Chapter 7
Ultrahigh Pressure Treatment

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Abstract Ultrahigh pressure, also called high hydrostatic pressure, is an important physical process to modify starch. In this chapter, the effects of ultrahigh pressure on physicochemical properties (including gelatinization, rheological and digestibility properties) and structures (including granular, crystalline and molecular structures) of starches are reviewed. Many studies show that ultrahigh pressure can realize starch gelatinization at room temperature. However, the pressure-induced and heat-induced gelatinization have different characteristics. In present, the potential applications mainly include the preparation of pregelatinized starch and cold water-swelling starch, as well as chemical modified starch. The future research can focus on the structural recombination of starch treated at lower pressure (lower than gelatinization pressure) and the performance of dry starch in ultrahigh pressure treatment.

Keywords Ultrahigh pressure · Gelatinization · Crystalline structure

7.1 Introduction

Ultrahigh pressure (UHP), also called high hydrostatic pressure (HHP), is often defined as pressure exceeding 100 MPa. The implementation of UHP technology depends on the UHP equipment. A typical laboratory-scale UHP equipment includes a pressure vessel, closures for sealing the vessel, pumps to intensify the high pressure, and a controlling system, in general with cavity volume of 10 mL to 5 L. A commercial UHP equipment has a product handling system to transfer the product without stirring apparatus and difficult to realize the continuous monitoring of structure and properties changes (Bolumar et al. 2015) (Fig. 7.1). Depending on the equipment, the pressure settings vary from 100 to 900 MPa but frequently in the

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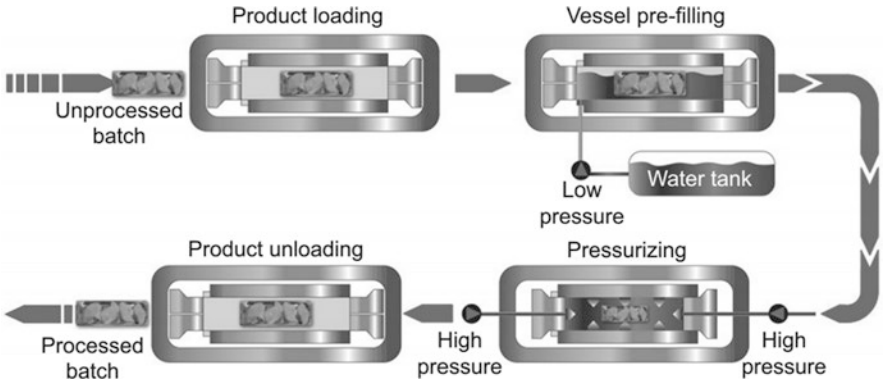

Fig. 7.1 Scheme of high pressure processing. (Source: Courtesy of Francisco Purroy (Hiperbaric, Spain)) (Bolumar et al. 2015)

range of 400–600 MPa in an industrial environment (Bolumar et al. 2015). Pressure transmits through a specific medium, which in most cases is water but is replaced by oil at a higher pressure (usually exceeds 600 MPa).

UHP is traditionally applied in ceramics, synthetic materials, steel, and superalloy production (Mota et al. 2013). The original application of UHP in food industry was reported in increasing shelf life of milk in 1899. At present, the application of UHP mainly involves in food nonthermal sterilization, inactivation of enzyme, macromolecular modification, and quality improvement for end-use products such as meats and wines. Since 1981, as the gelatinization of starch at room temperature is reported by Thevelein and his co-workers, the UHP treatment of starch attracts more and more attention (Thevelein et al. 1981).

Most often, starches are subjected to UHP treatments as suspensions in water. In contrast, less information is available for dry (lower moisture content) starch. Without adequate moisture, starch granules show high-pressure resistance. Only extreme UHP (>600 MPa) treatment can alter the shape and surface appearance of dry starch granules, as well as destroy the crystalline structure (Liu et al. 2008; Slominska et al. 2015; Kudla and Tomasik 1992a, b).

