

Rheological, Pasting, and Textural Properties of Starch



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Abstract Native starch is an important raw material used in the industry. Rheological, pasting, and textural properties of starch are the major functional properties to determine its applications. Key rheological properties of starch include rheology of starch during heating, viscosity of starch paste, and rheological features of starch gel. The pasting properties of starch are commonly quantified by measuring changes in viscosity during the heating and cooling of starch dispersions. The textural characteristics of starch gels have an important role in the classification of sensory and quality of foods. In this this chapter, the rheological, pasting, and textural properties of starch from different botanical sources are compared, and the impacts of other ingredients (sugars, salts and lipids) on the properties are summarized. The relationship of starch functionalities with food quality is also summarized. The information provided will be useful for the applications of starch in the industry.

Keywords Starch · Rheology · Pasting property · Texture · Food quality

1 Introduction

Starch is the main component of many edible plants and widely used in food, material, chemical, and medical industries [1]. Starch occurs naturally as semicrystalline granules with hierarchical structure, which is composed of amylose molecules (mostly unbranched) and amylopectin molecules (highly branched) [2]. The rheological behavior, pasting, and textural properties of starch are the main functional characteristics that determine its application [3, 4], which are largely affected by the structural changes in starch during gelatinization and retrogradation. As a starch suspension is heated to gelatinization temperature, the starch granules absorb water and swell, the amylopectin double helices dissociate, and the amylose molecules

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121

leach out, leading to the formation of a starch paste or gel [5, 6]. Upon cooling, the dissociated starch chains recrystallize gradually into an ordered structure, the viscoelasticity and hardness of starch gel gradually increase [7]. Currently, many methods have been used to characterize the rheological, pasting, and textural properties of starch. The Brabender Viscograph and Rapid Visco Analyser (RVA) have been widely used for the determination of pasting properties of starch [1, 8, 9]. Researchers generally use a dynamic rheometer for studying the rheological behavior of a starch paste or gel [10–13]. The textural characteristics of starch are the main indicators of the sensory and quality of starchy foods, measured by the texture analyzer [14]. Quality and shelf-life of starch-based foods are largely controlled by starch functional characteristics. Therefore, this chapter will summarize the rheological, pasting properties, and texture of starch and their effects on food quality.

2 Rheological Behavior of Starch

Starch shows different deformation and flow characteristics under the action of external forces, which is called the rheological behavior of starch [15]. The elastic or storage modulus (G'), viscous or loss modulus (G''), and loss tangent ($\tan \delta$) are the main parameters that describe the rheological behavior of starch. A $\tan \delta$ value of <1 means a more elastic and solid material, whereas $\tan \delta > 1$ describes a more viscous and liquid material [12]. The rheological properties of starch are related closely to the gelatinization and retrogradation of starch, including the rheological behavior of starch during gelatinization, the rheology of starch paste, and the viscoelasticity of starch gel during and after retrogradation [16].

During gelatinization, the G' value of starch progressively increases with temperature to a maximum (peak G') and then drops with continued heating. Simultaneously, the G'' value of starch shows similar changes. The dynamic rheological behavior of starch during heating is determined by source and structure of the starch. Starch with larger sized granules has higher G' , G'' values and lower $\tan \delta$, as observed with potato, rice, and wheat starches [17, 18]. During heating, the G' and G'' values of starch increase with the increasing amylose content [17, 19, 20]. In other words, waxy starches (composed almost entirely of amylopectin) have generally the lowest G' and G'' values [18]. The rheological behavior of starch during gelatinization is also determined by the lipids and proteins in starch. The peak G' of maize starch occurs at a higher temperature as the protein content of starch increases because the protective effect of proteins on starch granular integrity [21]. The lipids in starch decrease the G' and G'' values during cooking, due to the formation of amylose–lipid complexes, which inhibits the swelling of starch granules [22].

The fluid rheology of starch is of special significance for improving the quality of food [23]. In general, the fluid behavior of starch at steady-state flow is studied after starch gelatinization [24]. Viscosity is an important parameter to characterize the rheological behaviors of starch paste, considering starch is widely used as thickener

in yoghurt, breads, puddings, and other foods. After heating, the viscosity of starch paste shows generally a non-Newtonian fluid behavior that the shear stress fails to increase linearly with increasing shear rate [13]. The Bingham model, power law model, and Herschel–Bulkley model are used to the mathematically model the rheology of starch pastes [25]. Under steady-state shearing, starch pastes formed exhibit decreasing viscosity with increasing shear rate (i.e., shear-thinning behavior) [26], which is caused by shear-induced disruption of the swollen granules and leached starch components orienting themselves in the direction of stirring. The steady-state viscosity of starch pastes increases with increasing starch concentration, whereas it decreases at higher temperature [26, 27].

