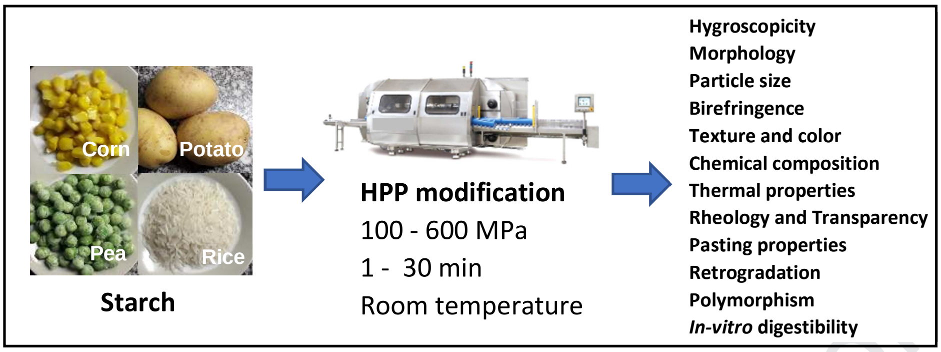

Impact of high pressure on starch properties: A review

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Abstract

Large amounts of different starches are produced worldwide since starch is widely used as a functional component in prepared foods and is one of the most important sources of energy for humans. However, in its native form starch does not have properties suitable for processing due to low thermal stability and high retrogradation. To promote and enhance these and other properties, starch is modified by chemical, physical, or enzymatic processes. Treatments such as high-pressure processing can be used to break/change non-covalent chemical linkages in and between starch molecules in order for starch to have the desired properties. The use of pressure can increase starch swelling and solubility depending on the temperature. Higher pressure levels can disrupt the starch granule morphology, induce the starch gelatinization and the granules birefringence can consequently decrease. Pressure can also alter significantly the thermal properties of starch, as well as its pasting properties, the dynamic oscillation and steady flow behavior of starch, and the amount of resistant/fast/slow digestible starch. The use of pressure can also delay/decrease starch retrogradation and change starch polymorphism from type A or C to type B. However, the change of these properties is always dependent on the pressure level, solvent type and treatment time used, but also from the starch type and origin. This paper revises the effect of high pressure on starch properties in order to improve their quality to obtain the desired properties that can promote human health.

Keywords

Starch pressure modification; thermal and pasting properties; starch retrogradation; *in-vitro* digestion; polymorphism; starch application.

1. Introduction

Starch is formed by small granules and its properties are influenced by the botanical origin, varying in size, morphology, shape, and size distribution of granules. Other factors such as the cultivation area and climate have also an impact on starch properties. Starch granules are almost exclusively composed of two polysaccharides, amylose and amylopectin, making up 98-99% of its dry weight. Along with them, minor components such as proteins, lipids, pentosans, and minerals can also be found (Schirmer, Jekle, & Becker, 2015). Amylopectin is usually found in larger quantities when compared to amylose, except for some high amylose starches, waxy starches, and starches obtained by genetic modification. Amylose is a linear carbohydrate formed by glucose residues linked by α-(1,4) linkages with a polymerization degree between 1000-10000 glucose units, while the amylopectin can surpass one million units. Aside from the α-(1,4) linkages, amylopectin also has α-(1,6) linkages and so is a branched carbohydrate (Bertoft, 2017). These structural differences between amylose and amylopectin give them different properties. For instance, amylose is unstable in aqueous solutions, while amylopectin is stable; amylose is almost insoluble in water, has low gelatinization temperature, viscosity, and thickening ability, but possesses higher retrogradation rate, whereas amylopectin has the opposite behavior (Schirmer *et al.*, 2015). Starch granules are formed by several alternating amorphous and semi-crystalline concentric growth rings that vary in number and size according to the starch botanical origin. The amorphous regions are formed by disordered amylose and amylopectin, while the semi-crystalline zones are composed of lamellar alternating crystalline and amorphous regions (Yang, Chaib, Gu, & Hemar, 2017).

The European Union produced 10.7 million tons of starch products in starch equivalents in 2018, which represents an increase of 30% since 2004 (European Starch Industry

Association, 2018a, b). Excluding the starch co-products, the consumption of starch and its based-products in 2018 reached 9.3 million tons in the European Union, of which 2% was consumed in feed, 40% in non-food application, and 58% in food. Of the consumed 9.3 million tons, 19% was modified starch, 28% was native starch, and 53% starch sweeteners.

Native starches are unchanged starches that are used in the paper and food industries as binding and thickening agents. Modified starches are altered native starches by chemical, physical or enzymatic processes that are used in various industries, to do sweeteners such as syrups, isoglucose, dextrose, fructose, maltodextrins, polyols, and caramels, which are obtained from starch hydrolysis and are mainly used in the food, beverage, and confectionery industries, but also in the fermentation and pharmaceutical sectors. The global production of starches generates high amounts of vegetable co-products (around 5 million tons, however highly variable with botanical origin and processing) and among the co-products composition, proteins are their most important molecules present and interesting due to its nutritional and functional value for both animal and human nutrition (European Starch Industry Association, 2018c).

High pressure (HP) is a non-thermal processing technology for food preservation that inactivates microorganisms related to foodborne diseases with minimal effects on food organoleptic and nutritional properties (Yordanov & Angelova, 2010). Since HP is a green and environmental-friendly technology and can alter non-covalent chemical linkages with minimal effects on covalent linkages, it can be used to modify starch in order to have tailor-made desired properties, since the native starch does not have the suitable properties for processing. In this sense, several studies have been investigating the influence of HP on starch properties (BeMiller & Huber, 2015). To our knowledge, the first study concerning this subject was published by Thevelein, Assche, Heremans, & Gerlsma (1981) to study HP impact on potato starch gelatinization temperature and since then, it has been extensively used to study the HP impact on remaining starch properties.

This review proposes to collect, comprehend and synthesize the impact of HP on starch fractions content from different starch sources, and to understand the HP effects on starch properties, in order to develop new research opportunities on the modification of starch by HP.

2. Starch types and classification

Starch can be categorized in several different ways. According to Santana & Meireles (2015), starch can be classified as conventional or non-conventional according to its botanical source. Some examples of conventional sources are corn, wheat or rice, while chestnut, apple, and pea, among others, are perceived as non-conventional. Another criterion for classifying starch is as rapidly digestible, slowly digestible, or resistant starch according to its hydrolysis velocity by the human enzymes (Jeong, Han, Liu, & Chung, 2019). A third possible way to classify starch can be made based on the absence of modification (native starch) or modified (modified starch), being the latter further subdivide in physically, chemically, enzymatically, or genetically modified starch, according to the modification technique (Zia-ud-Ding, Xiong, & Fei, 2017).

3. High-pressure technology: Principles and fundaments

High pressure is an emerging processing technology that relies on two principles: 1) the Isostatic principle, which states that no matter the size and geometry of the material, pressure acts in all directions, equally, instantaneously and homogeneously and 2) on the Le Chatelier’s principle, where for any phenomenon, with a decrease of its volume, pressure will enhance/lessen it, thus shifting the system towards a new state of equilibrium (Balasubramaniam, Martínez-Monteagudo, & Gupta, 2015). The general modification process of starch by HP can be divided into sample preparation, processing procedures and the clean-up. Firstly, a starch suspension is prepared by mixing starch and water in plastic bags to obtain a concentration that is usually between 4 and 33%. Then, the air inside the plastic bag is removed, sealed, loaded into an HP vessel that is filled with a pressure-transmitting liquid medium (usually water) by a booster pump. After the desired pressure is reached, the starch suspension is processed for the desired time. According to the literature, the usually applied pressures range between 100 to 600 MPa, the processing times vary from 2 to 30 min, and pressurizations are performed at room temperature (≤ 30ºC) (Briones-Labarca, Muñoz & Maureira, 2011; Guo *et al.*, 2015a; Leite, Jesus, Schmiele, Tribst & Cristianini, 2017; Li & Zhu, 2018; Li *et al.*, 2011). Once the suspension is treated, the pressure is dropped down to atmospheric pressure (0.1 MPa) in a very small period of time, causing alterations on the non-covalent bonds. These alterations change the functional properties of polysaccharides by altering their secondary and tertiary structures (Giacometti *et al.*, 2018; Xi, 2017). After the HP treatment, the sample bags are opened, vacuum-filtered, and the pressurized starch suspension can be treated in two different ways: 1) dried at 45 ºC, passed through a mesh sieve, sealed and stored in an airtight container at room temperature, or 2) frozen by liquid nitrogen, freeze-dried, grounded into a fine powder through mesh sieve, and stored at room temperature. Katopo, Song & Jane (2002) air-dried the starch samples after HP processing and found a small endothermic peak before the main peak due to starch retrogradation when evaluated the starch thermal properties. However, Li & Zhu (2018) freeze-dried its starch samples and no peak was observed. This may indicate that freeze-drying may lead to the retrogradation of the gelatinizes starches to a smaller extent than the air-drying method.

4. Impact of high pressure on starch content

From the reviewed articles, only a few cast some light on the impact of HP on the starch content (Table S1). Ahmed & Al-Attar (2017) performed an investigation to study the impact of HP at 400, 500, and 600 MPa during 10 min on chestnut flour. They reported that among the different HP levels non-significant differences were observed on total (46%), damaged (0.7%), and resistant (36%) starch yields. HP also did not have a significant effect on starch content when compared to 0.1 MPa. These results suggested that the crystallite regions formed by the resistant starch stay unchanged after treatment. Other authors extracted first the starch by different methodologies to be processed after by HP. Ahmed, Thomas, Arfat & Joseph (2018) treated quinoa starch during 15 min between 450 and 600 MPa and reported that total starch content decreased insignificantly from 64 to 60% as pressure increase for 450 and 600 MPa, respectively, but these results were significantly different when compared to the control (73.25%), while the damaged starch content increased significantly from 15.27% at 450 MPa to 17.39% at 600 MPa, respectively. These results indicated that starch damages were only severe at intermedium and high pressure, i.e., the occurrence of the destruction of the crystalline region. For total starch, similar findings were obtained by Liu *et al.* (2016a) and Liu, Wang, Cao, Fan & Wang (2016b) that treated buckwheat starch during 20 min from 120 to 600 MPa and reported a significant decrease of the total starch at 600 MPa in relation to 0.1 MPa. Regarding resistant starch, Ahmed, Thomas, Taher & Joseph (2016) reported that the increased lentil resistant starch content between 400 and 600 MPa, from 4.47 to 6.80%, respectively could have been caused by the temperature raising due to the adiabatic effect during pressurization. The temperature and pressure effect could have caused starch nuclei formation and starch recrystallization, which increased the resistant starch content. Briones-Labarca *et al.* (2011) and Briones-Labarca, Venegas-Cubillos, Ortiz-Portilla, Chacana-Ojeda & Maureira (2011) conducted studies to evaluate the impact of treatment time on digestible and resistant starch contents from algarrobo seeds and peeled apple at 500 MPa between 2 and 10 min. Time effect was not significant for the algarrobo seed resistant starch content, but it was significant for apple treatments performed for 4, 8, and 10 min, which represent an increase of 27%, 76%, and 84%, respectively, in relation to the untreated resistant starch. Concerning the digestible starch, the treatments performed during 4, 8 and 10 min were significant, increasing from 10.6% (untreated) to 19.8%, 17.5% and 31.5%, respectively for algarrobo seed, and from 75.5% (untreated) to 83.8%, 96.7% and 100.4%, respectively for apple.