Earlier reports were about pressure-induced gelatinization process and comparison with heat-induced gelatinization. In recent years, more investigations were conducted on the structure-properties relationship of starch and the potential application of UHP. Heat-induced gelatinization can be represented directly by using hot-stage polarized light microscope (HS-PLM), rapid visco analyzer (RVA), and differential scanning calorimeter (DSC). However, for pressure-induced gelatinization, it is difficult to carry out the pressure treatment and properties determination simultaneously due to instrumental limitation. The diamond anvil cell (DAC) combined with synchrotron radiation technology realizes the online analysis for lamellar structure change during pressure-induced gelatinization process but fails to obtain macro-

scopic properties because of the smaller sample capacity for this device. Almost all studies on pressure-induced gelatinization must prepare UHP-treated samples first. The gelatinization process is commonly evaluated by the degree of gelatinization, calculated by gelatinization enthalpy in DSC results. Besides, Bauer and Knorr characterized the gelatinization according to the electrical conductivity of UHP-treated starch and found the electrical conductivity correlated well with the degree of gelatinization (Bauer and Knorr 2004). This is applicable for the quick and simple determination of pressure-induced starch gelatinization.

Botanical source and pressure are the most important factors in pressure-induced gelatinization. Besides, concentration, holding time, temperature, and pH also influence the gelatinization of starch. Starches with different botanical sources vary in gelatinization pressure, usually evaluated by the gelatinization pressure, which is defined to be the initial pressure (or a pressure range) to induce starch gelatinization and generally determined by using polarizing microscope (PLM) or DSC. In general, without heating or addition of other components, a complete gelatinization usually needs 600 MPa (Liu et al. 2010). Potato starch (with B-type crystal) exceeds 600 MPa and is considered to have a higher-pressure resistance (Kawai et al. 2007). At present, it is still controversial whether or not UHP treatment at the pressure lower than gelatinization pressure can affect starch structure. Thus, study on the effects of UHP on starch structure at a lower pressure (lower than gelatinization pressure) is worth to carry out and will facilitate the comprehensive understanding of starch performance during UHP treatment processing.

7.2 The Effects of UHP on Starch Physicochemical Properties

7.2.1 Gelatinization Properties of Starch

The gelatinization properties are mainly reflected in the change of gelatinization enthalpy/temperature and viscosity. In general, UHP treatment lowers the gelatinization enthalpy in a certain pressure range, while gelatinization temperature decreases with increasing pressure (Table 7.1). However, Thevelein and Muhr reported that a treatment of potato starch in dilute (0.4%) suspension with pressures up to a relatively low pressure (<150 MPa) increased its gelatinization temperature (Thevelein et al. 1981; Muhr and Blanshard 1982). Rice, waxy maize, high-amylose maize, sorghum, and buckwheat starches also increase in gelatinization temperature (onset temperature) after UHP treatment (Table 7.1). This may be related to the preferential gelatinization of starch granules with low-pressure resistance or formation of new starch crystal with higher gelatinization temperature due to the retrogradation of starch molecules, while Kweon and his co-workers propose that the reason is the annealing of amylopectin (Kweon et al. 2008a).

Table 7.1 The effects of ultrahigh pressure (UHP) treatment on gelatinization enthalpy (△H) and onset gelatinization temperature (To) of various starches

Starch	Pressure (gelatinization pressure) /MPa	Starch content/%	Time/ min	△H	To	References
Potato	51–253	0.4	4	Decline	Rise	Thevelein et al. (1981)
Wheat, potato, smooth pea	58–401	0.4	–	Decline	Rise and decline	Muhr and Blanshard (1982)
Barley	450–600	10, 25	15, 30	Decline	–	Stolt et al. (2001)
Maize, waxy maize, tapioca, rice, potato, high-amylose maize	690	1:1, 1:2 (w/V)	5, 60	Decline	Decline (rise for waxy maize, rice, and high-amylose maize)	Katopo et al. (2002)
Potato	600	10	2, 3	Decline	Decline	Błaszczak et al. (2005a)
Potato	600–1000	10–70	60–3960	Decline	–	Kawai et al. (2007)
Sorghum	200–600 (600)	25	10	Decline	Rise	Vallons and Arendt (2009a)
Buckwheat	200–600 (600)	25	10	Decline	Rise	Vallons and Arendt (2009b)
Mung bean	120–600 (600)	20	30	Decline	Decline	Li et al. (2011a)
Rice	120–600 (600)	20	30	Decline (120–480 MPa)	Decline	Li et al. (2011b)
Lotus seed	100–600 (600)	15	30	Decline (100–500 Mpa)	–	Guo et al. (2015a)

