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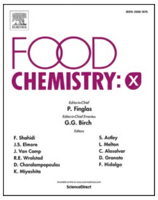

Characterization of the physicochemical, thermal and rheological properties of cashew kernel starch

Nan Chen [a,b], Qing Wang [a], Mu-Xuan Wang [a], Ning-yang Li [c], Annabelle V. Briones [d], L. Cassani [e], M.A. Prieto [e,*], Maricar B. Carandang [d], Chao Liu [a,*], Chun-Mei Gu [b,*], Jin-Yue Sun [a,*]

[a] *Key Laboratory of Novel Food Resources Processing, Ministry of Agriculture and Rural Affairs/Key Laboratory of Agro-Products Processing Technology of Shandong Province/Institute of Agro-Food Science and Technology, Shandong Academy of Agricultural Sciences, 202 Gongye North Road, Jinan 250100, China*
[b] *College of Food Science and Engineering, Jilin Agricultural University, Changchun 130118, China*
[c] *Key Laboratory of Food Processing Technology and Quality Control in Shandong Province, College of Food Science and Engineering, Shandong Agricultural University, Taian, China*
[d] *Industrial Technology Development Institute, Department of Science and Technology, DOST Complex, Gen. Santos Ave., Bicutan, Taguig City 1631, Philippines*
[e] *Nutrition and Bromatology Group, Department of Analytical Chemistry and Food Science, Faculty of Food Science and Technology, University of Vigo-Ourense, Campus, E-32004 Ourense, Spain*

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ABSTRACT

The study aimed to characterize physicochemical, thermal, and rheological properties of cashew nut starch (CNS) and then compare the obtained results with the properties of potato and corn starches. CNS showed higher gelatinization temperatures (112.29 °C) than those noted for potato and maize starches (78.44–94.65 °C). In addition, CNS had higher peak viscosity (19.03 mPa·s) than high amylose corn starch. The static shear rheological test indicated that the CNS followed a pseudoplastic behavior. In addition, CNS sample showed a thixotropic patter, which was less pronounced than that observed for potato starch, but higher than the value reported for high amylose corn starch. These results demonstrated that the shear resistance of CNS was lower than high amylose corn starch, but higher than potato starch. The storage and loss modulus (G' and G", respectively) of the CNS were higher than those reported for the rest of samples. In this line, elastic properties were predominant in CNS sample. In conclusion, results from this study provided insight into physicochemical and structural properties of cashew nut starch, which could represent a preliminary step for its future application in food processing.

Introduction

Starch is the primary source of energy in the human diet, and a natural energy reserve polysaccharide in plants. It is mainly composed of amylose and amylopectin glucans with α 1–4, or α 1–6 linkages, respectively, and may present a diverse branching degree and pattern (Ai & Jane, 2018; Cornejo-Ramírez et al., 2018). It is a biodegradable and resistant material, as well as easily available from widely different and extensively cultivated crops. The mechanistic properties of natural starches will vary depending on the plant source from which it is obtained, differing in terms of morphology, density, amylose/amylopectin composition, crystallization patterns, gelatinization properties, and water holding or rheological properties (Singla et al., 2020). These properties of starch are related to its amylose/amylopectin composition as well as its branching degree, which influences its gelatinization and rheological properties, and consequently, the resulting stiffness and viscosity (Cornejo-Ramírez et al., 2018). Natural starch can also be subjected to physical, chemical or enzymatic alterations to enhance its functional properties. Considering this, the characterization of natural or modified starches is essential to assess its potential application, being gelatinization and rheological properties the most decisive (Ai & Jane, 2015). As one of the main macronutrients, starch affects taste, appearance, processing properties, and also the beneficial health effects of foods. Nevertheless, it also plays a relevant role in industry as an emerging polymeric material, as well as an thickening, gelling, and encapsulation agent, among other industrial purposes (Ai & Jane, 2015; Vodnar et al., 2019). Currently, starches obtained from different vegetal sources are being used in industrial applications. For example, potato

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* Corresponding authors.
E-mail addresses: mprieto@uvigo.es (M.A. Prieto), liuchao555@126.com (C. Liu), jjnong2008@126.com (C.-M. Gu), moon_s731@hotmail.com (J.-Y. Sun).

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starch has been studied for decades and is currently used as a raw material for the development of biodegradable plastic products (Wu et al., 2009). In food industry, corn starch is extensively used as the main starch added in processed foods as thickening agent (Chen et al., 2018). Also, starch-rich matrices can be used as alternative substrates for the production of fermented beverages and foods (Precup et al., 2022; Teleky et al., 2020; Vodnar et al., 2019).