Upon cooling and storage, starch paste can form a viscoelastic gel. The elastic modulus (G') is an important indicator of gel strength. During retrogradation, the gelation of amylose firstly favors the development of starch gel structure [28], so the G' value of starch gel increases generally with increasing amylose content [29]. Then, the recrystallization of amylopectin is beneficial to the long-term development of gel structure [30]. Almost all non-waxy starches at a concentration of 6–8 wt% can form strong gels after retrogradation [31, 33]. Additives can also affect the viscoelasticity of starch gels. The addition of salt to starch leads to the difference in starch gel structures. The gel strength of starch increased as Na_2SO_4 , MgCl_2 , CaCl_2 , NaCl , and KCl were added into the starch but decreased with the addition of NaI , NaSCN , KI , and KSCN [32]. Fatty acids are conducive to the formation of starch gel [33], whereas sugars decrease the gel strength of starch [34].

3 Pasting Properties of Starch

Under controlled temperature profiles and shear forces, the changes that occur in starch-water systems throughout gelatinization and granule disruption are defined as pasting [35]. The pasting properties of starch can be quantified by measuring the viscosity of starch suspensions during heating and cooling. During heating, the viscosity increases to maximum and then decreases with further heating as a function of the changes in starch granules [36]. During cooling, the viscosity of starch paste increases with time, which is indicative of starch retrogradation [37]. A Rapid Visco Analyser (RVA) is most commonly used in the routine analysis of starch pasting properties. The RVA profiles provide information on pasting temperature (T_p), peak viscosity (PV, ability of granules to swell before rupturing), breakdown (BD, stability of hot paste to shear force), setback (SB, initial retrogradation of starch paste on cooling), and final viscosity (FV) [30].

Pasting properties of starch are determined by the starch structures. Amylopectin is the main component responsible for swelling of starch granules and increases in viscosity during heating, whereas amylose is often intertwined with amylopectin, limiting the swelling of starch granules. Hence, the peak viscosity (PV) of a starch paste decreases with increasing amylose content, such that waxy starches generally display a lower T_p and higher PV than the corresponding non-waxy starch

[38]. Upon cooling, a non-waxy starch has a greater setback (SB) value than its waxy variety, which is due to the amylose primarily favoring the short-term development of starch gel during cooling. Lipids, phosphomonoesters, and other minor components in starch granules have significant effects on the pasting behavior. During heating, amylose–lipid complexes that may have formed can be entangled with amylopectin molecules, inhibiting granule swelling and resulting in the increase of paste temperature (T_p) and the decrease of peak viscosity (PV). Wheat and barley starches showed higher T_p and lower PV than other normal cereal starches. The larger amounts of phospholipids in these two starches bind readily to amylose [39]. However, as the endogenous lipids of wheat starch are removed by sodium dodecyl sulfate, the starch exhibits similar T_p and PV compared with cassava starch and waxy corn starch [40, 41]. In contrast, the potato starch is negatively charged and mutually exclusive between granules as a result of the presence of phosphomonoesters in starch molecules, which can enhance the swelling of starch granules, greatly decrease the T_p , and increase the PV. Additionally, the large granule size of potato starch also contributes to the great increase of PV during cooking.

The presence of food additives such as proteins, lipids, salts, or sugars has also been shown to play a significant role in improving the pasting properties of starch. Addition of proteins generally retards the pasting process of starches, which is due to the competition for water between proteins and starch granules inhibiting the progression of starch gelatinization, leading to the delayed formation of viscosity peak [42]. As mentioned above, the addition of lipids increases the pasting temperature and decreases the viscosity of starch paste due to the formation of amylose–lipid complexes, which impede the swelling of starch granules [32, 43]. Recently, starch–protein–lipid ternary complexes have attracted attention due to interactions among these macronutrients during cooking influencing sensory, texture, and digestibility properties of finished foods. The formed starch–protein–fatty acid ternary complexes show higher viscosities than those of binary complex during the cooling and holding stages due to the emulsifying action of proteins [42, 44]. The addition of sugars such as sucrose, glucose, fructose, maltose, galactose, and lactose can increase the viscosity of starch [45, 46]. During cooking, the salt had the least effect on the pasting properties of almost all starches [40, 47]. However, the cation of salt can shield the negative charge of phosphomonoesters and reduce the charge repulsion, resulting in the formation of a low viscosity of potato starch paste [48].