As a kind of nonthermal processing technology, UHP is mainly applied at room temperature. However, in some case, it is interesting to discuss the gelatinization induced by pressure-heat combinations. For pressure-induced gelatinization at a constant holding time, either increasing temperature or pressure can promote starch gelatinization. In other words, the higher the temperature, the lower pressure to realize the complete gelatinization of starch (Bauer and Knorr 2005; Tan et al. 2009). On the other hand, at a constant temperature and pressure, the degree of gelatinization increases with increasing holding time. However, if the temperature and/or pressure is unable to induce starch gelatinization, it is invalid to prolong holding

time (Stolt et al. 2001; Bauer and Knorr 2005). In order to further understand the heat-pressure combination effect, the phase diagrams of various starches have been provided and used to estimate the degree of gelatinization after applying a certain pressure and temperature on a starch-water mixture with starch concentrations in the range of 5% and 60% w/w (Baks et al. 2008).

Just as heat-induced gelatinization, pressure-induced gelatinization is also influenced by solutes in the starch suspensions. The addition of sugar (20%) reduced gelatinization pressure (wheat starch/350 MPa tapioca starch/530 MPa, potato starch/700 MPa, 5% suspension, 15 min at 29 °C), whereas the degree of gelatinization is linearly correlated with the number of equatorial hydroxyl groups for different sugars (fructose, glucose, sucrose, trehalose) (Rumpold and Knorr 2005). UHP-induced gelatinization can also be affected by salt. The presence of salt significantly protected glass and crystalline transitions of wheat starch during the UHP treatment (Kweon et al. 2008b). Additionally, the influence of salts on the gelatinization pressure varies, and the extent of effect on the gelatinization pressure depends not only on the solute added but also on the source of starch (700 MPa, 15% suspension, 15 min at 29 °C) (Rumpold and Knorr 2005). At high chloride concentrations (>2 M), the impact of the salts on starch gelatinization augmentation followed the order $Na^+<K^+<Li^+<Ca^{2+}$, which corresponds to the order of the lyotropic series. At concentrations above 1 M, the effect of potassium salts on starch gelatinization upon pressurization also followed the order of the Hofmeister series ($Cl^-<Br^-<I^-<SCN^-$). This conclusion is helpful in the practical application of UHP-treated starch (Rumpold and Knorr 2005).

The change of viscosity in gelatinization process is mainly measured by RVA or the rheometer after UHP treatment. If the UHP-treated starch sample still appears a drastic increase in viscosity during heating, it indicates the treatment pressure is lower than the gelatinization pressure of the starch. In contrast, the treatment pressure is higher than gelatinization pressure. Thus, the gelatinization pressure can be obtained by comparing the RVA curves of samples treated at different pressures. Oh and his co-workers determined the gelatinization pressures (10% suspension, 30 min at 20 °C) of normal rice, waxy rice, normal corn, waxy corn, tapioca, and potato starches by using this method (Oh et al. 2008). More information can also be obtained by using RVA. The pasting properties of mung bean (20% suspension, 30 min at room temperature), rice (20% suspension, 30 min at room temperature), red adzuki bean (20% suspension, 15 min at 25 °C), and lotus seed starches (15% suspension, 30 min at room temperature) were reported (Li et al. 2011a, b, 2015; Guo et al. 2015a). Gelatinized starch (treated at 600 MPa) exhibits the lowest peak viscosity (PV), breakdown (BD), and setback (SB) (except for mung bean starch). PV is an indicator of early and rapid swelling of starch granules, and BD represents the stability and resistance of starch granules to shear stress, while SB represents the rapid retrogradation of leached amylose in starch. Therefore, UHP-gelatinized starch has generally a stronger starch aggregation, more stable hot paste, and lower retrogradation tendency compared with native starch, although some starches exist a varying trend. This could be due to some structural factors such as granular swelling, amylose leaching, and starch-water and amylose-lipid interaction.