Cashew (*Anacardium occidentale* L.) is native to Brazil and is now extensively grown worldwide. Cashew kernel has a high nutritional value (40–57 % lipid, 23–25 % carbohydrates and 20–25 % high-quality protein) and a unique flavor (Lima et al., 2012; C. Liu et al., 2018; Venkatachalam & Sathe, 2006; J. Yang et al., 2009). Cashew nut has shown to reduce the risk of cardiovascular disease and metabolic syndrome. Nowadays, the research on cashew nut is mainly focused on its kernel's protein and oil. For example, a study determined the molecular and functional properties of albumin, globulin and glutelin obtained from cashew nut protein isolates. This work unveiled that these were the main proteins present in cashew kernels, which showed a valuable essential amino acid composition (>30 %), as well as high hydrophobicity and low solubility (C. Liu et al., 2018). Another recent work studied the effect of microwave preheating extraction method on the chemical composition, oxidative stability, and bioactivity of different grade of cashew kernel oils (de Carvalho et al., 2018). The results showed that this oil held a moderate number of phenolic compounds that enhanced its oxidative stability and low acidity, indicating that it is an oil of high quality. Previous works on cashew nuts are limited and mainly focused on the recovery of polysaccharides from the nut's kernels as a mean to valorize this by-product or gum obtained from the tree as a gelling agent (Pinto et al., 2015). However, to our knowledge, there are no reports assessing the physical and chemical properties of isolated cashew starch, which limits its potential industrial applications, such as the production of bioplastics, its use as an encapsulation agent or as a substrate for fermentative processes. Therefore, the main aim of this paper was to study the physicochemical, thermal and rheological properties of the extracted cashew nut starch (CNS) and compare these results with those of other extensively used starches, high amylose corn starch (HACS) and potato starch (PS) and also defatted cashew nut powder (DCNP). There findings may provide theoretical support to expand the application scope and increase the added value of cashew nuts and starch for further uses in the industry.

Materials and methods

Materials

Cashew nuts were bought from Qingdao Guangrui Food Co., ltd. HACS was ordered from Henan Xinfuwang New Material Technology Co., ltd. PS was ordered from Ningxia Xuechuan Starch Company. All reagents used were of analytical grade (unless otherwise noted) and were obtained from Sinopharm Chemical Reagent Co., ltd. (Suzhou, China).

Isolation and purification of cashew starch

Isolation and purification of cashew kernel starch were carried out according to a previous method (Lawal & Adebowale, 2005) with some modifications. First, the cashew kernels were broken into 3–6 mm particles and were defatted with *n*-hexane for 6 h in beaker. Then, 1000 g of the obtained defatted cashew nut powder (DCNP) was suspended in 4000 mL of distilled water, and the pH was adjusted to 8.0 using NaOH solution (0.2 % w/v) and stirred for 4 h at room temperature. The suspension was centrifuged at 4500 rpm/min, and the supernatant was discarded. The residue was washed with 3500 mL of deionized water and ethanol (85 %) for three times. The supernatant was discarded after centrifugation, and the obtained residue CNS was freeze-dried and stored at low temperature for future use.

Amylose and amylopectin content determination

Amylose and amylopectin content was determined using iodine binding-spectrophotometry according to a previous study (Otegbayo et al., 2014). The amylose content was measured based on the formation of blue inclusion complexes due to the interaction of starch with polyiodide ions, determined at 450–900 nm using a spectrophotometer V-530. Gradient concentrations of amylase and amylopectin standard were used to obtain a linear relationship between concentration of amylase or amylopectin and absorbance. The amylose and amylopectin contents in the four samples were calculated according to the standard curves. The total starch content was calculated as: total starch content (%) = amylose content (%) + amylopectin content (%).

Rheological measurement

Steady and dynamic shear rheology was measured following a previously described method (Guo, 2018). The rheological property of starch was determined using a strain-controlled ARES rheometer (TA Instruments, New Castle, DE, USA). The data were fitted by the power-law model, which is extensively used to describe the flow properties of non-Newtonian fluids in theoretical analysis as well as in practical engineering applications, using the following equation:

$$\tau = K\gamma^n$$

Where τ is the shear stress (Pa), γ is the shear rate (1/s), K is the consistency coefficient (Pa s^n), and n is the flow behavior index (dimensionless) (Ma et al., 2019).

Steady shear rheological properties of starch paste

For this analysis, 2.0 g of starch samples were weighed and thoroughly mixed with deionized water to prepare a 5 % (w/v) suspension (dry weight). The suspension was heated at 90 °C in a thermostatic bath for 30 min to obtain the starch paste. Steady shear mode was performed using flat-plate system at 25 °C (25 mm diameter of the probe (PP25), 1000 μm gap). A rubber scraper was used to wipe off the excess paste, and a thin layer of silicone oil was applied at the edge of the paste to prevent moisture evaporation (Ma et al., 2019). The shear stress of starch samples was measured with the increase of shear rate (0.1 to 1000 s^{-1}) and decrease of shear rate (1000 to 0.1 s^{-1}). The Herschel-Bulkley model was used to fit the data points.

Determination of dynamic viscoelastic properties of starch paste

For this analysis, 2.0 g of starch samples were weighed and mixed with deionized water to obtain a 20 % dry weight starch suspension. The suspension was stirred at room temperature for five min. Dynamic shear mode was conducted using flat-plate system (25 mm diameter, and 1000 μm gap). A rubber scraper was used to wipe off the excess paste, and a thin layer of silicone oil was applied at the edge of the paste to prevent moisture evaporation (Ma et al., 2019).

Temperature scanning analysis: in the linear viscoelastic region of the sample (strain value set at 2 %), at 2 °C/min. The storage modulus (G'), loss modulus (G") and loss angle tangent (tan δ = G"/G') of starch samples were measured during the heating process from low temperature (25 °C) to high temperature (90 °C) and back to low temperature (25 °C).

