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Physico-chemical, textural and crystallinity properties of oxidized, cross-linked and dual- modified white sorghum starch

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Abstract

The isolated white sorghum *(Sorghum bicolor)* starch was chemically modified employing oxidation, cross-linking, and dual-modification (oxidation followed by cross-linking). The native and modified starches were analyzed for their physicochemical properties such as water binding capacity, paste clarity, swelling power and solubility and textural properties. The starches were also analyzed for thermal properties using differential scanning calorimeter, pasting properties using rapid visco-analyzer and crystallinity properties with the help of X-ray diffractometer. The amylose content of the modified starches was low in comparison to native starch and varied from 4.11 to 22.4%. Oxidation and dual-modification decreased the swelling power but increased the solubility of starch. A significant increase in hardness value of starch pastes was recorded after modification and it varied from 1.28 to 6.9 N. Chemical modification improved the thermal and pasting properties of white sorghum starch. Cross-linked starch showed the lowest value (1244 cp) whereas dual-modified starch showed the highest value (3110 cp) for peak viscosity. The native and modified starches showed 'A' crystallite pattern.

Introduction

Native starches are sometimes not suitable for industrial applications due to their insolubility in cold water, high gelatinization temperature, low freeze- thaw stability and resistance to enzymatic hydrolysis. Therefore, starches are modified chemically, physically and enzymatically to enhance their physicochemical properties and to overcome their application limitations. Chemical modification involves the addition of functional groups on the linear structure of glucose chains of starch molecules, thus improving the stability of starch granules during processing and expanding their utilization in many food applications. Oxidation of starch is an alternative to improve the starch properties and is the most important chemical modification in the starch industry. Oxidized starches are used in the application where adhesion and film formation properties of starch are desired (Sangseethong *et al*., 2010). The oxidized starches are reported to have low viscosity, high clarity, good stability, binding properties and film-forming properties. Oxidation is generally carried out by reacting specified amount of sodium hypochlorite with starch at specific temperature and pH (Wurzburg, 1986). Oxidation causes the depolymerization of granules, resulting in low viscosity and reduced tendency of amylose to retrograde (Rutenberg and Solarek, 1984). Cross-linking is a chemical modification which involves the formation of covalent bonds between the starch molecular chains that strengthens the granules. The main agents used for cross-linking are phosphoryl chloride ($POCl_3$), epichlorohydrin, sodium tripolyphosphate (STPP) and sodium trimetaphosphate (STMP). Hirsch and Kokini (2002) reported an increase in amylopectin content of starch after cross-linking resulting in more stable starch paste suitable for frozen foods. Cross-linked starches are more resistant to heat, acid, and shearing than their native parent starches and can be used in canned food (Mirmoghtadaie *et al*., 2009).

White sorghum *(Sorghum bicolor)* is an underutilized cereal crop that could serve as an alternative source of starch. Sorghum grain contains 68-75% starch depending on the climatic conditions and cultivar (Subramanian *et al.*, 1994). Sorghum is free from gluten which makes it useful for a person suffering from celiac disease. Sorghum starch has been reported to have functional properties comparable to that of corn starch (Perez *et al.*, 1997). Nowadays, corn and tapioca are the major starch sources in starch-based industries. However,

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sorghum is more economical than corn and tapioca; can be cultivated with minimum inputs and therefore, it can be utilized as alternate starch source for many industrial applications. The present investigation was undertaken with a view to study the effect of chemical modifications (oxidation, cross-linking, and dual-modification) on physicochemical, thermal, pasting and crystallinity properties of white sorghum starch to have an assessment of its applications in a variety of novel products.

Materials and Methods

Starch isolation

The starch was isolated using the procedure of Olayinka *et al*. (2013) with slight modifications. The cleaned grains were suspended in distilled water (1:5), pH was adjusted to 8.0 using NaOH solution (0.2% w/v) and steeped at room temperature for overnight. The steeped grains were washed to the neutralized pH, ground using distilled water, and filtered. The residue was rinsed with distilled water and discarded. The filtrate was centrifuged at 1,400 × g for 10 mins and the top layer (grey colored) was removed. The sample was washed, centrifuged (three-four times) until the top layer became white and dried at 40°C for 24 hr.

Starch oxidation

Oxidized starch was prepared using the method of Forssell *et al*. (1995) by adding 10 g of NaOCl (0.8 g of active chlorine/100 g of starch resulting in 0.8% active chlorine, w/w) drop-wise to the starch slurry (100 g starch in 200 ml water) while maintaining pH 9.0, with constant stirring. After an interval of 10 mins, the pH was adjusted to 7.0 and the oxidized starch was filtered, washed (four times), and dried at 45°C.

Carbonyl and carboxyl contents

The carbonyl content was determined using the procedure of Smith (1967). The carboxyl content of oxidized starch was estimated using the method of Chattopadhyay *et al.* (1997).