7.2.2 Rheological Properties of Starch Paste and Gel

Starch is mainly used in the food industry in the form of gelatinized starch. Therefore, the properties of starch paste and starch gel are widely studied. In steady-state rheological behavior, the consistency coefficient (K) value is an approximate measurement of the viscosity of the starch paste at rest. The elevating K value reflects the granular swelling and the increasing in degree of gelatinization. After UHP treatment for starch suspension, the K of starch paste increased with increasing pressure or holding time however existing a limit K value during the increasing of holding time (Stolt et al. 1999, 2001; Guo et al. 2015b; Jiang et al. 2015). Furthermore, increasing temperature could further increase the K value in a constant pressure (Tan et al. 2009).

The dynamic rheological behavior and textural parameters reflect the properties of gels, which are related to the retrogradation of starch molecules. The dynamic rheological test is generally carried out according to strain sweep measurement. The storage modulus G' is a measure of the energy stored in the sample. For a gel, it reflects the cross-link density of the network (Stolt et al. 1999). In most reports, G' value increases with increasing pressure or holding time; however, continuous increasing pressure or holding time could show an opposite effect for starch gels, indicating that excessive pressurization can produce weaker gel (Stolt et al. 1999; 2001; Tan et al. 2009; Guo et al. 2015b).

The gel prepared in a higher concentration (related to the source of starch) is usually measured by textural analyzer. The properties of pressure-induced gels differ from that of the heat-induced gels. Stute and his co-workers reported a rapid retrogradation peak in DSC curve for UHP-treated (wheat, corn, pea, waxy rice) starches (450–500 MPa, 25%, 15 min at 20 °C) (Stute et al. 1996), suggesting that amylose significantly retrogrades and mainly occurs within the granules because of the limited swelling of starch granules and a limited releasing of amylose during UHP gelatinization. Due to rapid retrogradation, UHP-induced gel is harder than heat-induced gels for tapioca starch (Vittadini et al. 2008). However, the contradictory results were reported for wheat starch (Douzals et al. 1998). Pressure-induced gel was softer but dense compared with heat-induced gel, indicating that starch gels obtained under pressure would be less sensitive to retrogradation. The retrogradation of pressure-gelatinized starches was slower than that of heat-gelatinized starches as observed with enzyme digestibility and starch-iodine reaction (Stolt et al. 2001). These results do not mean that all pressure-induced gels behave in a similar way.

The retrogradation properties of tapioca starch gels illustrate that UHP (600 MPa, 25% suspension, 10 min at 30–80 °C/20, 30 min at 30 °C) resulted in the formation of harder gel than thermal processing (25% suspension, 20 min at 90 °C) (Vittadini et al. 2008). The increased hardness induced by UHP (600 MPa) was found to be more significant in the samples processed at 30 °C compared with treatment at higher temperature (50 or 80 °C) (Vittadini et al. 2008). Longer UHP treatments (600 MPa, 25% suspension, 10–30 min at 30 °C) caused only a slight decrease in hardness and were significant only at longer processing times (30 min). These can

be explained by the different water-starch and/or starch-starch molecular interactions due to partial preservation of the granular structure in gel after UHP-induced gelatinization (Vittadini et al. 2008).