Frequency scanning analysis: samples were kept at 25 °C for 5 min. G', G") and tan δ were measured from low frequency (0.1 Hz) to high frequency (20 Hz) while temperature and strain were kept constant.

Differential scanning calorimetry (DSC)

Starch gelatinization was measured using a DSC (Q1000 Series, TA instruments, New Castle, Delaware, USA). Starch samples (3.0 mg, dry basis) were mixed with water (10 μL) in aluminum crucibles. After equilibration at 4 °C for 24 h and then at room temperature for 1 h, the crucible was held at 20 °C for 1 min in the DSC furnace (Zhu & Cui, 2020). An empty crucible was used as a reference. The sealed crucibles were heated from 25 °C to 200 °C at 10 °C/min. Onset (To), peak (Tp), conclusion (Tc) temperatures, and enthalpy change (ΔH) were determined.

Pasting property test

Starch was weighed and mixed with 25 mL distilled water. The mixture was stirred for 30 min to obtain starch suspensions with different concentrations (1 %, 2 %, 3 %, w/v). The suspensions were transferred into the aluminum canister of a Rapid Visco Analyzer (RVA, Newport Scientific, NSW, Australia) (Yanjun Zhang et al., 2016). All the pasting experiments were performed using the RVA Standard 1 profile. The samples were equilibrated at 50 °C for 1 min, heated to 95 °C within 220 s, held at 95 °C for 160 s, and then cooled back to 50 °C for 220 s. The paddle speed (rotor radius: 1 cm) was kept at 160 rpm in the process. The pasting curves and parameters were obtained by RVA system software.

Statistical analysis

All measurements were conducted in triplicate. Experimental data were expressed as mean ± standard deviation (SD). Statistical analysis was performed using Statistical Package for Social Science 23.0 (SPSS). Analysis of variance (ANOVA) and Duncan's multirange test were used to determine significant differences ($p < 0.05$).

Results and discussion

3.1 Composition of cashew kernel starch

The ratio of amylose to amylopectin can vary according to different genotypes, soil parameters, and climatic conditions, which usually determine the functional characteristics of starch (Shao et al., 2020). Based on amylose content, starch can be classified as waxy starch (0–5 %), very low-amylose starch (5–12 %), low amylose starch (12–20 %), and high amylose starch (25–>33 %) (Juliano, 1992). Amylose content in CNS was 60.7 %, which is significantly higher than that of registered for PS (19.45 %). Therefore, CNS represents a particularly high-amylose starch source with great potential to be used for the development of novel materials, as amylose-rich starch tends to present a lower branching degree and is more difficult to digest. Considering this, cashew starch could be considered a starch with a low glycemic index (Cano et al., 2014).

3.2 Steady shear rheological property

The flow curves of the starch pastes are presented in Fig. 1. All the four samples showed non-Newtonian fluid behavior, and the shear stress was increased with the increase of shear rate. The parameters of the power-law model used to describe the flow curves are summarized in Table 1. Results showed that experimental data fitted very well with the power-law models as all R^2 values ranged from 0.990 to 0.999. The flow behavior index (n) and consistency coefficient (K) are empirical constants, usually related to the type of starch, starch concentration, and test temperature (Ma et al., 2019). If $n = 1$ the fluid follows a Newtonian behavior, while if $n < 1$ the fluid follows a pseudoplastic pattern (Zimeri & Kokini, 2003). K is related to the concentration of the liquid, and naturally a higher K value implies a higher viscosity. It can be seen from Table 1 that the n values of all studied starches were<1, indicating that the samples showed a pseudoplastic behavior, relating to its higher stiffness. Regarding K values, CNS viscosity was lower than that observed in PS, but higher than HACS. This could be related to its higher amylose content, since higher content in amylose and is consistent with the results obtained for HACS, which served as a rigid starch polymer to stablish comparisons.

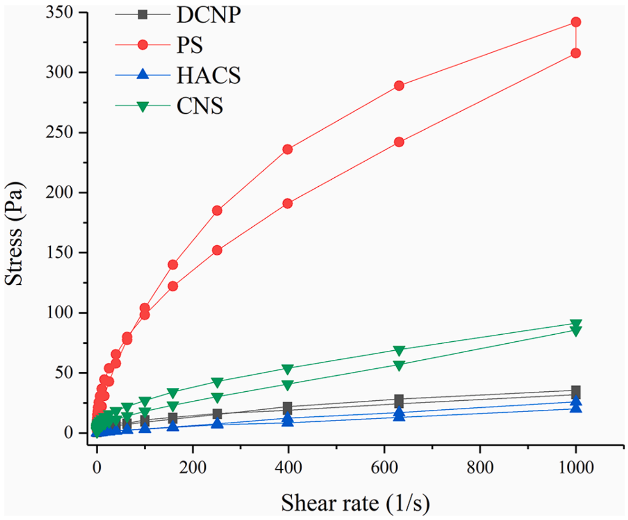

Fig. 1. Changes in shear stress of different starches with shear rate. CNS: cashew nut starch; HACS: high amylose corn starch; PS: potato starch; DCNP: defatted cashew nut powder.

Table 1
Fitting parameters of rheological equation of starch paste.