5. Effect of high pressure on starch properties

5.1. Hygroscopic properties

Table 1 summarizes the studies concerning the hygroscopic properties of native and pressurized starches at different temperatures. According to Ahmed *et al.* (2018), quinoa starch water holding capacity, solubility index, and the particle volume fraction increased with pressure from 300-600 MPa and with temperature from 25-70 ºC. The increased water capacity could be associated with the increased damaged starch content, since the forces responsible for granular restriction were broken, increasing the swelling and consequently the holding capacity. The increased solubility indexes indicated that occurred leaching of components soluble in water during HP processing, which were reinforced at 70 ºC. Ahmed *et al.* (2016) also reported that at 25 ºC, the holding water capacity and volume fraction properties of lentil starch increased significantly from 0.1 to 600 MPa ($p<0.05$). However, the solubility index decreased with pressure and was lowest at 600 MPa. These results are not in agreement with those reported by Ahmed & Al-Attar (2017), because the pressure had no significant effect on the water holding capacity, solubility index, and volume fraction of chestnut starch. Additionally, no statistical differences were observed on the damage starch content. Guo *et al.* (2015a) reported that swelling and solubility increased with the temperature from 85 to 95 °C. Increasing the pressure, both swelling, and solubility of lotus seed starch granules increased in the range of 55-75 °C when compared to the native samples. However, at 85-95 °C, values decreased with the increasing pressure. These results are similar to those reported by Li, Bai, Mousaa, Zhang & Shen (2012) for rice starch. From 50 to 90 ºC, swelling and solubility increased, while at 600 MPa, different tendencies were seen with the increasing temperature. These samples had higher swelling and solubility at lower temperatures (50-60 ºC) when compared to native starch, and lower swelling and solubility at higher temperatures (70-80 ºC). Li *et al.* (2011) reported that swelling and solubility at 90 ºC also decreased with pressure from 120 to 600 MPa for mung bean starch when compared to the native samples. Similar results were reported by Liu *et al.* (2018), Li & Zhu (2018), Li *et al.* (2018), Li *et al.* (2015), and Liu *et al.* (2016b) for pea, quinoa and maize, proso millet, red adzuki bean, and common buckwheat starches, respectively. Li *et al.* (2018) explained that the increase of swelling and solubility with temperature can be related to the granular damage. During heating and in excess of water, the hydrogen bonds among amylose and amylopectin are broken. Once broken, the hydroxyl groups of these polysaccharides are free to form bonds with the water molecules, thus swelling and solubility increases with temperature. Therefore, these parameters offer valuable precious information about these interactions, but also about the crystalline and amorphous regions during heating. Liu *et al.* (2016a) and Liu, Fan, Cao, Blanchard & Wang (2016c) reported that amylose-lipids crystals are formed at lower temperatures, which limits swelling. Above 85 ºC, the crystals melt and the swelling and solubility increase. This increment of swelling and solubility at lower temperatures at higher pressures may be due to amylose aggregation under pressure, which interferes with the lipid-starch bounds. At higher temperatures, the decreased swelling and solubility values can be due to amylose molecular rearrangement. According to Li *et al.* (2012), swelling is mainly caused by amylopectin. Because starch granules are often intact or partially destroyed after HP processing, amylose solubilization is limited. This may be due to the stabilization of the amylopectin by the remaining amylose, which prevents some crystalline structures from melting. Li *et al.* (2018) reported that this swelling and solubility reduction at a higher temperature and higher pressure can be due to granular compression and strengthening of the starch molecular bounds. One question that remains unanswered is how HP effects both solubility and swelling power (Liu *et al.*, 2016b).

5.2. Granule morphology, particle size, and birefringence

The granule morphology and particle size of native and pressurized starches are presented in Table 2. Li *et al.* (2018) treated proso millet starch with pressures ranging from 150 to 600 MPa, reporting that the native pattern of the starch granules was preserved at 150 and 300 MPa retained its native pattern, however at 450 MPa, the granules start to lose their structure. When granules were subjected at 600 MPa, granules structure was destroyed and formed a gel-like structure. Hu, Zhang, Jin, Xu & Chen (2017) reported that waxy wheat starch granules were intact at 300 MPa but got tighter and the surface was wrinkled. At 400 MPa some melting started to occur but still retained their native shape, but at 500 MPa irreversible losses and viscous regions were detected on the granule boundaries. At 600 MPa, the granules were destroyed and lost their shape. At this pressure level, similar findings were observed by Liu *et al.* (2016c) for sorghum, Liu *et al.* (2016b) for common buckwheat, Liu *et al.* (2016a) for tartary buckwheat, Li *et al.* (2011) for mung bean, Li *et al.* (2012) and Deng *et al.* (2014) for rice. Additionally, Guo *et al.* (2015a) verified an apparent increase ($p<0.05$) in the volume mean diameter, area mean diameter, and proportion at D10, D50, and D90, which represents the number of starch granules that are 10%, 50%, and 90% smaller than the average granule, with pressure treatment. Also, the volume mean diameter values were superior to the area mean diameter for pressurized samples. This is in accordance with Liu *et al.* (2018) findings for pea starches, but only partially in accordance with Leite *et al.* (2017) results, which observed only a small reduction ($p<0.05$) in these parameters at 600 MPa. The particle distribution was monomodal with an agglomeration of larger particles at higher pressures, explaining why the volume mean diameter values were superior to the area mean diameter. The first is more influenced by larger particles, while the latter is more influenced by smaller ones. Leite *et al.* (2017) also studied the effects of HP on pea starch dispersed in water and ethanol, concluding that the particles dispersed in water had higher mean diameter than the ones dispersed in ethanol, thus validating the importance of water to promote gelatinization under pressure conditions. Ahmed & Al-Attar (2017) verified a decrease in D90 ($p<0.05$) on chestnut granules treated at 600 MPa due to excessive pressure. In addition to the pressure, Błaszczaka, Valverde & Fornala (2005) reported for potato starch that increasing time was responsible for even more destruction of granules.

Starch granules also possess birefringence properties, which is characterized by the exhibition of the Maltese cross. These crosses are formed due to the radial orientation of the double helices of amylopectin in the crystalline regions when they are crossed by polarized light. When starch is treated with HP, the diffusion of water in these areas is incremented. This disrupts the amylopectin chains, leading to the disappearance of the Maltese crosses and the birefringence patterns (Deng *et al.*, 2014). Therefore, this property can be used to study gelatinization. Table 3 summarizes the studies concerning native and pressure-treated starches birefringence. Li *et al.* (2018) reported that proso millet, native starch exhibited the Maltese cross under the polarized light. At lower pressures (150-300 MPa), no special changes in the birefringence pattern were observed but at intermedium pressure (450 MPa), some losses of the birefringence pattern and crosses were observed. Finally, authors reported loss of the birefringence pattern and crosses at 600 MPa, indicating complete gelatinization. These results are in accordance with Guo *et al.* (2015b), Li *et al.* (2015), Li *et al.* (2012) and Deng *et al.* (2014), and Vallons & Arendt (2009) for lotus seed, red adzuki bean, rice, and sorghum starches, respectively. In a special case, Leite *et al.* (2017) reported that pea starch granules were swollen and gelatinized at 500 MPa, but almost none difference on the birefringence was detected due to the intermedium amylose content (33%) and birefringence was lost at 600 MPa.

5.3. Texture properties, color, and chemical composition

Table 4 summarizes some recent findings concerning the study of texture properties of native and pressurized treated starches. Liu *et al.* (2016a) reported reductions in texture, namely in hardness, adhesiveness, gumminess, and chewiness of pressurized tartary buckwheat gels. No differences in springiness were detected ($p>0.05$) and cohesiveness values were small for all treatment conditions. Similar results were reported by Liu *et al.* (2016b) for common buckwheat. Vittadini, Carini, Chiavaro, Rovere & Barbanti (2008) evaluated the effect of pressure on tapioca starch gel texture properties. These authors reported that thermal treated fresh gels were less hard than the pressurized ones, the cohesiveness was similar for all gels, and no adhesiveness was detected. After one-month storage, the appearance of the gels stored at 4º C was comparable to the appearance of the original ones, while storage at -18 ºC altered gels texture. In terms of hardness, both refrigerated and frozen gels had similar values. However, the hardness of pressure-treated frozen gels was significantly higher than the refrigerated equivalents. These results are not completely in accordance with those of Li & Zhu (2018), who reported that pressure treatment had little effects on quinoa and maize gels stored at 4 ºC for 1 day or 1 week, but quinoa gel had lower factorability and hardness than maize gel.

Apart from texture, color is another important sensorial attribute that is closely associated with food quality and in Table 5 are reviewed the last studies concerning the color of native and pressurized treated starches. Ahmed *et al.* (2018) reported that HP conduces to a reduction in L values and an increase in $a*$ and $b*$ parameters, being the lowest L, and highest $a*$ and $b*$ obtained at 600 MPa for quinoa starch. These results indicate that starch treated at 600 MPa showed lower lightness and increased red and yellowness. These results are in partial accordance with Ahmed & Al-Attar (2017), whom reported no significant changes in the *L* and *b**, but *a** values increased at 600MPa for chestnut starch ($p<0.05$). Ahmed *et al.* (2016) observed a decrease in *L* and *b** values for lentil starch, but the *a** values increased at 600 MPa, indicating that starch had become less yellow after pressure treatment.

Besides HP capacity to slightly change the color, it also can be used to retain the chemical composition of starches. In Table 6 are summarized the main findings concerning the study of the chemical composition of native and pressurized starches. Liu *et al.* (2016b) reported that moisture content of common buckwheat starch decreased with pressure treatment but was only statistically significant for 600 MPa (10.5%) when compared to 0.1 MPa (11.2%), while the protein and fat contents were not statistically affected by the pressure treatment. Leached amylose content increased significantly with pressure from 30.4% at 120 MPa to 35.4% at 600 MPa in relation to the 0.1 MPa (28.1%). According to the authors, it was the result of amylose-amylopectin and amylose-lipid interactions. Amylopectin degradation by HP was also pointed out as a possible reason for such increase. These results are in accordance with those reported for tartary buckwheat starches by Liu *et al.* (2016a). Ahmed & Al-Attar (2017) also reported that changes in moisture, ash, protein, and total starch contents with pressure treatment were not significant. Ahmed *et al.* (2018) also reported that pressure treatment did not influence the composition of quinoa starch.