7.2.3 Starch Digestibility

The amylase digestibility of pressure-treated starch was first discussed in 1989 by Hayashi and Hayashida (1989). The author indicates that the amylase digestibility increases with increasing pressure because of the starch gelatinization. However the formation of new structure during long-period pressure treatment decreases the digestibility. The relationship between starch structure and the content of resistant starch (RS) or slowly digestible starch (SDS) after UHP treatment was studied (Mu et al. 2015). General, more SDS and RS were observed in UHP-gelatinized starches than in heat-gelatinized starches (Bauer et al. 2005; Tian et al. 2014). Linsberger-Martin and his co-workers reported that increasing pressure, holding time, or temperature led to increases in RS (Linsberger-Martin et al. 2012). However, Deng and his co-workers (20% suspension, 30 min at 25 °C) proposed that excessive pressurization (600 MPa) and cycle UHP treatment (15 + 15 min) decreased the RS but increased the SDS content of rice starch (Deng et al. 2014). Additionally, UHP treatment could further induce increasing RS in starch paste (Bauer et al. 2005). In comparison, resistant (RS3, retrograded starch) and waxy corn starches treated by UHP are characterized by the lower levels of released glucose after enzymatic digestion, compared with that for wheat, potato, tapioca, and corn starches (Papathanasiou et al. 2015). Besides, initial rate of glucose production obtained from heat-induced gelatinization is faster than that obtained from the UHP treatment, in spite of the equilibrium yield of glucose found to be similar (Papathanasiou et al. 2015).

The gels prepared by UHP treatment have the potential application in drug release. The drug release rate depends on the starch source. Gel-forming polymer containing potato starch exhibits faster drug dissolution, while the pressurization of maize starch results in a gel exhibiting sustained drug release (Szepes et al. 2008). Overall amylose content, pressure, and starch source are important factors in affecting the digestibility of starch treated with UHP (Dupuis et al. 2014).

7.3 The Effects of UHP on Starch Structure

7.3.1 Granular Micrograph Structure

Granular micrograph variation can intuitively reflect the effects of UHP on various starches. Light microscope (LM) and scanning electron microscope (SEM) are the main tools to observe starch granules. Atomic force microscope (AFM) and confocal laser scanning microscopy (CLSM) are also utilized to observe the surface and internal structure in detail.

Starch granules in pressure-induced gelatinization are inclined to show a restricted swelling and a lower release of amylose in UHP treatment, differed from heat-induced gelatinization (Stute et al. 1996). This is possibly caused by the absence of shear forces, and no hot paste is formed in UHP treatment (BeMiller and Huber 2015). Another explanation could be that amylose somehow stabilizes the starch granule structure under pressure (Stolt et al. 2001; Douzals et al. 1998).

Corn (300–600 MPa, 30% suspension, 15 min at room temperature) and red adzuki bean (150–600 MPa, 20% suspension, 15 min at 25 °C) starch show a granular maintaining with rough surface followed by complete disintegration (Li et al. 2015, 2016; Stute et al. 1996). Rice starch (120–600 MPa, 20% suspension, 30 min at 25 °C) presents an angular destruction (Li et al. 2011b). Mung bean (120–600 MPa, 20% suspension, 30 min at room temperature), lotus seed (100–600 MPa, 15% suspension, 30 min at room temperature), buckwheat (200–600 MPa, 25% suspension, 10 min at 20 °C), and sorghum starches (200–600 MPa, 25% suspension, 10 min at 20 °C) are inclined to form a doughnut-shaped structure (Fig. 7.2a–c) (Vallons and Arendt 2009a, b; Li et al. 2011a; Guo et al. 2015a).

The inner structure destruction (gel-like network formation) along with maintaining of external structure for potato starch granules during UHP treatment (600 MPa, 10% suspension, 3 min at 20 ± 2 °C) was observed by Błaszczak and his co-workers, indicating the special granular structure of potato starch, which may be related to the characteristic surface organization of potato starch (Fig. 7.2d) (Błaszczak et al. 2005a). The results of Gebhardt and his co-workers obtained by micro small-angle and wide-angle X-ray scattering (SAXS/WAXS) also support this conclusion (Gebhardt et al. 2007). On the basis of AFM results, the number of surface blocklets of rice starch granules increases, and the diameter decreases after treatment at a relatively low pressure (200 MPa, 20% suspension, 30 min at 25 °C). When the pressure reaches 600 MPa, starch granules show totally different structures with more fine and flat surfaces (Deng et al. 2014).