Sample		CNS	HACS	PS	DCNP
Up	K (Pa·sn)	94.015 ± 0.451^b	2.314 ± 0.031^d	111. 299 ± 0.6^a	17.548 ± 1.277^c
	N	0.588 ± 0.041^b	0.811 ± 0.013^a	0.473 ± 0.028^c	0.624 ± 0.05^b
	R^2	0.998	0.997	0.997	0.998
Down	K (Pa·sn)	48.69 ± 1.139^b	2.2 ± 0.045^d	71.799 ± 0.48^a	9.191 ± 0.693^c
	n	0.747 ± 0.011^b	0.931 ± 0.035^a	0.523 ± 0.002^c	0.718 ± 0.007^b
	R^2	0.996	0.997	0.999	0.996
K_d		0.538 ± 0.023^b	0.245 ± 0.041^d	0.434 ± 0.022^c	0.666 ± 0.028^a

Notes & abbreviations: DCNP, Degreased cashew nut powder; PS, Potato starch; HACS, High amylose corn starch; CNS, Cashew nut starch. Results are means ± standard deviations of triplicate analysis. Values with the different letters in the same column are significantly different ($p < 0.05$).

Thixotropy is one of the essential rheological properties of water-soluble polymer solutions, which affects the taste, softness and overall palatability of food matrices. The thixotropic curves of all samples are shown in Fig. 1. The hysteresis area gives an idea about the degree of thixotropy: the higher the hysteresis area, the greater thixotropic behavior (Ma et al., 2019). In this sense, the greater thixotropic behavior was seen in PS sample, followed by CNS. This indicated that the shear resistance of CNS paste was higher than that of PS. However, both DCNP and HACS displayed the worse thixotropy behavior, being HACS the sample displaying the worst results. The lower thixotropy behavior of HACS compared with PS has been reported previously (Yayuan Zhang et al., 2011). For DCNP, these findings may be due to the presence of other components in the cashew powder, very possibly related to the high levels of protein reported for this type of sample (C. Liu et al., 2018). For shear sensitive samples, which is the case of PS, the two curves do not coincide but form a thixotropic ring, indicating that the sample sensitivity to shear is time-dependent, as reported in previous studies (Sikora et al., 2015). This occurs when the shear rate increases and the starch structure will change accordingly. When the shear rate of starch decreases at a slow pace, its network structure may stand the previous structural destruction rate, but if this happens in a relatively short time, its viscosity curve cannot be restored to its original shape, which results in a closed thixotropic ring is formed. Thus, the shapes obtained for all samples in the graphed results indicate that the material does follow a pseudoplastic behavior.

When starch is subjected to external shear action, its internal structure is destroyed so that the arrangement of macromolecules is reoriented, the flow resistance is reduced, and then the apparent viscosity of starch is reduced. In addition, under the action of external forces, some larger aggregates and solids formed in the system (such as the residual tissue after starch gelatinization) will be also deformed in the direction of shear, following the phenomenon of shear thinning. Intermolecular forces of linear molecular chains in the solution system are weakened, while the intermolecular unwinding can cause an increase of shear-thinning. Shear-thinning behavior is critical in food processing. When the shear rate is low, the high viscosity can prevent the sample from settling or sinking in the tank, at the same time, low density enables the model to form a film and be easy to clean.

3.3 Dynamic rheological properties

Dynamic modulus is a good characterization tool for studying the interaction between the dispersed and continuous phases in some polymeric solutions. Storage energy modulus (G’), also known as elastic modulus, refers to the energy stored in a substance or recovered after a sinusoidal oscillation deformation and stands for the elastic nature of the substance. Loss modulus (G’’), also known as viscous modulus, refers to the energy consumed or lost during sinusoidal deformation of each cycle and represents the viscous nature of matter (Wang et al., 2020). The ratio of energy storage modulus to loss modulus is the tangent of phase shift δ between stress and strain vectors, that is, the tangent of loss angle (Tan δ = G“/G’), which represents the damping capacity of the material.

Fig. 2 (A and B) shows the evolution of G’ and G“ of starch pastes with temperature. Results showed that G’ and G” of CNS sample were stable at the range of 25 °C to 65 °C. As temperature increased up to 75 °C, G’ and G“ achieved a maximum that began to decrease with temperature. During heating, starch particles absorbed water and expanded, so their volume increased. At this time, amylose is exuded from starch particles and then intertwine with starch particles to form a network structure (Rao & Tattiyakul, 1999; Singh & Singh, 2001). The continuous heating process may partially melt the microcrystals and cause the swelling particles to soften again (Singh & Singh, 2001; Wong & Lelievre, 1982; H. Yang & Park, 1998). The decrease in G’,G” may also be caused by the rupture of starch particles that have expanded to an extreme degree and consequently turn more fragile (Tsai et al., 1997).