5.4. Thermal properties

Table 7 summarizes several results concerning the thermal properties of native and pressure-treated starches. By using barley starch, Stolt, Oinonen & Autio (2001) reported that the enthalpies decreased as the pressure increased, thus the gelatinization degree increased for a given processing time. Leite *et al.* (2017) reported that pea starch presented a small degree of gelatinization (31%) when the pressure reached 400 MPa, causing an enthalpy reduction from 3.79 to 2.57 J/g ($p<0.05$). Complete gelatinization was obtained by using higher pressure (500 and 600 MPa) and no endothermic peak was detected. Liu *et al.* (2018) also reported that for a pressurization time of 30 min, the enthalpy of pea starch decreased significantly from 150 (5.7 J/g) to 450 MPa (3.8 J/g) when compared to the native sample (6.2 J/g), but no gelatinization peaks were detected at 600 MPa. The reduction of enthalpy is related to the energy needed to disrupt the hydrogen intra-helixes bonds of the crystalline regions. Therefore, the decrease of enthalpy means that less energy is needed to disrupt these bonds because the crystalline regions (degree of crystallinity) get more disrupted with the increase in pressure treatment. This result is in accordance with Guo *et al.* (2015a), Li *et al.* (2011) and Li *et al.* (2012) for lotus seed, mung bean, and rice starches. However, these results are divergent from those obtained by Li *et al.* (2015) and Li *et al.* (2018), which reported that adzuki bean and proso millet were fully gelatinized at 600 MPa after 15 min. According to Ahmed *et al.* (2018), the destruction of the crystalline regions requires the disruption of intrahelical hydrogen bonds, which may vary from different starches. Ahmed *et al.* (2018) reported that quinoa starch at 600 MPa for 15 min was gelatinized, but Li & Zhu (2018) were capable to fully gelatinized quinoa starch at 600 MPa after 5 min indicating that the usage of smaller treatment times is enough to gelatinize quinoa starch by HP. Sorghum starch used by Ahmed *et al.* (2016) was fully gelatinized at 600 MPa for 10 min. Furthermore, some authors observed incomplete gelatinization in some starches. Partial gelatinization of 57% for maize starch processed at 600 MPa for 5 min (Li & Zhu, 2018), 79% for waxy wheat processed at 600 MPa for 30 min (Hu *et al.*, 2017), 40% for chestnut treated at 600 MPa for 10 min (Ahmed & Al-Attar, 2017), 67%, 53%, and 62% for tartary buckwheat, sorghum and common buckwheat pressurized at 600 MPa for 20 min, respectively (Liu *et al.*, 2016a, b, c). All these results indicate that a combination of higher pressures with higher temperatures and/or longer treatment times might be useful to fully gelatinize starches. Vallons & Arendt (2009) observed that the percentage of starch granules gelatinized for both pressure and temperature treatments followed a sigmoid curve, reaching complete gelatinization at 600 MPa or 75 ºC. Additionally, the percentage of damaged starch was linearly related with the degree of gelatinization (r^2 of 0.9917 and 0.9927 for pressure and temperature treatments, respectively).

Some authors verified that pressure treatments were able to alter significantly the gelatinization temperatures. Liu *et al.* (2016b), Liu *et al.* (2016c), and Liu *et al.* (2016a) reported that the decrease of gelatinization temperatures and the respective range of gelatinization temperatures was positively correlated with pressure. According to these authors, with the decrease of starch crystallinity (enthalpy) less energy is needed to gelatinize the starch, thus a reduction of the temperatures is observed. Additionally, the temperature gelatinization range provides information concerning the crystalline region stability. The decreasing range values of temperature gelatinization according to the increasing pressure indicated that pressure treatment destroyed the crystalline regions on starch, thus these regions got more instable with the pressure treatment. These results are in accordance with the ones obtained by Guo *et al.* (2015a), Li *et al.* (2011), Liu *et al.* (2018), and Li *et al.* (2012), but are only partially in agreement with the results obtained by Li *et al.* (2015) and Li *et al.* (2018), which observed that the onset and peak temperature of the pressure treated starches was superior compared with the native corresponding temperatures. In the last research work, the authors explained that the increased temperatures could be explained by the formation of amylose-lipid complexes during treatment.

Stolt *et al.* (2001) reported that increasing pressure rises the peak temperature for the same treatment time and at constant pressure treatment, increasing treatment time rises the peak temperature. Vallons & Arendt (2009) observed that the gelatinization temperatures values increased with increasing pressure and found a good correlation between the enthalpy and the peak temperature for pressure and temperature treatments (r^2>0.98). Błaszczaka *et al.* (2005) reported at a pressure of 600 MPa, potato starch with a 2- and 3-minute treatment presented lower enthalpies (5.55 and 4.31 J/g, respectively) when compared to untreated starch (15.96 J/g). Leite *et al.* (2017) reported that gelatinization temperatures change with the pressure treatment but with no statistical difference, as observed by Ahmed & Al-Attar (2017).

5.5. Dynamic oscillation and steady flow

Table 8 summarizes the main scientific works concerning the dynamic oscillation properties of native and pressure-treated starches. Dynamic oscillation properties structural information of the starches and distinguish between the elastic and viscous contributions to measured stress as a function of frequency by measuring storage (*G'*) and loss (*G''*) moduli, respectively. These tests are performed within the linear viscosity region and since the strain used is small, the structure of the samples can be preserved. Guo *et al.* (2015b) reported that the dynamic frequency sweep of lotus seed starch indicated that *G'* values were superior to *G"*, with no crossover and were frequency-dependent, thus displaying a solid-like weak gel. Moduli values increased up to 500 MPa, but at 600 MPa decreased due to excessive pressure treatment. Additionally, the gel capacity to recover the original structure under lower shear after high shear conditions decrease with pressure, i.e., pressure-treated starches were less structured and less elastic than the native samples. For chestnut starch suspension, Ahmed & Al-Attar (2017) also reported that *G'* was superior to *G"* and moduli were frequency-dependent, indicating that gels were solid-like with weak structure. Moduli values also increased with the pressure treatment from 0.1 to 600 MPa. These results are according to Jiang, Li, Hu, Wu & Shen (2015a) and Jiang, Li, Shen, Hu & Wu (2015b) for mung bean and rice starches. Furthermore, the complex viscosity increased with pressure treatment, indicating an increase in the mechanical properties (Ahmed & Al-Attar 2017). Increasing the pressure from 0.1 to 600 MPa, the slope of logarithmic plots of *G'* versus frequency increased from 0.10 to 0.13, indicating the viscoelasticity properties of gels transformed from a solid-like to a liquid-like gel. This is in accordance with Ahmed, Varshney & Ramaswamy (2009) from lentil dispersion. The slope of logarithmic plots of *G'* versus frequency increased with the pressure level. The complex viscosity increased with pressure as a function of the frequency plot, indicating an increase in viscoelasticity and changing from viscoelastic solid to a fluid one. However, Ahmed *et al.* (2016) reported different results for its lentil starch. The ln (*G'*) *vs* ln (ω) slop curves decreased from 0.36 at 0.1 MPa to 0.06 at 600 MPa. With the increasing pressure, *G'* dependency of frequency decreased and at 500 and 600 MPa was independent. This indicated that the gels formed at these pressure treatments were stronger gels.

The steady flow behavior of native and pressure-treated starches is summarized in Table 9. These studies give information about the starch response in different shear-rate regimes by measuring apparent viscosity. Jiang *et al.* (2015a) observed that the mung bean shear-stress-shear rate curves were convex, where the shear stress increased with the pressure treatment for the same shear rate. The index values were lower than 1, indicating that starches had shear thinning behavior and values decreased with the increasing pressure treatment up to 480 MPa. The consistency coefficient increased with pressure, indicating an increase in the apparent viscosity at higher pressures. For a given shear rate, apparent viscosity between 240-480 MPa was higher than the native starch but dropped at 600 MPa. Additionally, the hysteresis loop, an index of the energy needed to destroy the structure, also increased until 480 MPa but dropped at 600 MPa. These results were similar to those reported by Jiang *et al.* (2015b) but using rice starch. Guo *et al.* (2015b) also reported that lotus seed starch had a shear thinning behavior. With the increasing pressure, the decreasing index and the increasing consistency coefficient values indicated that thinning behavior was reinforced with pressure and the resistance to flow and stress was higher. The yield stress, that corresponds to the minimum stress required to start flow, decreased with the treatment pressure. Moreover, Li & Zhu (2018) reported that overall, the pressure treatment reduced the thinning behavior of both quinoa and maize starches. The index values ($n<1$) of quinoa increased significantly from 0.44 at 500 MPa to 0.51 at 600 MPa, but the index values for maize only increased significantly at 600 MPa. This indicates that flow behavior moved towards a Newtonian flow.

5.6. Pasting properties

According to Liu *et al.* (2016b), the structural changes on starch by the application of pressure restrict the leaching of amylose and amylopectin, increasing pasting temperature, and reducing viscosity. Table 10 shows the studies related to the pasting properties (pasting temperature, peak time, and viscosity, respectively) of several starch sources.

Pasting temperature corresponds to the temperature at which gelatinization of starch begins (Schirmer *et al.*, 2015). Liu *et al.* (2016b), Liu *et al.* (2016a), Li *et al.* (2015), Liu *et al.* (2016c), and Li *et al.* (2018) reported that pressurized buckwheat, red adzuki bean, sorghum, and proso millet starches had higher pasting temperatures compared to 0.1 MPa treated starch, showing the highest value at 600 MPa. Li *et al.* (2015) and Guo *et al.* (2015a) also reported that the pasting temperature increased from 0.1 to 500 MPa and from 0.1 to 600 MPa for both lotus seed and mung bean starches, respectively. At these high-pressure levels, the pasting temperature was highest. Liu *et al.* (2018) reported that pasting temperature values of pea starch did not change significantly from 150 to 450 MP, but at 600 MPa the lowest temperature values were observed. Similar results were reported by Li & Zhu (2018) for quinoa and maize starches, and by Ahmed *et al.* (2016) for lentil starch showing that pasting temperature decreased from 0.1 to 600 MPa, reaching the lowest value at 600 MPa.

In relation to the peak time, the time at which maximum intensity of gelatinization is reached, Liu *et al.* (2016b), Liu *et al.* (2016a), Liu *et al.* (2016c), Ahmed *et al.* (2016), Li *et al.* (2015), and Li *et al.* (2018) reported that pressurized buckwheat, sorghum, lentil, red adzuki beans, and proso millet starches, respectively had higher pasting temperatures compared to 0.1 MPa treated starch, showing the highest value at 600 MPa. Jiang *et al.* (2015b), Jiang *et al.* (2015a), and Li *et al.* (2011) reported that starches treated until 360-480 MPa had a significantly lower peak time when compared with the native starches, but increased further with higher pressure treatment, reaching increase peak time values and the highest values were observed at 600 MPa. Guo *et al.* (2015a) and Li *et al.* (2015) reported that lotus seed and red adzuki bean starches treated at 600 MPa had the highest peak time when compared to the other treatments. For Leite *et al.* (2017), the peak time for pea starch changed non-significantly with the pressure treatment (p>0.05). The highest value was obtained at 600 MPa but was not statistically significant in relation to the control.