7.3.2 Order and Disorder Structure

As a kind of semicrystalline polymer, the spherocrystal structure of starch induces the polarization cross under polarizing microscope. The crystalline structure is destroyed, and polarization cross disappears, as well as gelatinization enthalpy decreases during common heat gelatinization, indicating an order-disorder transformation. Polarizing microscope (PLM), differential scanning calorimetry (DSC), and X-ray diffraction (XRD) are frequently applied to study on order and disorder structure change of starch after UHP treatment.

Starch crystal exists in four different forms and shows different XRD patterns. In general, cereal starches generate A-type XRD patterns, B-type patterns exist in tuber and high-amylose starches, and legume, root, and some fruit and stem starches show C-type patterns. V-type patterns are also present in high-amylose starch or retrograded starch and are in the form of the amylose single helices co-crystallized with compounds such as iodine, dimethyl sulfoxide (DMSO), alcohols, or fatty

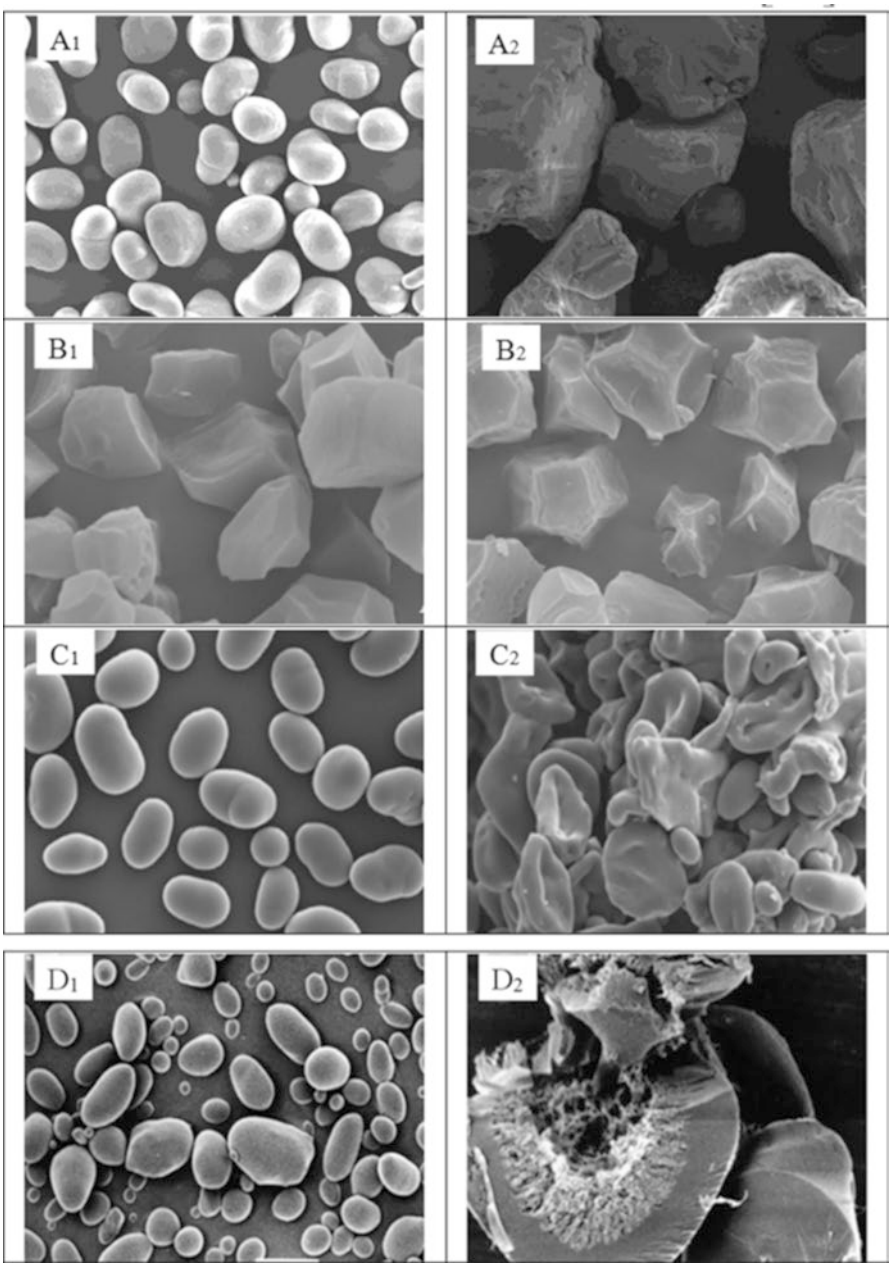

Fig. 7.2 Scanning electron micrographs of typical native ($\mathbf{A_1}$ red adzuki bean starch, $\mathbf{B_1}$ rice starch, $\mathbf{C_1}$ mung bean starch, $\mathbf{D_1}$ potato starch) and UHP-treated starch granules ($\mathbf{A_2}$ 600 MPa, 20% suspension, 15 min at 25 °C; $\mathbf{B_2}$ 480 MPa, 20% suspension, 30 min at room temperature; $\mathbf{C_2}$ 600 MPa, 10% suspension, 30 min at room temperature; $\mathbf{D_2}$ 600 MPa, 10% suspension, 3 min at 20 °C) (Błaszczak et al. 2005a; Li et al. 2011a, b, 2015)

acids (Buléon et al. 1998). Most A-type and C-type starches can be completely gelatinized at 600 MPa except in some rare starches such as taro, wrinkled pea, and babassu starches (5% suspension, 15 min at 20 °C). This pressure cannot induce the gelatinization of starch with B-type pattern (potato starch, 5% suspension, 15 min at 20 °C) (Oh et al. 2008; Stute et al. 1996; Yang et al. 2016; Rubens et al. 1999), suggesting a better pressure resistance of B-type starches. Potato starch can just be gelatinized completely when the pressure reaches 800 