The maximum G’ value of CNS (5724.53 Pa) indicated that this matrix displays a good viscoelasticity behavior with a higher cross-linking degree. Further heating resulted in prolonged rupture, disintegration, and microcrystalline melting of starch particles, thus showing a reduction in G’ and G”. Consistently with the results described above for other mechanical properties, HACS displayed moderate viscoelasticity up to 70 °C, but still several folds lower than CNS. However, both PS and DCNP, were not reported to have significant viscoelastic dynamics. The results are in agreement with previous studies, which reported a stronger viscoelasticity behavior for HACS samples, compared with PS samples (Yayuan Zhang et al., 2011; Zhou et al., 2015). Fig. 2 (C and D) shows changes in G’ and G“ of starch pastes as temperature decreased. Considering these results paired to those presented in Fig. 3, it is apparent that G’ is generally greater than G”, because G’ and G“ are representative parameters in dynamic rheology (J. Wang et al., 2012). This indicates that starch had elastic and viscous properties at the same time, and elasticity was dominant. Partial chain segments of amylose

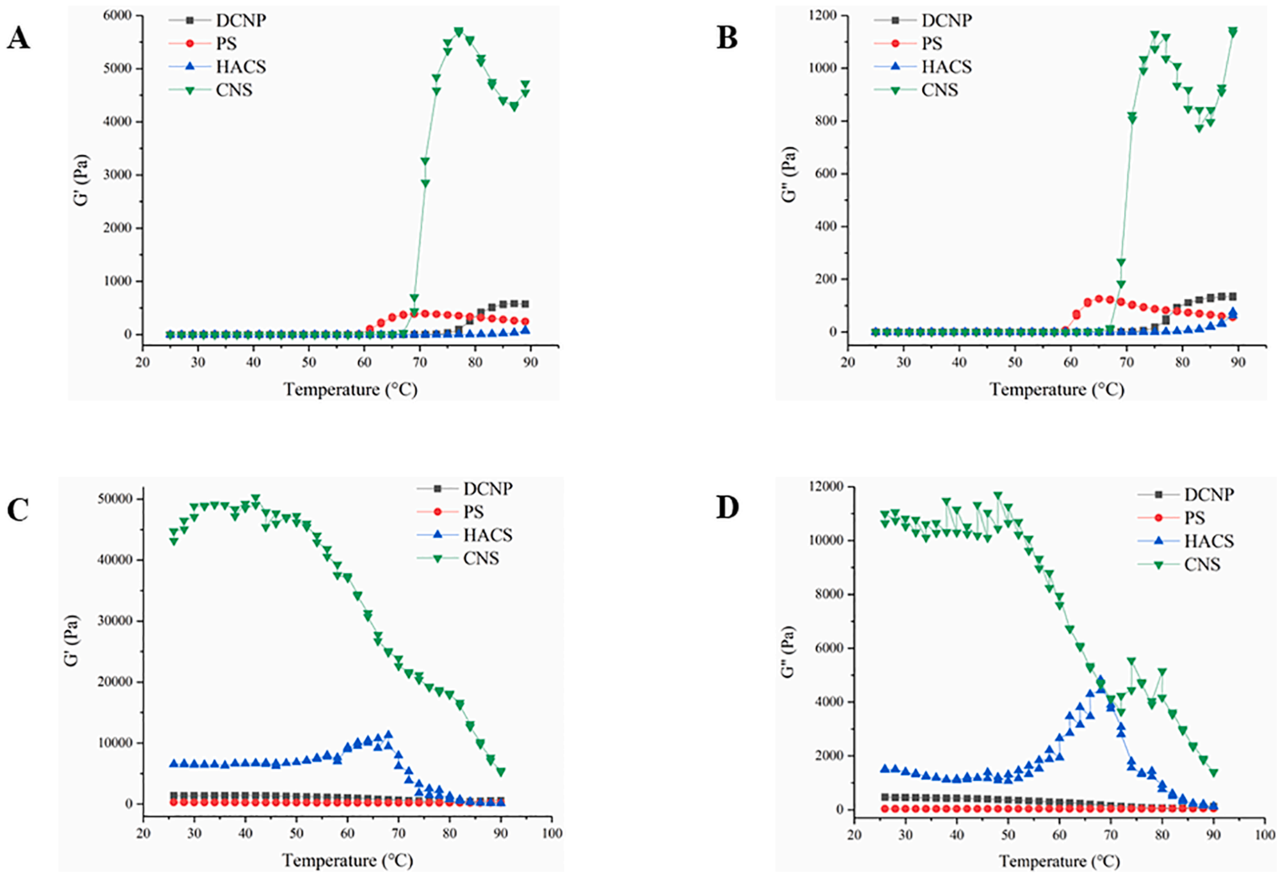

Fig. 2. Effects of different starches on G’ and G“ with increasing (A and B) and decreasing (C and D) temperature. **CNS**: cashew nut starch; **HACS**: high amylose corn starch; **PS**: potato starch; **DCNP**: defatted cashew nut powder.