4 Textural Properties of Starch

Textural properties of starch gels are very important criteria to evaluate the performance of starch in a food system. Upon retrogradation, non-waxy starch pastes transform into a firm gel of tree-dimensional networks, whereas waxy starch pastes form a soft gel consisting of aggregates [49]. In general, stronger starch gels are associated with higher amylose content [50]. Amylose-based networks provide the

elasticity and strength of starch gels against deformation [49], while soft gels containing aggregates show greater penetration, stickiness, and adhesion [30]. Amylose retrogradation determines the initial hardness of a starch gel and the stickiness and digestibility of processed foods [30]. On the other hand, retrogradation of amylopectin determines the long-term development of gel structure and crystallinity of processed starch involving in the staling of bread and cakes [51].

Texture profile analysis (TPA) is the most commonly used to study the textural properties of starch gels and starch-based food systems. In a TPA test, the sample is subjected to twice cyclic processes of exerting and removing compressive force, and five primary characteristics of a gel are obtained: hardness, cohesiveness, adhesiveness, elasticity (also called springiness), and brittleness (also called fracturability) [30]. Moreover, several additional texture characteristics such as gumminess (hardness \times cohesiveness) and chewiness (hardness \times cohesiveness \times springiness) can be derived [30]. Among these texture characteristics, the hardness of starch gels has an important role in the classification of sensory and quality of starch-based foods [14]. In general, the hardness of starch is positively correlated with starch concentration [52]. As mentioned above, due to amylose crystallization (short-term) and amylopectin retrogradation (long-term), the hardness of starch gels increases with time [13]. The hardness of starch gels increases during the initial stage of storage at a constant temperature but then changes only slightly on longer storage [53]. In comparison, freeze-thaw cycle treatment results in hardness developing and remaining more or less the same during the whole process [54]. Under the same conditions, maize, wheat, and potato starches show similar hardness values which are higher compared with that of a tapioca starch gel [52]. This is due to the relatively low amylose content of tapioca starch and the large loss of granular integrity in the gel [55].

In contrast to amylose content, lipid content is negatively correlated with gel hardness. The formation of amylose–lipid complexes reduces the amount of amylose available for network formation [40]. Additives such as sugars are commonly used in starch-based foods in order to optimize the process operation and cause some textural modification [45]. The increased gel hardness in wheat and potato starch in the presence of sucrose, glucose, and glycerol has been reported [45]. This increased gel hardness has been attributed to the formation of a strong amylose gel matrix network via changes of conformational ordering and intermolecular association of amylose chains [45]. Polymeric constituents of food, such as proteins, also affect the textural properties of the starch gel. A mixed gel of oat starch and skim milk powder was harder than mixed gels of oat starch–whey protein concentrate and of oat starch–whey lactalbumin mixed gels [4], which is explained as being due to casein micelles, soluble milk minerals, and lactose in milk providing more junction zones for an intermolecular association of amylose continuous network [45].

5 Relationship with Food Quality

Starch is widely used in many food formulations to improve quality attributes and shelf-life. The two main uses are as thickening and gelling agents which are determined by the rheological, pasting, and textural properties of starch. After heating to above the gelatinization temperature, starch suspensions can develop significant viscosity. The viscosity of the resultant starch paste determines its thickening power of starch for various applications [56]. As thickening agents, starch has been used in soups, gravies, salad dressings, sauces, and toppings. The shear thinning behavior of starch paste is also of practical relevance for many food products, such as processed cheeses, yoghurts, and foods produced by extrusion [5, 57]. After cooling and storage, some starch pastes can form viscoelastic gels. Maize starch gels with different hardness have been classified into the five dietary groups, which provides valuable information on standard criteria and guidelines for diets customized for the elderly [14]. As a gelling agents, starch is extensively used in products like jam, jelly, marmalade, and restructured and low-calorie foods [58].

6 Conclusions

This chapter provides a summary of the rheological, pasting, and textural properties of starch. The relationship of these properties with food quality contributes to an understanding of starch functionality and its applications in the food industry. In complex food systems, the rheological, pasting properties, and texture of starches are influenced by other food components such as proteins, lipids, and salts, which affect the quality and shelf-life of food. Therefore, future work should construct a food model composed of starch and other food components, investigating the effect of the interactions among food constituents on the functionality of starch and the quality of relevant starch-based foods.

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