MPa at low starch concentration (10–20%, 1 h at 40 °C) and the required pressure to realize complete gelatinization increases with increasing starch concentration (Kawai et al. 2007). A- and C-type patterns could be converted into B-type patterns during UHP treatment, which is attributed to water being introduced into the crystalline packing unit under UHP (Liu et al. 2010). Nevertheless, there are still some exceptions (unchanged), as shown in Table 7.2.

Studies on the lamellar and double helix structure for starch granules after UHP treatment provide further information on the order and disorder structures. The influence of UHP treatment (waxy corn and Hylon VII starches, 650 MPa, 30% suspension, 9 min at 20 °C; rice starch, 20% at 25 °C, 200 MPa, 30 min/200 MPa, 15 + 15 min/600 MPa, 30 min/600 MPa, 15 + 15 min) on C1 and C4 peaks is obvious as determined by using solid-state ^{13}C CP/MAS NMR, indicating the decrease of double helix and the increase of single helix (Deng et al. 2014; Błaszczak et al. 2005b). This is attributed to the unwinding of double helix during UHP treatment. The synchrotron SAXS results illustrated the pressure-induced compression for waxy corn and potato starches. The average thickness of long period (≈9 nm) and amorphous layers decreased with increasing pressure, while the thickness of the crystalline layer first increased and then decreased (Yang et al. 2016). The compression effect is identified as the "shock absorbers" of amorphous layer and acting as a protection for crystalline layer during compressive forces. On the other hand, the initial increase of the thickness of the crystalline layer is likely to indicate the annealing of starch (Yang et al. 2016). Additionally, compared with waxy corn starch, the decrease of long period with pressure (up to 750 MPa) is less for waxy potato starch, indicating the B-type starch (waxy potato starch) is much less compressible compared to A-type starch (waxy corn starch), which is identified to be caused by the different amylopectin structures. These conclusions are benefit to the understanding of the high-pressure resistance of B-type crystal starches (Yang et al. 2016).