Regarding viscosity, Liu *et al.* (2016b), Liu *et al.* (2016a), and Liu *et al.* (2016c) reported that viscosity of pressured treated buckwheat and sorghum starches decreased with the increasing pressure in comparison to the native starch and the lowest viscosity values were observed at 600 MPa. These results are partially in accordance with those reported by Guo *et al.* (2015a) for lotus seed starches. From 100-500 MPa, the peak, trough, and final viscosity values increased in relation to the native starch, but the breakdown and setback viscosity values decreased. At 600 MPa, viscosity decreased and had the lowest values. Ahmed & Al-Attar (2017) reported that from 0.1 to 600 MPa, the breakdown and setback viscosities of chestnut starches decreased significantly. Li *et al.* (2015) reported that red adzuki bean starch treated at 600 MPa had the lowest viscosity values when compared to the other pressure and 0.1 MPa treatments.

In general, Jiang *et al.* (2015a) results showed that mung bean viscosity values increased from 120 to 480 MPa when compared to 0.1 treatment, but at 600 MPa decreased significantly (p<0.05). This is according to Liu *et al.* (2018), who reported an increment of pea starch viscosity between 150 and 450 MPa, but at 600 MPa was observed a decrease. Jiang *et al.* (2015b) reported that viscosity increased significantly at 600 MPa when compared at 0.1 MPa, but the breakdown was not significant. Pressure-treated mung starch starches showed increased viscosity, but the breakdown viscosity decreased in relation to the native starch (Li *et al.*, 2011). In general, Leite *et al.* (2017) also reported that the viscosity values increased from 0.1 to 600 MPa, the pressure at which the highest viscosity values were observed.

5.7. Gels clarity and Transparency

Li *et al*. (2015) treated red adzuki bean starch by using HP from 150 to 600 MPa and verified that the pressure-treated starches had lower clarity (transmittance of ≈5.7% at 600 MPa) when compared to the native starch (transmittance of ≈6.7%). Additionally, with the increasing pressure from 150 to 600 MPa the transmittance decreased significantly and at 600 MPa was obtained the lowest value. According to the authors, several factors influence the light transmission and there were less swollen starch granules in native starch gels than the pressure treated ones, leading to higher transmittance of native starch than pressure-treated ones. Some leaching might occur during pressure treatment, accelerating the retrogradation process, thus decreasing transmittance. Furthermore, syneresis of gels increased significantly when the pressure increased from 150 to 600 MPa when compared to the native starch, indicating that pressure-treated starch pastes had higher retrogradation tendency. These results suggest that HP can be an interesting technique for the production of pasta since can accelerate starch retrogradation rate. Li *et al.* (2011) also observed that mung bean gels had the lowest light transmittance values at 600 MPa (≈2.5%) when compared to the native starch (≈4.5%) at the beginning of the storage. Additionally, these authors reported that light transmittance decreased for all gels with storage time from 0 to 120 hours and could be attributed to the creation of junction zones that resulted from the interaction of the leached starch molecules. The decrease of light transmittance was attributed to the increased retrogradation of starch.

5.8. Retrogradation properties

Table 11 summarizes several papers concerning the study of starch retrogradation properties. Guo *et al.* (2015b) reported that lotus seed starch treated with pressure (100-600 MPa at 25ºC for 30 min) showed lower recrystallization rate and bigger Avrami exponent values when compared to the native starches during storage at 4ºC, indicating that native lotus seed starch retrogrades faster than the starches treated with pressure. The Avrami exponent values are an indication of the morphology of the starch crystals in a nucleation process. Hu *et al.* (2011) verified that pressure-treated starch (600 MPa for 30 min) had a lower recrystallization rate and bigger Avrami exponent values when compared to thermally treated starch (boiling water for 30 min) during storage, indicating that retrogradation of the former was slower than the latter. Also, the pressure used to treat rice starch led to less amylose leaching than the thermal treatment, due to the intact granule structure. When waxy rice starch was analyzed, authors verified that pressure treatment did not affect its retrogradation properties and no significant difference was observed between both thermal and pressure treatment, due to the small amounts of amylose and the destruction of granules when treated with HP. Vittadini *et al.* (2008) observed reduced retrogradation in all pressurized treated tapioca starch gels (600 MPa for 10-30 min at 50-80 ºC) as compared to the thermally treated gel (90 ºC for 20 min), for both storage temperatures (4 and -18 ºC). The pressurized treated starch gels had lower retrogradation enthalpies and onset temperatures than the thermally treated gels. However, these studies are not in complete accordance with Stolt *et al.* (2001), who reported no significant differences for barley starch retrogradation behavior between pressurized (550 MPa at 30 ºC for 10, and 60 min) and thermal treated samples (0.1 MPa at 90 ºC for 30 min) in storage, but enthalpy increased with storage time at 4 ºC, indicating the formation of amylopectin crystals. Li *et al.* (2018) also observed that proso millet starch crystallinity and retrogradation enthalpies increased with the time from 3 to 192 hours at room temperature. Furthermore, retrogradation studies performed by Li & Zhu (2018) with quinoa and maize starches after two weeks between 100-600 MPa at room temperature for 5 min, reported that pressure treatments did not have a significant effect on the thermal temperatures and retrograding enthalpies when compared to the native samples ($p>0.05$). For the latter, quinoa retrograding enthalpies were significantly smaller than the maize enthalpies.

5.9. Starch structure and polymorphism

Starch crystalline structure is related to the arrangement of the amylopectin chains into double helices and according to the X-ray diffraction pattern they are categorized as type A, B or C. The main difference between the first two is that helices are more compacted in A than B, but the latter has a more hydrated core. However, the type-C starch pattern has not been entirely understood whether is a mixture of type-A and -B starch patterns or a different one (Copeland, Blazek, Salman & Tang 2009). The effect of pressure on the X-ray diffraction peaks of several type-A and -B starches was studied by Liu *et al.* (2011) that concluded that diffraction peaks get weaker with the increasing pressure due to the disruption of the starch structure crystals during gelatinization. Also, the effect of HP is superior for type-A starches than for type-B. In other words, the gelatinization pressures are lower for type-A than type-B. X-ray diffraction patterns of type-A and C starch tend towards a type-B after gelatinization induced by pressure treatment, while B kept their original pattern as observed by Ahmed & Al-Attar (2017) for chestnut starch (Table 12).

Guo *et al.* (2015a) reported that lotus seed starch was type-C and the 14.86º, 17.75º, and 22.82º peaks had increased intensity at 600 MPa, indicating that the X-ray diffraction pattern changed to type-B. Pressure induced polymorphism transition by facilitating the rearrangement of the amylopectin chains and the combination of water and starch molecules. Similar changing of the diffraction pattern from type-C to type-B was reported by Li *et al.* (2011), Ahmed *et al.* (2016), and Liu *et al.* (2018) for mung bean, lentil, and pea starches, respectively. Red adzuki bean starch also revealed a type-C pattern but, despite a decrease in the intensity of the diffraction peaks with the increasing pressure from 150 to 600 MPa. Any alteration on the diffraction pattern after the treatment with pressure was observed also by Li *et al.* (2015). According to the authors, these results could be attributed to insufficient pressure or to the compressive effects in the amorphous regions.

Li *et al.* (2012) reported polymorphism shift of rice starches from type-A to B, where the 15.04º, 23.02º, 26.3º, and 30.26º diffraction peaks had decreased intensity, the 16.84º and 17.96 peaks merged, and the 20.02º peak remained unchanged at 600 MPa. Deng *et al.* (2014) reported that rice starch changed polymorphism from type-A to B at 600 MPa, but the RMN spectrum did no confirmed the X-ray results. The C1 resonances of native rice starch showed a triplet at 98.9, 99.8 and 101.1 ppm, and the other at 102.2 ppm, indicating an A-type starch. After pressure treatment, similar resonances were observed, but with lower intensity. These results suggested pressure effects on the molecular packing in the crystalline regions were insufficient. This result is not in accordance with Guo *et al.* (2015b), who reported that lotus seed starch had changed its polymorphism form A-type to a B-type structure at 600 MPa, which had two major peaks at 100 and 101 ppm. Relative crystallinity and intensity of the three peaks decreased with pressure, suggesting a decrease in the amorphous content and thus increased gelatinization with pressure. Hu *et al.* (2017), Li *et al.* (2018), Liu *et al.* (2016c), Liu *et al.* (2016a), and Liu *et al.* (2016b) observed changes on the diffraction patterns from type-A to type-B for waxy wheat, proso millet, sorghum, tartary buckwheat and common buckwheat starches, respectively. In a special and extreme case, Ahmed *et al.* (2018) reported that quinoa starch completely lost its diffraction peaks at 600 MPa treatment.

5.10. *In-vitro* digestibility

Table 13 summarizes studies concerning the *in-vitro* starch enzymatic digestibility, including the digestion conditions used and main conclusions reported by authors. Hu *et al.* (2017) studied the *in-vitro* digestibility of waxy wheat starch, concluding that contents of digestible starch content increased from 300 to 600 MPa, while resistance starch decreased. Similar results were obtained by Deng *et al.* (2014) for rice starch, reporting that despite not detecting significant differences on these starch fractions between the control and starch treated at continuous 200 MPa for 30 min, the contents of digestible starch increase and resistant starch decreased significantly when treated at 600 MPa and discontinuous 200 MPa for 15x2 min. However, these results are not in accordance with those of Liu *et al.* (2018), who reported that pea starch hydrolysis increased with the digestion time. Native starch had the highest hydrolysis and increasing the pressure from 150 to 600 MPa, the hydrolysis and amounts of digestible starch decreased, while the resistant starch content increased. The treatment at 600 MPa had the lowest rapid digestible starch and the highest resistant starch content levels (54.2% and 36.6%, respectively) when compared to the native starch (58.9% and 24.1%, respectively). Alteration of the starch structure was observed with pressure, i.e. the interactions between amylose and amylopectin chains, the enzymes had lower susceptibility towards the modified starch, decreasing hydrolysis and altering starch fraction contents. Liu *et al.* (2016a), Liu *et al.* (2016b), and Liu *et al.* (2016c) observed similar results for tartary buckwheat, common buckwheat, and sorghum starches, respectively. According to the authors, the study of starch digestibility is pertinent for the glycemic index and on the prevention of non-insulin dependent diabetes. Therefore, the starch modified by HP has potential in the prevention of chronical illnesses and in health maintenance. Resistant starch can protect against colon cancer, maintenance of cholesterol levels, decrease the glycemic index, and reduce insulinemic responses. The increase of resistant starch content was an indication of stronger interactions between amylose and amylopectin chains. Several factors can affect the enzymatic susceptibility of starch, including the amylose content and starch crystalline structure. They found that amylose content and crystallinity of pressurized starches were superior to the native starch, leading to a lower hydrolysis rate. However, it was observed an increase in slowly digestible starch contents with pressure treatment, which could have happened due to the intact structure of starch granules or the formation of small quantities of lipid-amylose complexes. Interestingly, these authors observed that pressure-treated starches had a different polymorphism (B-type) than the native one (A-type). Therefore, HP is a good technology to obtain starches with increased potential health benefits. Colussi *et al.* (2017) evaluated the effect the HP processing in combination with starch retrogradation on potato starch *in-vitro* gastro small intestinal digestion. The authors reported a significant reduction of 10-15% in the hydrolysis of starch modified by 6 cycles of 10 min at 400 MPa with retrogradation in relation to the native and only HP processed starch. Similar results were observed for modification by 3 cycles at 600 MPa, however with lower hydrolysis values. Additionally, the behavior of the starch modified by 6 cycles at 600 MPa and by 6 cycles at

400 MPa was similar. This data suggest that HP processing promoted the formation of resistant and slowly digestible starch, as observed by Liu *et al.* (2016a), Liu *et al.* (2016b), and Liu *et al.* (2016c) for tartary buckwheat, common buckwheat, and sorghum starches, respectively.