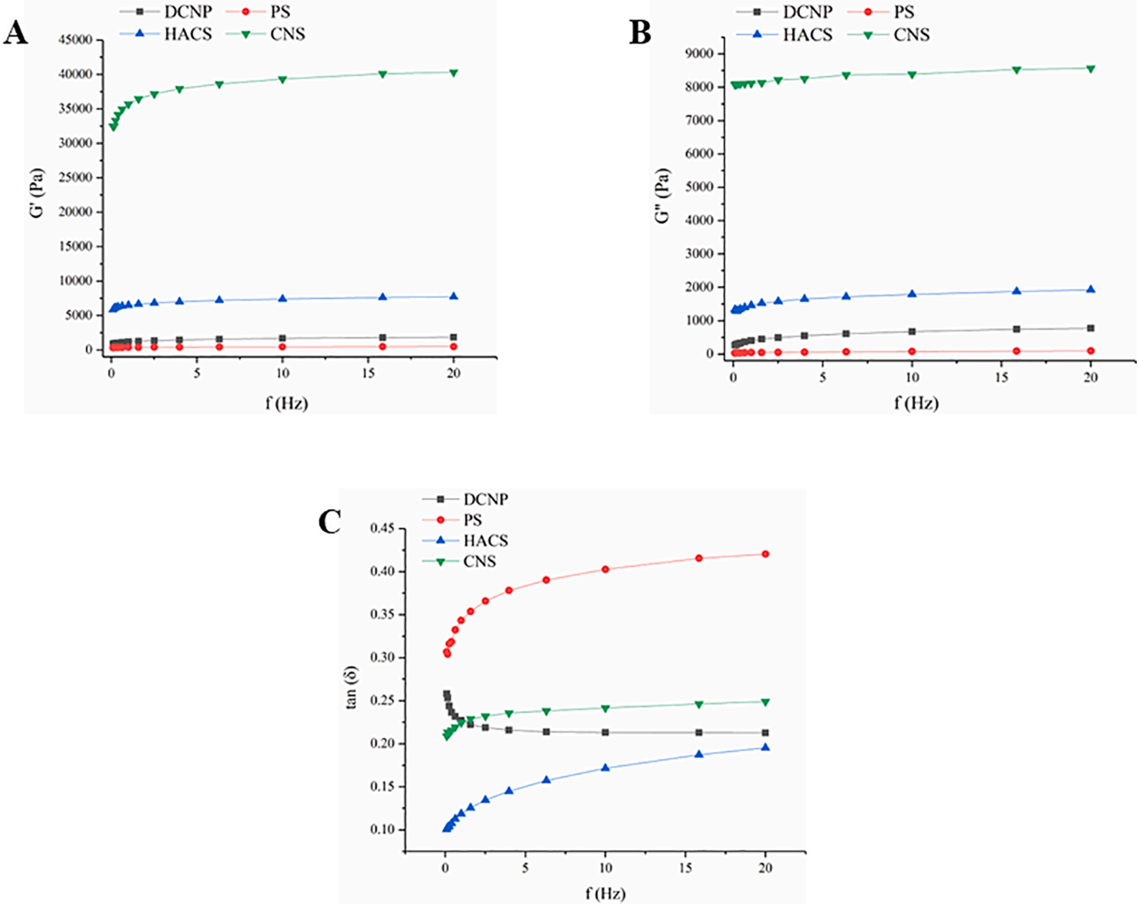

Fig. 3. Effects of different starches on G' (A); G" (B) and tan δ (C) with frequency. **CNS**: cashew nut starch; **HACS**: high amylose corn starch; **PS**: potato starch; **DCNP**: defatted cashew nut powder.

and branch points of amylopectin constitute the amorphous region of starch particles, which indicates the elastic deformation of starch particles.

Over the years, frequency scanning has been widely used to study the characteristics of starch (Du et al., 2002). Fig. 3 displays the evolution of G', G" and tan δ of samples as function of frequency. As can be seen from Fig. 3 A and B both G' and G" of CNS sample gradually increased as frequency raised, indicating an increase in elasticity and viscosity of sample. CNS sample showed the stronger viscoelasticity behavior, indicating that the internal structure of CNS was close, and its energy recovery ability was stronger after being denatured by an external force, followed by HACS and DCNP.

The larger the loss angle tangent value (Tan δ = G"/G') is, the larger the viscosity ratio, and the system behaves like a fluid. Conversely, the smaller the Tan δ is, the system, behaves like a solid. Tan δ of all starch gels was<1 at the lower angular frequency (Fig. 3 C), suggesting that all starch gels showed pseudoplastic behavior. Tan δ was<1 for all the tested samples when frequency was increased up to 20 Hz, indicating that the four starch pastes exhibit typical soft gel dynamic rheological property. In this regard, as expected, PS showed the higher tan δ, while HACS displayed the lowest at all frequencies, as also observed in previous studies (Li & Yeh, 2001; Yayuan Zhang et al., 2011; Zhou et al., 2015). With the increase of scanning frequency, the tan δ of CNS became larger than that observed for HACS and smaller than PS sample, indicating that the elasticity and viscosity of CNS were higher than PS.

3.4 Thermal properties

Higher gelatinization temperature indicates more ordered crystal structure or higher double helix content of starch. A stable double helix contributes to the dense accumulation of amylopectin in the crystal region and improves the thermal stability of starch structure. Results showed that ΔT (T_C-T_O) = 19.57 °C of CNS was the highest among all the four samples, indicating that CNS had the most stable and uniform crystallization zone (Table 2). PS and HAGS showed intermediate values, with a ΔT of 17.77 and 11.11 °C, respectively, which are in agreement with the results of previous authors (Błaszczak et al., 2005; Li & Yeh, 2001; Liu et al., 2006). The gelatinization enthalpy value (ΔH) of CNS was the lowest (178.967 J/g), suggesting that the energy needed to

Table 2
Differential scanning calorimetry values of different starches.