Cross-linking of starch

Cross-linked starch was prepared by adding the mixture of STMP and STPP (99/1% w/w, 2 g) in the starch slurry (50 g starch in 100 ml water) that had been adjusted to pH 11 with 1N NaOH, and stirred for 3 hr at 45°C (Chung *et al.*, 2008). The starch slurry was neutralized by adding 1 N HCl. The treated starch was then washed with distilled water 3 times (300ml each times) and then dried at 40°C for overnight in a convection oven. The powdered starch was sieved through 240 mm mesh screen and kept in air tight container.

The degree of cross-linking was calculated using the method of Kaur *et al*. (2006).

Oxidized cross-linked starch (Dual-modified starch)

Oxidized cross-linked starch was prepared by oxidation (Forssell *et al.*, 1995) followed by cross-linking (Chung *et al*., 2008) of starch.

Chemical composition of starch

Moisture, ash, fat, and protein content of white sorghum starch were analyzed using the standard AACC methods (2000). The amylose content was determined according to the procedure of Williams *et al*. (1970).

Water binding capacity

The water binding capacity of starches was determined using the method of Yousif *et al*. (2012). The starch suspension was prepared by dissolving 1 g of starch in 15 ml distilled water, agitated for 2 mins and centrifuged at 1250 × *g* for 20 mins. The supernatant was decanted and wet starch was weighed. The amount of water (%) absorbed by the sample was reported as water binding capacity.

Swelling power and solubility

The swelling power and solubility of starches were determined using the method of Waliszewski *et al.* (2003). Starch sample (1.0 g) was accurately weighed and transferred into clean dried centrifuged tubes and weighed (W1). The sample was then dispersed in 10 ml of distilled water, heated for 30 mins over a temperatures range of 50 to 90°C. The mixture was cooled to room temperature and centrifuged for 15 mins at 3000 × *g*. The residue was weighed (W_2) for the calculation of swelling power. Aliquots of the supernatant were dried to a constant weight at 110°C and the remnants obtained after drying the supernatant represented the amount of starch solubilized in water. The swelling power was calculated using the following formula:

$$\text{Swelling power} = W_2\text{-}W_1 \text{ / Weight of starch}$$

Paste clarity

The method of Perera and Hoover (1999) was used for determination of paste clarity. The starch suspension (1%) was gelatinized in a boiling water bath with constant stirring for 1 hr. The gelatinized starch solution was cooled to room temperature and percent transmittance (%T) was measured at 650 nm.

The samples were then stored at 4°C and %T was measured after every 24 hr for 5 days.

Textural properties

Starch gels prepared from native and modified starches were analyzed for their textural properties using TA/XT Plus equipment (Stable Microsystems, Surrey, England). The starch gels were prepared by heating the starch suspension (6%) to 95°C for 15 mins and then cooled to 50°C.The gels were allowed to stand for 15 mins at this temperature, cooled to room temperature and stored at 4°C for 24 hr. The texture of starch gels was measured by penetrating a cylindrical probe (P/25-diameter) up to 10mm in gel samples.

Thermal properties

Thermal properties of native and modified starches were measured using a differential scanning calorimeter (DSC-821, Mettler Toledo, Switzerland) as described earlier by Yadav *et al.* (2013). Thermal properties of samples were reported as onset temperature (T_o), peak temperature (T_p) and conclusion temperature (T_c). Peak height index (PHI) and gelatinization range (R) were also computed from observed data.

Pasting properties

Pasting properties of native and modified starches were measured with the help of rapid visco-analyzer (RVA Starch Master TM, Newport Scientific, Warriewood, Australia). Test profile STD1 (Newport Scientific Method1, Version 5, 1997) was used for determination of pasting characteristics. The sample (3.0 g) was dispersed in water (25.0 ml) and stirred in an RVA container initially at 960 rpm for 10s and finally at 160rpm for the remaining test. The temperature profile was started from 50°C for 1 mins followed by ramping the temperature linearly to 95°C in 3 mins and 42 s, holding for 2 mins, and 30s, cooling the system to 50°C in 3 mins and 48s and ending the process in 13 mins.

X-ray diffraction studies

The X-ray diffraction measurements were carried out by an X-ray diffractometer (Rikagu ultima IV) using a copper anode X-ray tube (Cu-Kα radiation). Each sample was exposed to the X-ray beam at a voltage of 45 kV and current of 40 mA. The diffraction angle ranged from 2ɵ = 5 to 50 with a count time of 1.0 s, and the rotary speed of the sample holder was 30 min^{-1}.

$$\text{Crystallinity (\%)} = A_c / (A_c + A_m) \times 100$$

Where, A_c - crystalline area

A_m - amorphous area

Statistical analysis

All observations were taken in triplicate. Three independent replicates (n = 3) were obtained from each treatment and the results were reported as means ± standard deviation (SD). Analysis of variance was performed by one and two way ANOVA analysis (SPSS 19.0) followed by Tukey's HSD post hoc comparison test at $p<0.05$.