6. Conclusion and future perspectives

This revision highlights that HP has a significant impact on starch content, chemical properties like swelling and solubility, birefringence, thermal, pasting, retrogradation, polymorphism, and in-vitro enzymatic digestibility of starch, but also on the physical properties such as grain morphology, crystallinity degree, starch color, gels texture and clarity/transparency. The change of these properties is very dependent on the pressure used to treat starch, justifying why some authors were capable to fully gelatinize starches, while others remained partially gelatinized. Additionally, the starch type and origin also have an important paper on the changes by HP. From the reviewed articles, one question encountered that remains opened and needs a possible explanation is how swelling and solubility decreases with pressure at higher temperatures. Therefore, more studies are needed to cast some light on this question. The effects of HP on starches can be useful to the starch industry in order to improve the starch quality and to help to obtain the desired properties and to improve or change nutritional and health properties.

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Literature Cited

Ahmed, J., & Al-Attar, H. (2017). Structural properties of high-pressure-treated chestnut flour dispersions. *International Journal of Food Properties*, *20*(sup1), S766–S778.

Ahmed, J., Thomas, L., Arfat, Y. A., & Joseph, A. (2018). Rheological, structural and functional properties of high-pressure treated quinoa starch in dispersions. *Carbohydrate Polymers*, *197*, 649–657.

Ahmed, J., Varshney, S. K., & Ramaswamy, H. S. (2009). Effect of high pressure treatment on thermal and rheological properties of lentil flour slurry. *LWT - Food Science and Technology*, *42*(9), 1538–1544.

Ahmed, J., Thomasa, L., Tahera, A., & Joseph, A. (2016). Impact of high pressure treatment on functional, rheological, pasting, and structural properties of lentil starch dispersions. *Carbohydrate Polymers J*, *152*, 639–647.

Balasubramaniam, V. M., Martínez-Monteagudo, S. I., & Gupta, R. (2015). Principles and Application of High Pressure-Based Technologies in the Food Industry. *Annual Review of Food Science and Technology*, *6*(1), 435–462.

Bertoft, E. (2017). Understanding Starch Structure: Recent Progress. *Agronomy*, *7*(3), 2–29.

Błaszczaka, W., Valverdeb, S., & Fornal, J. (2013). Effect of high pressure on the structure of potato starch. *Carbohydrate Polymers*, *59*, 377–383.

Briones-Labarca, V., Muñoz, C., & Maureira, H. (2011). Effect of high hydrostatic pressure on antioxidant capacity, mineral and starch bioaccessibility of a non conventional food: Prosopis chilensis seed. *Food Research International*, *44*(4), 875–883.

Briones-Labarca, V., Venegas-Cubillos, G., Ortiz-Portilla, S., Chacana-Ojeda, M., & Maureira, H. (2011). Effects of high hydrostatic pressure (HHP) on bioaccessibility, as well as antioxidant activity, mineral and starch contents in Granny Smith apple. *Food Chemistry*, *128*(2), 520–529.

Colussi, R., Kaur, L., Zavareze, E. R., Dias, A. R. G., Stewart, R. B., Singh, J. (2017). High pressure processing and retrogradation of potato starch: Influence on functional properties and gastro-small intestinal digestion in vitro. *Food Hydrocolloids*, *75*, 131-137.

Copeland, L., Blazek, J., Salman, H., & Tang, M. C. (2009). Form and functionality of starch. *Food Hydrocolloids*, *23*(6), 1527–1534.

Deng, Y., Jin, Y., Luo, Y., Zhong, Y., Yue, J., Song, X. *et al.* (2014). Impact of continuous or cycle high hydrostatic pressure on the ultrastructure and digestibility of rice starch granules. *Journal of Cereal Science*, *60*(2), 302–310.

European Starch Industry Association. (2018a). EU starch market data. Retrieved October 20, 2018, from https://www.starch.eu/the-european-starch-industry/#data

European Starch Industry Association. (2018b). EU starch market in figures. Retrieved October 20, 2018, from https://www.starch.eu/the-european-starch-industry/#data

European Starch Industry Association. (2018c). What is starch? Retrieved October 20, 2018, from https://www.starch.eu/starch/#

Giacometti, J., Kovačević, D. B., Putnik, P., Gabrić, D., Bilušić, T., Greta, K. *et al.* (2018).

Extraction of bioactive compounds and essential oils from mediterranean herbs by conventional and green innovative techniques: A review. *Food Research International*, *113*(November), 245–262.

Guo, Z., Zeng, S., Lu, X., Zhou, M., Zheng, M., & Zheng, B. (2015a). Structural and physicochemical properties of lotus seed starch treated with ultra-high pressure. *Food Chemistry*, *186*, 223–230.

Guo, Z., Zeng, S., Zhang, Y., Lu, X., Tian, Y., & Zheng, B. (2015b). The effects of ultra-high pressure on the structural, rheological and retrogradation properties of lotus seed starch. *Food Hydrocolloids*, *44*, 285–291.

Hu, X. P., Zhang, B., Jin, Z. Y., Xu, X. M., & Chen, H. Q. (2017). Effect of high hydrostatic pressure and retrogradation treatments on structural and physicochemical properties of waxy wheat starch. *Food Chemistry*, *232*, 560–565.

Hu, X., Xu, X., Jin, Z., Tian, Y., Bai, Y., & Xie, Z. (2011). Retrogradation properties of rice starch gelatinized by heat and high hydrostatic pressure (HHP). *Journal of Food Engineering*, *106*(3), 262–266.

Jeong, D., Han, J. A., Liu, Q., & Chung, H. J. (2019). Effect of processing, storage, and modification on *in-vitro* starch digestion characteristics of food legumes. A Review. *Food Hydrocolloids*, *90*, 367-376.

Jiang, B., Li, W., Hu, X., Wu, J., & Shen, Q. (2015a). Rheology of Mung Bean Starch Treated by High Hydrostatic Pressure. *International Journal of Food Properties*, *18*(1), 81–92.

Jiang, B., Li, W., Shen, Q., Hu, X., & Wu, J. (2015b). Effects of high hydrostatic pressure on rheological properties of rice starch. *International Journal of Food Properties*, *18*(6), 1334–1344.

Katopo, H., Song, Y., & Jane, J. (2002). Effect and mechanism of ultrahigh hydrostatic pressure on the structure and properties of starches. *Carbohydrate Polymers*, 47, 233–244.

Leite, T. S., Jesus, A. L. T., Schmiele, M., Tribst, A. A. L., & Cristianini, M. (2017). High pressure processing (HPP) of pea starch: Effect on the gelatinization properties. *LWT - Food Science and Technology*, *76,* 361–369.

Li, G., & Zhu, F. (2018). Effect of high pressure on rheological and thermal properties of quinoa and maize starches. *Food Chemistry*, *241*, 380–386.

Li, W., Bai, Y., Mousaa, S. A. S., Zhang, Q., & Shen, Q. (2012). Effect of High Hydrostatic Pressure on Physicochemical and Structural Properties of Rice Starch. *Food and Bioprocess Technology*, *5*(6), 2233–2241.

Li, W., Gao, J., Saleh, A. S. M., Tian, X., Wang, P., Jiang, H. *et al.* (2018). The Modifications in Physicochemical and Functional Properties of Proso Millet Starch after Ultra-High Pressure (UHP) Process. *Starch*, *70*(5–6), 1700235.

Li, W., Tian, X., Liu, L., Wang, P., Wu, G., Zheng, J. *et al.* (2015). High pressure induced gelatinization of red adzuki bean starch and its effects on starch physicochemical and structural properties. *Food Hydrocolloids, 45*, 132–139.

Li, W., Zhang, F., Liu, P., Bai, Y., Gao, L., & Shen, Q. (2011). Effect of high hydrostatic pressure on physicochemical, thermal and morphological properties of mung bean (*Vigna radiata* L.) starch. *Journal of Food Engineering*, *103*(4), 388–393.

Liu, H., Fan, H., Cao, R., Blanchard, C., & Wang, M. (2016c). Physicochemical properties and in vitro digestibility of sorghum starch altered by high hydrostatic pressure. *International Journal of Biological Macromolecules*, *92*, 753–760.

Liu, H., Guo, X., Li, Y., Li, H., Fan, H., & Wang, M. (2016a). In vitro digestibility and changes in physicochemical and textural properties of tartary buckwheat starch under high hydrostatic pressure. *Journal of Food Engineering*, *189*, 64–71.

Liu, H., Wang, L., Cao, R., Fan, H., & Wang, M. (2016b). In vitro digestibility and changes in physicochemical and structural properties of common buckwheat starch affected by high hydrostatic pressure. *Carbohydrate Polymers*, *144,* 1–8.

Liu, M., Wu, N. N., Yu, G. P., Zhai, X. T., Chen, X., Zhang, M. *et al.* (2018). Physicochemical properties, structural properties, and in vitro digestibility of pea starch treated with high hydrostatic pressure. *Starch*, *70*(1–2), 1700082.

Liu, Y. Q., Liu, Y. N., Li, H., Shen, R. L., Li, X. H., & Yang, L. Z. (2011). The Study on gelatinization pressure of starch by ultra-high pressure processing. *Advanced Materials Research*, *295–297,* 131–134.

Santana, Á. L., & Meireles, M. A. A. (2015). New Starches are the Trend for Industry Applications: A Review. *Food and Public Health*, *4*(5), 229-241.

Schirmer, M., Jekle, M., & Becker, T. (2015). Starch gelatinization and its complexity for analysis. *Starch*, *67*, 30–41.

Stolt, M., Oinonen, S., & Autio, K. (2001). Effect of high pressure on the physical properties of barley starch. *Innovative Food Science and Emerging Technologies*, *1*(3), 167–175.

Thevelein, J. M., Assche, J. A. Van, Heremans, K., & Gerlsma, S. Y. (1981). Gelatinisation temperature of starch, as influenced by high pressure. *Carbohydrate Research*, *93*, 304–307.

Vallons, K. J. R., & Arendt, E. K. (2009). Effects of high pressure and temperature on the structural and rheological properties of sorghum starch. *Innovative Food Science and Emerging Technologies*, *10*(4), 449–456.

Vittadini, E., Carini, E., Chiavaro, E., Rovere, P., & Barbanti, D. (2008). High pressure-induced tapioca starch gels: physico-chemical characterization and stability. *European Food Research and Technology*, *226*(4), 889–896.