Starch	DCNP	PS	HACS	CNS
To (°C)	112.287 ± 0.18^{a}	86.647 ± 0.206^{d}	97.77 ± 0.171^{b}	92.91 ± 0.61^{c}
Tp (°C)	126.477 ± 0.211^{a}	117.383 ± 0.499^{d}	119.373 ± 0.522^{c}	122.41 ± 0.098^{b}
Tc (°C)	116.123 ± 0.461^{a}	104.417 ± 0.482^{d}	109.213 ± 0.638^{c}	112.82 ± 0.827^{b}
ΔT (°C)	3.837 ± 0.631^{d}	17.77 ± 0.92^{b}	11.11 ± 0.89^{c}	19.573 ± 1.165^{a}
△H (J/g)	208.857 ± 0.703^{b}	183.583 ± 0.45^{c}	247.523 ± 0.82^{a}	178.97 ± 0.487^{d}

Notes & abbreviations: DCNP, Degreased cashew nut powder; PS, Potato starch; HACS, High amylose corn starch; CNS, Cashew nut starch; To, Onset temperature; Tp, Peak temperature; Tc, Conclusion temperature; ΔT, Gelatinization point; ΔH, Enthalpy of gelatinization. Results are means ± standard deviations of triplicate analysis. Values with the different letters in the same column are significantly different ($p < 0.05$).

meet gelatinization point of the CNS grains was lower than that of PS (183.583 J/g). These results about thermal properties are consistent with the determined chemical composition, since DCNP showed a ΔH of 208.857 J/g and a poor ΔT (3.837 °C), indicating a worse crystallization uniformity and a higher need of energy to reach gelatinization, possibly due to the presence of other chemical components besides starch in the cashew sample. However, the polymerization and branching pattern must also play a relevant role besides chemical composition, considering HACS showed the highest ΔH (247.523 J/g) and significantly lower ΔT (11.11 °C) than DCNP or CPS. In this regard CNS could be used as gelling, thickening or stabilizer agent in food industry, due to its suitable thermal parameters.

3.5 Pasting property

Starch pasting property is determined by various factors, including amylose content, granular morphology, architecture and integrity, amylopectin structure, and the composition of non-starch components such as lipids and phosphate groups (Srichuwong & Jane, 2007; Vamadevan & Bertoft, 2015). The pasting curves of starch samples at different concentrations (1 %, 2 %, 3 %, 4 %, respectively) were showed in Table 3. The peak viscosity of CNS (18.4 mPa·s) was lower than PS sample (170.7 mPa·s) but higher than HACS (3.78 mPa·s). The higher the peak viscosity of starch is, the greater of the expansion force is, indicating that the expansion force of CNS was higher than HACS but lower than PS. The falling value of CNS was lower (6.32 mPa·s) than PS (99.333 mPa·s) and higher than HACS (1.318 mPa·s). The lower falling value indicates better thermal stability of starch. In this way, CNS showed better thermal stability than PS. In addition, the final viscosity of CNS was higher (19.033 mPa·s) than HACS (1.318 mPa·s). Paste forming temperature of starch with different concentration is shown in Table 3. The gelatinization temperature of CNS sample was higher than PS (59.893 °C) and HACS (90.253 °C), indicating that the viscosity and gelatinization temperature of CNS (94.65 °C) was relatively higher. These results suggested that the crystallization zone was stable and uniform, and the melting energy was less, which could be interesting for food industry. Thus, CNS could be explored as a new alternative gluten-free ingredient.

Conclusions

The present study aimed to characterize the selected physicochemical, thermal, and rheological properties of cashew nut starches and compared them with the properties of high-amylopectin potato starch and high amylose corn starch as control samples to stablish potentially significant differences between these extensively studied biopolymers and cashew. The data obtained in the present work supplies a scientific basis to consider the development of high value-added functional products and/or polymers using cashew kernel starch as raw material.

The cashew kernel starch held 60.7 % amylose, which makes it a high amylose starch. The initial gelatinization temperature (T_0) and ΔH of CNS sample were 92.91 ± 0.61 °C and 178.97 ± 0.49 J/g, respectively, indicating that the crystallization zone was stable and uniform, and the melting energy was less, which could be interesting for food processing industry, and is consistent with its amylose composition. Results on gelatinization characteristics of cashew kernel starch revealed that the peak viscosity value of starch was 18.40 Pa·s, the final viscosity was 19.03 Pa·s, the gelatinization temperature was 94.65 °C, the falling value was 12.08 Pa·s, and the regression value was 12.71 Pa·s. These results indicate that CNS sample had high expansion force, good stability, large viscosity, high gelatinization temperature, and slow short-term aging rate. Results about static shear rheology showed n index of CNS sample was<1, indicating that it followed a pseudoplastic behavior, and the consistency coefficient was 94.015 Pa·s, suggesting that viscosity was high. Dynamic shear rheology showed that the storage modulus was more significant than the loss modulus, indicating that starch had elastic and viscous properties at the same time, and elasticity was dominant.

Overall, results about the specific physicochemical and structural properties of CNS sample provide clues for further development of CNS in food industry, including its use as thickening, gelling or stabilizing agents.