Results and Discussion

Chemical composition

The white sorghum starch was analyzed for its chemical composition. The protein content of native starch was 2.32%. The native white sorghum starch showed low fat (1.52%) and ash content (0.41%). This indicated that the extracted starch had high purity and was suitable for further analysis. The results were similar to those reported by Olayinka *et al*. (2013) for white sorghum starch. The native white sorghum starch showed the moisture content of 8.77% and this low value was beneficial in terms of the shelf life of the starches. However, the value for moisture content was lower than the value reported by Olayinka *et al.* (2013) for native white sorghum starch (10.3%). The yield of starch was 65%, which was similar to as reported by Elevina et al. (1997). The amylose content of native, oxidized, cross-linked and oxidized cross-linked sorghum starch was observed to be 22.4, 15.1, 11.3 and 4.10% respectively. A reduction in amylose content of oxidized starch, cross-linked starch, and dual-modified starch was observed in comparison to native starch. The similar reduction in amylose content was reported earlier for oxidized starch of Bambara groundnut (Adebowale *et al*., 2002). The reduction of amylose during oxidation might be due to the reason that it readily reacted with NaOCl. The linear structure of amylose makes it more susceptible to oxidative degradation. In the case of cross-linked starch, increased substitution of the functional group transforms the starch to a highly cross-linked form, which may be the reason for the reduction in amylose content.

Degree of modification of starch

The degree of modification in oxidized starch is measured by the concentration of carboxyl groups. The carbonyl and carboxyl content of oxidized sorghum starch were observed to be 0.07 and 0.26% respectively. Starch molecules are first oxidized to carbonyl groups and then to carboxyl groups

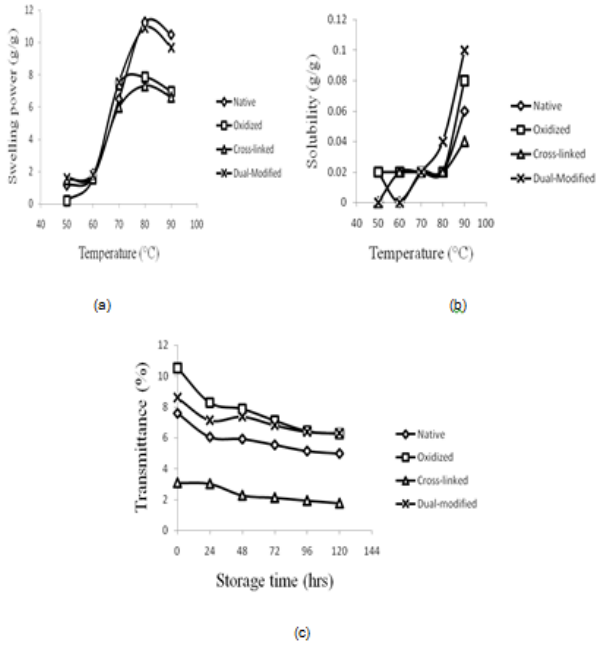

Figure 1. (a) Swelling power (b) solubility and (c) light transmittance of native and modified white sorghum starches as affected by temperature

(Kuakpetoon and Wang, 2006). The major functional group produced during oxidation was carboxyl whereas the carbonyl group was formed in the minor amount. It was reported that oxidation of starch using hypochlorite under alkaline conditions favored the formation of carboxyl groups (Wurzburg, 1986). Vanier *et al.* (2012) characterized bean starches oxidized with different levels of NaOCl and observed an increase in the carboxyl content with increase in concentration of active chlorine. The degree of cross-linking of cross-linked sorghum starch was observed to be 56.18% that is very high due to increase in the concentration of phosphate salts. STMP/STPP increases the degree of cross-linking. The cross-linked starch granules showed a high number of cross-links of amylose chains. A similar result was reported by Koo *et al.* (2010).

Water binding capacity

The physicochemical properties of starch perform an important role in the preparation of various products. Water binding capacity (WBC) describes the association of a product with water under conditions where water is limiting. WBC of oxidized (62.72%) and dual modified starches (67.73%) was observed to be lower than native starch (75.30%). The low WBC of starches might be due to reduction of amorphous regions in the starch granules resulting in decrease of number of available binding sites for water (Lawal, 2004). Wootton and Bamunuarachchi (1978) also observed reduction in WBC of chemically modified starches. They reported that the reduction in WBC of chemically modified starches might be due to blocking of water binding sites on the starch molecules. Cross-linked starch showed significantly higher WBC (95.02%) compared to native starch. The increase in WBC might be due to the leaching of amylose and loss of crystalline structure (Gunaratne and Hoover, 2002).