Xi, J. (2017). Ultrahigh pressure extraction of bioactive compounds from plants-A review. *Critical Reviews in Food Science and Nutrition*, *57*(6), 1097–1106.

Yang, Z., Chaib, S., Gu, Q., & Hemar, Y. (2017). Impact of pressure on physicochemical properties of starch dispersions. *Food Hydrocolloids*, *68*, 164–177.

Yordanov, D. G., & Angelova, G. V. (2010). High Pressure Processing for Foods Preserving. *Biotechnology & Biotechnological Equipment*, *24*(3), 1940–1945.

Zia-ud-Ding, Xiong, H., & Fei, P. (2017). Physical and chemical modification of starch. A Review. *Critical Reviews in Food Science and Nutrition*, *57*(12), 2691-2705.

Table 1: Hygroscopic properties of treated starches.

Starch source	P (MPa)	T (ºC)	t (min)	Main findings	Reference
Lentil	400-600	25	ND	Water holding capacity increased from 0.1 to 600 MPa. Those values among the pressure level were significantly different. Increasing the pressure, the solubility decreased, and particle volume fraction increased.	Ahmed *et alet al*. (2016)
Quinoa	300-600	25-70	ND	Water holding capacity, solubility, and particle volume fraction increased from 0.1MPa to 600 MPa and from 25 to 75 ºC.	Ahmed *et al.* (2018)
Chestnut	400-600	25-70	ND	Increasing the pressure, solubility and particle volume fraction did not change. Increasing the temperature, solubility and particle volume fraction increased. Water holding capacity at 25-70 ºC, pressure treated values were lower than the control. Water holding capacity values increased from 25 to 70 ºC.	Ahmed & Al-Attar (2017)
Lotus seed	100-600	55-95	30	Swelling and solubility increased from 55 to 95 ºC. At 85-95 ºC, pressure treatment decreased significantly swelling and solubility. At 55-75 ºC, pressure treatment increased significantly swelling and solubility.	Guo *et al.*, (2015a)
Rice	120-600	50-90	30	Swelling and solubility increased from 50-90 °C. From 50-60 ºC at 600 MPa, swelling and solubility values were higher than the native. At 70-90 ºC opposite results were found.	Li, Bai, Mousaa, Zhang, & Shen (2012)
Mung bean	120-600	90	30	From 0.1 to 600 MPa, swelling and solubility decreased. Differences were significant, except from 0.1 to 240 MPa.	Li *et al.* (2011)
Pea	150-600	30-90	30	Generally, solubility and swelling increased from 30-90 °C. From 30-70 °C at 600 MPa, starch had higher solubility and swelling. At 600 MPa and 90 ºC, solubility and swelling had lower values.	Liu *et al.* (2018)
Quinoa and Maize	100-600	55-90	ND	Solubility and swelling of quinoa were higher than maize. Above 500 MPa, solubility and swelling at high temperatures tended to decrease. Pressures higher than 400 MPa, solubility and swelling had higher values at lower temperatures. Swelling and solubility at lower temperatures decreased up to 400 MPa. Increase of pressure to 600 MPa, values decreased.	Li & Zhu (2018)
Proso millet	150-600	50-90	ND	Swelling and solubility increased with pressure from 50-60 ºC. At 70 ºC and 600 MPa had the highest solubility and lowest swelling. At 80-90 ºC, swelling and solubility decreased for pressurized samples in relation to the native.	Li *et al.* (2018)
Sorghum	120-600	50-90	30	Swelling increased from 50-90 ºC. From 50-60 ºC, swelling had the highest values at 600 MPa. Compared to native at 70-90 ºC, swelling decreased with increasing pressure.	Liu, Fan, Cao, Blanchard, & Wang (2016c)

P: Treatment pressure; t: Analysis time; T: Analysis temperature; ND: no data.

Table 1: Hygroscopic properties of treated starches (continued).

Starch source	P (MPa)	T (ºC)	t (min)	Main findings	Reference
Common buckwheat	120-600	50-90	30	From 50-90ºC, swelling and solubility increased. At 50-60ºC, swelling and solubility had the highest values at 600 MPa. Opposite results were observed at higher temperatures. Compared to native, treated starch had lower swelling and solubility at 70-90 ºC. This reduction was correlated with the increasing pressure.	Liu *et al*. (2016b)
Red adzuki beans	150-600	50-90	30	Solubility increased from 150-600 MPa. From 50-90 ºC, solubility did not varied significantly. Solubility from 450-600 MPa at 90 ºC was lower than at 50-80 ºC. Swelling increased from 50-90 ºC. At 50-60 ºC, swelling increased with increasing pressure (highest value at 600 MPa). At 80-90 ºC, swelling decreased with increasing pressure (lowest value at 600 MPa).	Li *et al*. (2015)
Tartary buckwheat	120-600	50-90	30	At 50-90 ºC, swelling and solubility increased. At 50-60 ºC, swelling and solubility had the highest values at 600 MPa. Opposite was observed at higher temperatures. Compared to native, treated starch had lower swelling and solubility at 70-90 ºC. This reduction was correlated with the increasing pressure.	Liu *et al*. (2016a)

P: Treatment pressure; t: Analysis time; T: Analysis temperature; ND: no data.

Table 2: Grain morphology and particle size of starch granules treated with different pressures.

Starch	P (MPa)	T (ºC)	t (min)	Main findings	Reference
Waxy wheat	300-600	room	ND	At 300 MPa, granules had intact structure but were tighter, rougher with wrinkles. At 400 MPa, granules packed tighter had little surface melting. At 500 MPa, granules had irreversible loss and had viscous gel-like regions At 600 MPa, structure was destroyed.	Hu, Zhang, Jin, Xu, & Chen (2017)
Lotus seed	100-600	room	30	Native granules were smooth with elliptical shape. Pressure ≤500 MPa had no significant changes in granules morphology. At 600 MPa, granules were collapsed and had doughnut-shape.	Guo *et al*. (2015a)
Sorghum	120-600	room	20	Native granules had irregularly shape with smooth surfaces. From 120-360 MPa, granules structure was intact. At 480 MPa, granules were swelled and collapsed. At 600MPa, were deformed and had appeared to have fused.	Liu *et al*. (2016c)
Common buckwheat	120-600	room	20	Native granules had irregular shapes with smooth surfaces. Granules shape was intact from 120–360 MPa. At 480 MPa, were collapsed and had a doughnut shape. At 600 MPa were gelatinized, deformed, and collapsed.	Liu *et al*. (2016b)
Tartary buckwheat	120-600	room	20	Native granules had irregular shapes with smooth surfaces. Granules shape was intact from 120–360 MPa. At 480 MPa, granules were collapsed and had a doughnut shape. At 600 MPa granules were gelatinized, deformed, and collapsed.	Liu *et al*. (2016a)
Mung bean	120-600	room	30	Native granules had kidney and ellipse shapes with smooth surface. From 120-480 MPa granule size did not changed, but shape and surface did. Granules at 600 MPa collapsed and had a doughnut-shape.	Li *et al*. (2011)
Rice	120-300	room	30	Native granules had polyhedral and irregular. Changes in the granules were not obvious from 120-480 MPa. At 600 MPa, granules loss structure and had a gel-like appearance.	Li *et al*. (2012)
Rice	200-600	25	30 15x2	Native granules had polygonal or irregular shapes. At 200 MPa, the surfaces were rough and had gel-like boundaries. At 600 MP, granules were destroyed, and the gel-like regions expanded.	Deng *et al*. (2014)
Proso millet	150-600	ND	15	Native granules had several shapes. At 450 began to lose the granular structure. At 600 MPa were disrupt and disintegrated into gel-like structures.	Li *et al*. (2018)

P: Treatment pressure; t: Treatment time; T: Treatment temperature; ND: no data.

Table 2: Grain morphology and particle size of starch granules treated with different pressures (continued).

Starch	P (MPa)	T (ºC)	t (min)	Main findings	Reference
Pea	150-600	30	25	Native granules had irregular oval shapes with smooth surface. At 150-450 MPa, some granules were broken. At 600 MPa, granules were collapsed and had irregular shapes. Particle size distribution increased significantly at 600 MPa.	Liu *et al.* (2018)
Pea	300-600	25	15	Mean particle size decreased slightly at 600 MPa. Size distribution had large particles agglomeration at 500-600 MPa. At 400 MPa, larger particles could be attributed to hydration. At 500-600 MPa, the increase in particle size could be ascribed to entrance of water by pressure.	Leite *et al.* (2017)
Chestnut	400-600	ND	10	Native granules had various shapes and smooth surface. At 600 MPa, granules surface was smooth with a minor crack. D90 decrease significantly in particle size possibly due to excessive pressure.	Ahmed & Al-Attar (2017)
Sorghum	300-600	20	10	Some native granules were small and polygonal and smaller, and others were round and bigger. At 600 MPa (100% gelatinization), most granules retained some integrity.	Vallons & Arendt (2009)
Potato	600	20	2-3	Like the native granules, most pressure treated ones retain shape and many had significant deformations. Some had clear gel-like structures. With 3 min treatment, time was responsible for higher granule destruction.	Błaszczaka, Valverdeb & Fornal (2013)

P: Treatment pressure; t: Treatment time; T: Treatment temperature; ND: no data.

Table 3: Birefringence of starch granules treated with different pressures.

Starch	P (MPa)	T (ºC)	t (min)	Main findings	Reference
Lotus seed	100-600	25	30	Native granules had birefringence under polarized light. No relevant changes were found at 400 MPa. Birefringence pattern was weaker at 500 MPa and some granules loss it. Birefringence pattern was loss at 600 MPa, but some remained.	Guo *et al*. (2015b)
Red adzuki bean	150-600	room	15	Native granules had birefringence under polarized light. No relevant changes were found at 150-450 MPa. Granules lost birefringence at 600 MPa.	Li *et al*. (2015)
Rice	120-600	room	30	Native granules had birefringence under polarized light. No relevant changes were found at 120-360 MPa. At 480 MPa occurred some partial loss of birefringence. Complete birefringence loss was observed at 600 MPa.	Li *et al*. (2012)
Rice	200-600	25	30; 15x2	Native granules had birefringence under polarized light. No special changes in birefringent occurred at 200 MPa. At 600 MPa was observed partial polarization cross losses, especially after cycle pressure processing.	Deng *et al*. (2014)
Proso millet	150-600	ND[d]	15	Native granules had birefringence under polarized light. No relevant changes were found at 150-300 MPa. At 450MPa occurred some birefringence loss. Birefringence pattern was loss at 600 MPa.	Li *et al*. (2018)
Sorghum	300-600	20	10	Native granules had birefringence under polarized light. Birefringence decreased with increasing pressure above 300 MPa. A significant birefringence loss occurred at 400 MPa. Birefringence pattern was loss at 600 MPa.	Vallons & Arendt (2009)
Pea	300-600	25	15	No special changes in birefringent occurred up to 500 MPa. Birefringence pattern was loss at 600 MPa.	Leite *et al*. (2017)

P: Treatment pressure; t: Treatment time; T: Treatment temperature; ND: no data.