7.3.3 Molecular Structure

Błaszczak and his co-workers found that corn amylopectin formed a polydispersed product after UHP treatment (690 MPa, 30% suspension, 3 min at 20 °C), measured by using HPLC, indicating molecular degradation (Błaszczak et al. 2005b). However, it is not valid for high-amylose corn starch (Hylon VII). Guo and his co-workers utilized high-performance size-exclusion chromatography and multiangle laser-light scattering and refractive index detectors (HPSEC–MALLS-RI) to study the influence of UHP (15% suspension, 30 min at room temperature) on

Table 7.2 The effects of ultrahigh pressure (UHP) treatment on of starches

Starch	Pressure (gelatinization pressure)/MPa	Starch content/%	Time/min	PLM Polarization cross	XRD Crystal form	References
A-type						
Maize, waxy maize, tapioca, rice	690	1:1,1:2	5,60	–	A→B	Katopo et al. (2002)
Waxy corn	650	30	3–9	Disappeared (9 min)	Unchanged	Błaszczak et al. (2005b)
Sorghum	200–600 (600)	25	10	Disappeared (500 MPa)	–	Vallons and Arendt (2009a)
Buckwheat	200–600 (600)	25	10	Disappeared (400 MPa)	–	Vallons and Arendt (2009b)
Rice	120–600 (600)	20	30	–	A→B	Li et al. (2011b)
Rice	200, 600	20	30	–	A→B	Deng et al. (2014)
Waxy corn, corn	100–600	40	30	Partially disappeared (600 MPa)	A→B	Yang et al. (2016)
B-type						
Potato, high-amylose maize	690	1:1,1:2	5		Unchanged	Katopo et al. (2002)
B+V-type						
*Hylon VII	650	30	3–9	Unchanged (9 min)	Unchanged	Błaszczak et al. (2005b)
*G50, G80	100–600	40	30	Unchanged (600 MPa)	Unchanged	Yang et al. (2016)
C-type						
Mung bean	120–600 (600)	20	30	–	C→B	Li et al. (2011a)
Lotus seed	100–600 (600)	15	30	–	C→B	Guo et al. (2015a)
Red adzuki bean	150–600 (600)	20	15	Disappeared (600 MPa)	Unchanged	Li et al. (2015)

*Hylon VII is high-amylose (70%) corn starch
G50 and G80 are high-amylose corn starches, containing 50% and 80% amylose, respectively

molecular weight distribution of lotus seed starch and suggested that the *Mw* and *Mn* values decreased with increase of pressure, indicating that lotus seed starch was slightly degraded during UHP treatment and formed molecular chains with a low degree of polymerization (Guo et al. 2015a). More studies in molecular structure of pressure-treated starch need to be carried out.

7.4 The Potential Applications of UHP

The potential application of UHP is necessarily related to the superiority of UHP treatment and modified starch. Generally, UHP treatment can induce starch gelatinization at room temperature, providing a method for the preparation of pregelatinized starch and cold water-swelling (CWS) starch. However, considering the requirement of special equipment and the discontinuous product preparation process, UHP treatment shows no advantages as compared to the thermal process. Nevertheless, application of UHP treatment is feasible in starch-containing high value-added or heat-sensitive system. On the other hand, compared with heat-gelatinized starch, UHP-gelatinized starch shows a diverse interior structure organization and has better granular maintaining. This is very important because many potential applications are based on this characteristic, including preparation of resistant starch (*RS*). Additionally, some reports indicate that UHP-modified starch can be applied in the binding of aroma compounds and textural improvement (Błaszczak et al. 2007; Zhang et al. 2014).

Recently, the utilization of UHP in preparation of chemical modified starch was introduced. Combining chemical modification with UHP technology has been applied in acid hydrolysis (Lee et al. 2006; Choi et al. 2009a), hydroxylpropylation (Chotipratoom et al. 2015), acetylation (Choi et al. 2009b; Colussi et al. 2014; Kim et al. 2010), cationization (Chang et al. 2014), and cross-linking (Hwang et al. 2009; Kim et al. 2012) of starches. The maintenance of granular structures along with the improvement of reaction efficiency by UHP-assisted modification facilitates the industry application, although the structure-properties relationship needs to be further studied.

In general, many factors such as starch source, pressure, temperature, concentration, and holding time can affect the starch properties; therefore, the application of UHP depends on the reasonable selection of these parameters and further illustrating the structure-properties relationship. Investigations on the structural recombination of starch treated at lower pressure (lower than gelatinization pressure) and the performance of dry starch in UHP treatment will be helpful to broaden the application of UHP-treated starch.

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