CRediT authorship contribution statement

Nan Chen: Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation. **Qing Wang:** Writing – review & editing, Visualization, Investigation. **Mu-Xuan Wang:** Visualization, Software, Investigation. **Ning-yang Li:** . **Annabelle V. Briones:** . **L. Cassani:** . **M.A. Prieto:** . **Maricar B. Carandang:** . **Chao Liu:** Visualization, Investigation. **Chun-Mei Gu:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization, Funding acquisition. **Jin-Yue Sun:** Writing – review & editing, Resources, Project administration, Methodology, Conceptualization, Funding acquisition.

Table 3

Pasting parameters of mixed systems of different concentrations of starches.

Samples		PV (mPa·s)	TV (mPa·s)	FV (mPa·s)	BD (mPa·s)	SB (mPa·s)	PT (°C)
DCNP	1 %	2.203 ± 0.091^{hi}	2.203 ± 0.091^{gh}	1.683 ± 0.015^{h}	0.68 ± 0.082^{ij}	0.161 ± 0.01^{g}	74.58 ± 1.103^{f}
	2 %	3.257 ± 0.542^{gh}	3.257 ± 0.542^{f}	2.66 ± 0.079^{h}	0.61 ± 0.2^{ij}	0.28 ± 0.128^{g}	82.94 ± 4.626^{c}
	3 %	5.767 ± 0.105^{f}	5.767 ± 0.105^{e}	4.793 ± 0.17^{g}	1.493 ± 0.124^{hi}	0.52 ± 0.123^{g}	62.617 ± 0.851^{h}
	4 %	8.69 ± 0.199^{e}	6.46 ± 0.07^{e}	7.033 ± 0.055^{f}	2.23 ± 0.262^{gh}	0.573 ± 0.119^{g}	65.91 ± 1.273^{g}
PS	1 %	18.533 ± 0.503^{d}	10.01 ± 0.01^{d}	17.533 ± 0.808^{e}	8.523 ± 0.5^{e}	7.523 ± 0.818^{e}	68.16 ± 0.961^{g}
	2 %	65 ± 1.637^{c}	38.333 ± 1.528^{c}	59.567 ± 1.358^{c}	26.667 ± 1.617^{c}	21.233 ± 1.882^{c}	59.707 ± 0.252^{i}
	3 %	127.133 ± 0.808^{b}	72 ± 1^{b}	119.233 ± 2.479^{b}	55.133 ± 0.231^{b}	47.233 ± 1.595^{b}	59.647 ± 0.116^{i}
	4 %	170.7 ± 1.473^{a}	99.333 ± 1.155^{a}	170.1 ± 0.854^{a}	71.367 ± 0.551^{a}	70.767 ± 0.681^{a}	59.893 ± 0.11^{i}
HACS	1 %	1.44 ± 0.017^{i}	1.13 ± 0.027^{i}	1.363 ± 0.032^{h}	0.31 ± 0.044^{j}	0.232 ± 0.031^{g}	67.62 ± 1.198^{g}
	2 %	1.442 ± 0.014^{i}	1.13 ± 0.01^{i}	1.443 ± 0.015^{h}	0.312 ± 0.014^{j}	0.313 ± 0.016^{g}	76.74 ± 0.37^{ef}
	3 %	3.78 ± 0.223^{g}	1.233 ± 0.006^{hi}	1.473 ± 0.038^{h}	2.547 ± 0.222^{g}	0.24 ± 0.036^{g}	79.87 ± 1.547^{d}
	4 %	1.64 ± 0.026^{i}	1.318 ± 0.016^{hi}	1.318 ± 0.016^{hi}	0.322 ± 0.037^{j}	0.226 ± 0.014^{g}	90.253 ± 1.135^{b}
CNS	1 %	1.947 ± 0.244^{i}	1.29 ± 0.02^{hi}	1.53 ± 0.01^{h}	0.49 ± 0.085^{j}	0.24 ± 0.017^{g}	78.44 ± 0.765^{de}
	2 %	2.547 ± 0.015^{hi}	1.697 ± 0.05^{hi}	2.53 ± 0.01^{h}	0.85 ± 0.044^{ij}	0.833 ± 0.04^{g}	79.837 ± 0.492^{d}
	3 %	6.51 ± 0.301^{f}	2.893 ± 0.076^{fg}	6.3 ± 0.168^{f}	3.617 ± 0.253^{f}	3.407 ± 0.108^{f}	93.113 ± 0.467^{a}
	4 %	18.4 ± 0.872^{d}	6.32 ± 0.22^{e}	19.033 ± 1.168^{d}	12.08 ± 0.676^{d}	12.713 ± 1.04^{d}	94.65 ± 0.386^{a}

Notes & abbreviations: DCNP, Degreased cashew nut powder; PS, Potato starch; HACS, High amylose corn starch; CNS, Cashew nut starch; PV, Peak viscosity; TV, Trough viscosity; FV, Final viscosity; BD, Breakdown viscosity; SB, Setback viscosity; PT, Pasting temperature. Results are means ± standard deviations of triplicate analysis. Values with the different letters in the same column are significantly different ($p < 0.05$).

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: M.A. Prieto reports financial support was provided by Government of Spain. L. Cassani reports financial support was provided by Government of Galicia. Jinyue Sun reports financial support was provided by Shandong University.

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Ethics statement

The research did not include any human subjects and animal experiments.

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