43 **Table 4**: Texture of starch (gels) treated with different pressures.

Starch	P (MPa)	T (ºC)	t (days)	Parameter	Force (g) AP/HP (MPa)	Reference
Tartary buckwheat	120-600	4	overnight	Hardness	148.7/22.3	Liu *et al.* (2016a)
				Adhesiveness	146.5/27.6[a]	
				Gumminess	93.0/9.1	
				Chewiness	96.9/9.3	
				Springiness	0.96/0.98[a]	
				Cohesiveness	0.652/0.415	
Common buckwheat	120-600	4	overnight	Hardness	83.6/6.8	Liu *et al.* (2016b)
				Adhesiveness	113/9.7[a]	
				Gumminess	55.5/3.3	
				Chewiness	52.7/3.2	
				Springiness	0.95/0.98[b]	
				Cohesiveness	0.664/0.488	
Tapioca	600	ND	1	Hardness	ND	Vittadini, Carini, Chiavaro, Rovere, & Barbanti (2008)
				Cohesiveness		
				Adhesiveness		
Tapioca	600	4 and -18	28	Hardness	ND	
				Cohesiveness		
Quinoa	100-600	4	1	Hardness	25.8/31.1	Li & Zhu (2018)
				Factorability	22.6/28.9	
				Adhesiveness	-211/-186[a]	
				Cohesiveness	0.637/0.52[b]	
Quinoa	100-600	4	7	Hardness	25.9/28.7	
				Factorability	28.1/23.6	
				Adhesiveness	-194/-186[a]	
				Cohesiveness	0.589/0.506[b]	
Maize	100-600	4	1	Hardness	54.1/42.9	
				Factorability	40.6/40.3	
				Adhesiveness	-219/-262[a]	
				Cohesiveness	0.557/0.51[b]	
Maize	100-600	4	7	Hardness	58.3/53.6	Li & Zhu (2018)
				Factorability	48.9/37.5	
				Adhesiveness	-235/-233[a]	
				Cohesiveness	0.458/0.441[b]	

44 a) Value expressed in force per time (g.s); b) dimensionless parameter; P: Treatment pressure; t: Storage time; T: Storage temperature; AP/HP:
45 Atmospheric pressure/High pressure; ND: no data.

Table 5: Color of treated starches.

Starch	P (MPa)	T (ºC)	t (min)	Parameter	Values[a] AP/HP (MPa)	Reference
Quinoa	300-600	ND	15	Redness	0.52/1.56	Ahmed *et al.* (2018)
				Yellowness	9.6/16.41	
				Lightness	88.50/80.63	
Chestnut	300-600	ND	10	Redness	2.20/2.75	Ahmed & Al-Attar (2017)
				Yellowness	13.37/13.60	
				Lightness	83.50/83.06	
Lentil	400-600	ND	10	Greenness	0.03/0.12	Ahmed *et al.* (2016)
				Yellowness	2.37/2.08	
				Lightness	81.91/78.53	

a) Dimensionless parameter; P: Treatment pressure; t: Treatment time; T: Treatment temperature; AP/HP: Atmospheric pressure/High pressure; ND: no data.

Table 6: Chemical composition of treated starches.

Starch	P (MPa)	T (ºC)	t (min)	Parameter	Content (%) AP/HP (MPa)	Reference
Common buckwheat	120-600	room	20	Moisture	11.20/10.50	Liu *et al*. (2016b)
				Ash	1.10/0.89	
				Fat	0.50/0.45	
				Protein	0.35/0.32	
				Total starch	89.90/88.70	
				Amylose	28.10/35.40	
Tartary buckwheat	120-600	room	20	Moisture	12.6/11.5	Liu *et al*. (2016a)
				Ash	0.90/0.82	
				Fat	0.40/0.36	
				Protein	0.48/0.42	
				Total starch	91.8/89.5	
				Amylose	29.1/34.2	
Quinoa	300-600	ND	15	ND	ND	Ahmed *et al*. (2018)
Chestnut	300-600	ND	10	Moisture	< 1.5	Ahmed & Al-Attar (2017)
				Ash	1.8/2	
				Fat	0.4/0.79	
				Protein	7.5/7.8	
				Total starch	47.30/46.08	

P: Treatment pressure; t: Treatment time; T: Treatment temperature; AP/HP: Atmospheric pressure/High pressure; ND: no data.

Table 7: Thermal properties of treated starches.

Starch	P (MPa)	To (ºC) AP/HP (MPa)	Tp (ºC) AP/HP (MPa)	Tc (ºC) AP/HP (MPa)	ΔTr (ºC) AP/HP (MPa)	ΔH (J/g) AP/HP (MPa)	GD (%) AP/HP (MPa)	Reference
Barley	400-550	ND	ND	ND	ND	ND	ND	Stolt, Oinonen, & Autio (2001)
Pea	300-600	53.61/ND	58.79/ND	62.78/ND	9.17/ND	3.75/ND	0/100	Leite *et al.* (2017)
Pea	150-600	64.0/ND	69.7/ND	74.3/ND	10.3/ND	6.2/ND	0/100	Liu *et al.* (2018)
Red adzuki bean	150-600	61.22/ND	68.35/ND	78.99/ND	17.77/ND	6.76/ND	0/100	Li *et al.* (2015)
Proso millet	150-600	64.16/ND	68.45/ND	79.09/ND	14.93/ND	10.58/ND	0/100	Li *et al.* (2018)
Lotus seed	100-600	67.75/ND	73.75/ND	79.16/ND	11.47/ND	13.11/ND	0/100	Guo *et al.* (2015a)
Mung bean	100-600	59.9/ND	67.8/ND	79.3/ND	20.3/ND	9.9/ND	0/100	Li *et al.* (2011)
Rice	120-600	58.1/ND	65.1/ND	76.5/ND	20.5/ND	11.8/ND	0/100	Li *et al.* (2012)
Quinoa	300-600	59.69/ND	65.96/ND	ND	ND	4.33/ND	0/100	Ahmed *et al.* (2018)
Quinoa	100-600	59.5/ND	64.6/ND	74.6/ND	15.1/ND	14.9/ND	0/100	Li & Zhu (2018)
Maize	100-600	68.3/45.5	72.3/52.8	78.3/62.0	10.0/16.5	14.3/6.1	0/57	Li & Zhu (2018)
Lentil	400-600	55.71/ND	63.72/ND	ND	ND	8.8/ND	0/100	Ahmed *et al.* (2016)
Sorghum	300-600	62.3/ND	67.0/ND	72.0/ND	9.7/ND	2.53	0/100	Vallons & Arendt (2009)
Waxy wheat	300-600	61.17/45.34	64.87/53.70	71.19/62.57	10.02/17.23	13.48/2.81	0/79	Hu *et al.* (2017)
Chestnut flour	400-600	ND	67.4/68.4	ND	ND	4.83/2.9	0/40	Ahmed & Al-Attar (2017)
Tartary buckwheat	120-600	70.5/62.1	77.0/98.5	83.9/71.6	13.4/9.5	19.8/6.6	0/67	Liu *et al.* (2016a)
Sorghum	120-600	71.5/63.0	77.0/67.5	85.3/72.1	13.8/9.1	22.4/10.6	0/53	Liu *et al.* (2016c)
Common buckwheat	120-600	65.5/61.6	76.5/69.5	80.3/71.4	14.8/9.8	22.5/8.6	0/62	Liu *et al.* (2016b)
Potato	600	65.04/58.79	70.08/65.70	77.17/72.57	12.13/13.78	15.96/4.31	0/73	Błaszczaka *et al.* (2013)

P: Treatment pressure; To: Onset temperature; AP/HP: Atmospheric pressure/High pressure; Tp: Peak temperature; Tc: Conclusion temperature; ΔTr: Gelatinization temperature range; ΔH: Gelatinization enthalpy; GD: Gelatinization degree; ND: no data.

Table 8: Dynamic oscillation properties of treated starches.

Starch	P (MPa)	T (ºC)	f (rad/s)	S (%)	Main findings	Reference
Lotus seed	100-600	25	0.1-100	0.5	*G'* > *G''* with no crossover. Moduli increased from 100 MPa to 500 MPa and decreased at 600 MPa. The capacity to recover the original structure under low-shear conditions after pressure treatment decreased with increasing pressure.	Guo *et al.* (2015b)
Chestnut dispersion	300-600	25	~0.63-63	0.1	*G'* > *G''* increased with frequency. Moduli increased from 0.1 to 600 MPa. Complex viscosity increased with pressure. Slope of logarithmic plots of *G'* versus frequency increased from 0.1 to 600 MPa.	Ahmed & Al-Attar (2017)
Lentil dispersion	450. 350 and 650	20	~0.63-63	ND[a]	*G'* > *G''* and pressure treatment increased moduli values. Slope of logarithmic plots of *G'* versus frequency increased with pressure treatment. Complex viscosity increased with pressure.	Ahmed, Varshney, & Ramaswamy (2009)
Mung bean	120-600	25	0.1–100	0.5	*G'* > *G''* with no crossover. Moduli increased with frequency and with pressure treatment, Moduli increased rapidly at lower frequencies and slowly at higher ones.	Jiang, Li, Hu, Wu, & Shen (2015a)
Rice	120-600	25	0.1–100	0.5	*G'* > *G''* with no crossover. Moduli increased with frequency and with pressure treatment, Moduli increased rapidly at lower frequencies and slowly at higher ones.	Jiang, Li, Shen, Hu, & Wu (2015b)
Lentil	400-600	25	~0.063-63	0.01	*G'* increased with increasing pressure. *G'* > *G''* with no crossover. Slope of logarithmic plots of *G'* versus frequency decreased from 0.1 to 600 MPa.	Ahmed *et al.* (2016)

a) ND, no data (performed within the linear viscoelastic range); P: Treatment pressure; T: Analysis temperature; f: Frequency; S: Strain, *G'*: Storage modulus; *G''*: Loss modulus.

Table 9: Steady flow behavior of treated starches.

Starch	P (MPa)	T (ºC)	t (min)	SR (s^{-1})	Index value[a] AP/HP (MPa)	K ($Pa.s^n$) AP/HP (MPa)	Yield stress (Pa) AP/HP (MPa)	Flow model	Reference
Mung bean	120-600	20	30	0-300	0.24/0.28	28.23/86.81	ND	Power law (r^2>0.95)	Jiang *et al.* (2015a)
Rice	120-600	25	30	0-300	ND	ND	ND	ND	Jiang *et al.* (2015b)
Lotus seed	100-600	25	3	0-300	0.487/0.211	6.61/41.31	35.81/19.61	Herschel-Bulkley (r^2>0.99)	Guo *et al.* (2015b)
Quinoa	100-600	25	5	0.1-1000	0.38/0.51	6.50/2.10	3.73/0.57	Herschel-Bulkley (-)	Li & Zhu (2018)
Maize	100-600	25	5	0.1-1000	0.59/0.63	1.82/0.45	8.2/0.55	Herschel-Bulkley (-)	Li & Zhu (2018)

a) Dimensionless parameter; P: Treatment pressure; T: Assay temperature; t: Shear rate increasing time; SR: Shear rate range; K: consistency coefficient; AP/HP: Atmospheric pressure/High pressure; ND: no data.

Table 10: Pasting properties of treated starches.

Starch	P (MPa)	PT (ºC) AP/HP (MPa)	Pt (min) AP/HP (MPa)	PV (Pa s) AP/HP (MPa)	TV (Pa s) AP/HP (MPa)	BD (Pa s) AP/HP (MPa)	FV (Pa s) AP/HP (MPa)	SB (Pa s) AP/HP (MPa)	Reference
Common buckwheat	120-600	63.7/68.8	4.26/5.73	4.019/0.371	ND	1.641/0.150	4.293/0.568	1.915/0.347	Liu *et al.* (2016b)
Sorghum	120-600	63.0/66.5	4.19/4.87	4.464/1.611	ND	2.701/0.457	3.397/2.314	1.734/1.160	Liu *et al.* (2016c)
Tartary buckwheat	120-600	62.9/68.2	4.06/5.82	3.803/0.398	ND	1.612/0.129	4.208/0.543	2.017/0.278	Liu *et al.* (2016a)
Lotus seed	100-600	79.9/ND	6.2/7.0	1.3377/0.2102	1.2437/0.1853	0.0937/0.0194	1.9132/0.3454	0.6703/0.1601	Guo *et al.* (2015a)
Red adzuki bean	150-600	50.63/92.33	4.50/7.00	5.252/0.613	3.751/0.506	1.501/0.107	4.936/0.889	1.185/0.383	Li *et al.* (2015)
Mung bean	120-600	72.0/72.7	4.2/5.6	6.207/5.761	5.818/5.346	3.369/0.324	4.276/7.945	1.493/2.570	Li *et al.* (2011)
Mung bean	120-600	ND	13.01/14.81	2.61/3.12	1.38/2.65	1.23/0.47	3.84/2.60	1.23/052	Jiang *et al.* (2015a)
Quinoa	100-600	67.4/50.0	ND	6.29/5.48	ND	ND	ND	ND	Li & Zhu (2018)
Maize	100-600	75.2/68.9	ND	3.62/3.18	ND	ND	ND	ND	Li & Zhu (2018)
Pea	150-600	70.3/61.8	4.7/7.0	2.9090/0.5240	2.2750/0.4730	6.340/0.500	3.924/0.693	1.6540/0.2200	Liu *et al.* (2018)
Pea	300-600	ND	6.16/6.22	0.30297/0.45533	0.09367/0.08233	0.20900/0.37300	0.28433/0.33300	0.19067/0.25067	Leite *et al.* (2017)
Rice	120-600	ND	11.5/17.2	0.265/1.077	0.235/1.040	0.030/0.037	0.569/1.593	0.334/0.533	Jiang *et al.* (2015b)
Lentil	400-600	64.1/56.5	9/44.43	$958^a/520^a$	$586^a/517^a$	$372^a/3^a$	$1666^a/688^a$	$1080^a/171^a$	Ahmed *et al.* (2016)
Proso millet	150-600	57.40/89.56	4.33/5.47	2.807/0.252	1.061/0.402	1.746/0.123	0.2694/0.725	1.634/0.321	Li *et al.* (2018)
Chestnut	500-600	62.6/61.9	3.9/4.2	$1087^a/1026^a$	$825^a/903^a$	$262^a/123^a$	$839^a/852^a$	$14^a/(-51)^a$	Ahmed & Al-Attar (2017)

a) Value expressed in Brabender unities (BU); P: Treatment pressure; PT: Pasting temperature; Pt: Peak time; PV: Peak viscosity; TV: Trough viscosity; BD: Breakdown; FV: Final viscosity; SB: Setback; AP/HP: Atmospheric pressure/High pressure; ND: no data.

Table 11: Retrogradation properties of starch gels treated with different pressures.

Starch	P (MPa)	T (ºC)	t (days)	Main findings	Reference
Lotus seed	100-600	4	14	Enthalpy increased with storage time, but decrease with pressure. Pressurized starch had bigger Avrami exponent values and smaller recrystallization rates than the native starch.	Guo *et al*. (2015b)
Rice	600	4	35	Retrogradation of pressure-treated rice starch was lower than the heat treated (boiling water for 30 min). Pressure-treated rice starch had higher Avrami exponent and a lower recrystallization rates in relation to the heat treatment, indicating that pressure slowed retrogradation.	Hu *et al*. (2011)
Waxy rice	600	4	35	Treatments did not affect waxy rice starch retrogradation properties and amylose leaching.	Hu *et al*. (2011)
Tapioca	600	4 and -18	28	Reduced retrogradation in pressure treatment when compared to the heat treatment (water at 90ºC for 20 min). In general, frozen pressure treated gels had lower retrogradation that refrigerated.	Vittadini *et al*. (2008)
Barley	550	4	7	Enthalpy increased with increasing storage time. Increased pressurization did not change the retrogradation behavior. Similar Main findings were obtained for the heat treatment (water at 90º for 30 min).	Stolt *et al*. (2001)
Proso millet	600	room	8	Crystallinity increased with the retrogradation time. Enthalpy increased with storage time.	Li *et al*. (2018)
Maize and Quinoa	100-600	4	14	Pressure had little affected on retrogradation when compared to the control.	Li & Zhu (2018)

P: Treatment pressure; t: Storage time; T: Storage temperature.

128 **Table 12**: Polymorphism and X-ray diffraction peaks of treated starches.

Starch	NP	Np (º)	P (MPa)	FN	CRY (%) AP/HP (MPa)	Reference
Chestnut	B	15, 17, and 22.5 (double)	400-600	B	ND	Ahmed & Al-Attar (2017)
Lotus seed	C	14.86, 16.96, 17.75, 22.82	100-600	B	ND	Guo *et al.* (2015a)
Mung bean	C	15.08, 17.2, 17.92, 22.92, 26.34	120-600	B	ND	Li *et al.* (2011)
Lentil	C	15.4, 17.2, 23.1	400-600	B	ND	Ahmed *et al.* (2016)
Pea	C	15.3, 17.2, 17.7, 23.3, 25.9	150-600	B	ND	Liu *et al.* (2018)
Red adzuki bean	C	15, 17, 20	150-600	C	ND	Li *et al.* (2015)
Rice	A	15.04, 16.84, 17.96, 23.02, 20.04, 26.3, 30.26	120-600	B	ND	Li *et al.* (2012)
Waxy wheat	A	15, 17, 17.9, 23	300-600	A+B	37.03/16.93	Hu *et al.* (2017)
Proso millet	A	15, 17, 18, 23	150-600	B	38.87/9.1	Li *et al.* (2018)
Sorghum	A	15.3, 17.34, 18.08, 23.28	120-600	B	38.0/24.4	Liu *et al.* (2016c)
Tartary buckwheat	A	15.22, 17.32,18.14, 23.12	120-600	B	38.8/26.2	Liu *et al.* (2016a)
Common buckwheat	A	15.22, 17.32, 18.14, 23.12	120-600	B	39.3/26.2	Liu *et al.* (2016c)
Quinoa	A	14.88, 16.93, 17.56, 22.73	300-600	ND	ND	Ahmed *et al.* (2018)
Rice	A	15, 23, and unresolved doublet (around 17 and 18)	200-600	B	28.1/18.4	Deng *et al.* (2014)

129 NP: Native pattern; Np: Native diffraction peaks; P: Treatment pressure; Final pattern observed at the highest-pressure treatment; CRY: Crystallinity;
130 AP/HP: Atmospheric pressure/High pressure; ND: no data.
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135 **Table 13**: *In-vitro* enzymatic digestion conditions of treated starches.

Starch	P (MPa)	Enzymatic conditions	Main findings	Reference
Waxy wheat	300-600	α-amylase (290 U/ml) + amyloglucosidase (15 U/ml) [phosphate buffer (pH 5.2); 37 ºC; 120 min]	Increasing the pressure level, the rapid and slow digestible starch contents increased, and the resistant starch content decreased.	Hu *et al.* (2017)
Rice	200-600	α-amylase (275 U) + amyloglucosidase (70 U) [sodium acetate-acetic acid buffer (pH 6); 37 ºC; 240 min]	No significant differences were found in rapid digestible, slow digestible, and resistant starches between the control and sample treated at continuous 200 MPa for 30 min, but other high-pressure treatments resulted in significant increases in rapid and slow digestible starch, and resistant starch decreases.	Deng *et al.* (2014)
Pea	150-600	ND	Hydrolysis increased with digestion time. Native starch had higher hydrolysis than the pressurized starches. Increasing pressure, the hydrolysis decreased, rapid and slow digestible starch amount decreased, and resistant starch content increased. At 600 MPa had the lowest rapid digestible starch content and the highest resistant starch levels.	Liu *et al.* (2018)
Sorghum	120-600	Pepsin [HCl-KCl buffer (0.05M, pH 1.5); 40 ºC; 60 min] + α-amylase (2.6 UI) [Sodium acetate buffer (0.5 M, pH 6.9); 37 ºC; 3h] + amyloglucosidase [sodium acetate buffer (0.4M, pH 4.75); 60ºC; 45 min]	Hydrolysis increased with digestion time. Native starch had higher hydrolysis than pressurized starches. Reduction in hydrolysis was correlated with increasing pressure, rapid digestible starch content decreased, but slow digestible starch and resistant starch contents increased. At 600 MPa: lowest rapid digestible starch, and the highest slow digestible starch and resistant starch contents.	Liu *et al.* (2016c)
Tartary buckwheat	120-600	Pepsin [HCl-KCl buffer (0.05M, pH 1.5); 40 ºC; 60 min] + α-amylase (2.6 UI) [Sodium acetate buffer (0.5 M, pH 6.9); 37 ºC; 3h] + amyloglucosidase [sodium acetate buffer (0.4M, pH 4.75); 60ºC; 45 min]	Hydrolysis increased with digestion time. Native starch had higher hydrolysis than pressurized starches. Reduction in hydrolysis was correlated with increasing pressure, rapid digestible starch content decreased, but slow digestible starch and resistant starch contents increased. At 600 MPa: lowest rapid digestible starch, and the highest slow digestible starch and resistant starch contents.	Liu *et al.* (2016a)
Common buckwheat	120-600	ND	Hydrolysis increased with digestion time. Native starch had higher hydrolysis than pressurized starches. Reduction in hydrolysis was correlated with increasing pressure, rapid digestible starch content decreased, but slow digestible starch and resistant starch contents increased. At 600 MPa: lowest rapid digestible starch, and the highest slow digestible starch and resistant starch contents.	Liu *et al.* (2016b)

136 P: Treatment pressure; ND: no data.

Highlights

1. Starch properties can be differently altered depending on origin and pressure level

2. Pressure can increase starch swelling and solubility depending on the temperature

3. Pressure can alter significantly starch thermal and pasting properties

4. Pressure can delay/decrease starch retrogradation and change starch polymorphism

5. Pressure can alter the amount of resistant/fast/slow digestible starch

Disclosure Statement

The authors declare no competing financial interests.