Swelling power and solubility

The swelling power and solubility of native and chemically modified starches were assessed over a temperature range of 50 - 90˚C at 10˚C intervals (Figure 1a and 1b). The results indicated that swelling power and solubility of all the starch samples increased with increase in temperature. The maximum increase in swelling power was observed between the temperature ranges of 80-90°C. A significant reduction in swelling power of oxidized starch was observed. The oxidation resulted in the structural disintegration of starch granules and thus, decreased the swelling power (Lawal, 2004). A decrease in swelling power of cross-linked starch was observed over native starch due to the bridging of intermolecular bonds by phosphorous residual after cross-linking (Chung *et al*., 2004). Jyothi *et al*. (2006) also observed a decrease in swelling power with an increase in the degree of cross-linking of cassava starch. A similar decrease in swelling behavior was also observed in the case of dual-modified starch in comparison with native starch. The degree of cross-linking of dual modified starch could be higher than cross-linked starch and thus, resulted in reduced swelling power. Cross-linked starch showed lower solubility than native starch because cross-links provided the strength to the structure of starch granules and prevented them from leaching out, thus resulted in low solubility. However, the solubility of oxidized and dual-modified starch was higher than native starch which might be due to the weakening of the structure of starch granules and de-polymerization, thereby increasing the leaching of amylose from the starch granules. Similarly, an increase in temperature resulted in leaching of a higher amount of amylose from the starch, as granules gelatinized more at the higher temperature. The solubility of oxidized starch was initially same as that of native starch but at higher temperatures, it increased significantly than native starch. A similar result for solubility of oxidized starch has been reported by earlier researchers (Adebowale *et al*., 2002; Xiao *et al*., 2012).

Paste clarity

The effect of refrigerated storage on the paste

Table 1. Textural properties of native and modified white sorghum starches

Treatments	Hardness (N)	Adhesiveness (N sec.)	Springiness	Cohesiveness	Gumminess	Chewiness	Resilience
Native	1.28±0.02^{a}	1.30±0.56^{b}	0.68±0.03^{c}	0.37±0.02^{b}	647.80±12.3^{c}	437.80±5.23^{c}	0.12±0.01^{a}
Oxidized	5.37±0.05^{c}	1.74±0.02^{c}	0.43±0.02^{a}	0.25±0.01^{a}	134.30±5.21^{a}	57.20±2.23^{a}	0.13±0.01^{a}
Cross-linked	6.90±0.85^{d}	1.27±0.36^{b}	0.63±0.01^{b}	0.37±0.01^{b}	323.00±9.36^{b}	202.30±5.32^{b}	0.14±0.01^{a}
Dual-modified	4.92±0.54^{b}	0.65±0.01^{a}	0.99±0.05^{d}	0.47±0.03^{c}	771.80±6.58^{d}	762.20±10.2^{d}	0.25±0.02^{b}

The values are expressed as the mean ± SD of three independent determinations
The values in a same column having similar superscripts do not differ significantly ($p \leq 0.05$)

Table 2. Thermal properties of native and modified white sorghum starches

Treatments	T_o(°C)	T_p(°C)	T_c(°C)	ΔH_{gel}(J/g)	PHI	R
Native	70.04±1.12^{b}	73.91±1.14^{ab}	80.0±1.23^{a}	2.61±0.23	0.80±0.01^{a}	9.36
Oxidized	69.87±0.89^{b}	72.80±1.23^{a}	80.0±0.65^{a}	2.68±0.05	0.92±0.03^{a}	10.13
Cross-linkec	71.05±1.15^{b}	74.07±0.69^{b}	92.1±2.23^{b}	6.09±0.12	2.02±0.24^{c}	21.00
Dual-modifie	69.38±1.10^{a}	73.22±0.78^{ab}	95.0±1.52^{c}	6.08±0.25	1.58±0.51^{b}	26.62

T_o.= Onset temperature; T_p = Peak temperature; T_c = Conclusion temperature; ΔH_{gel} = Enthalpy of gelatinization; PHI = Peak height index; R =gelatinization range
The values are expressed as the mean ± SD of three independent determinations
The values in a same column having similar superscripts do not differ significantly ($p \leq 0.05$)

clarity of native and modified starches is presented in Figure 1c. The transmittance (%) from starch pastes of oxidized and dual-modified starch was observed to be higher than that of native starch. The oxidized sorghum starch showed the highest percent transmittance. The introduction of carbonyl and carboxyl groups combined with disintegration of structure within the starch granules of oxidized and dual-modified starch increased the light transmittance (%) or paste clarity. Ali and Hasnain (2014) also reported an increase in percent transmittance in oxidized white sorghum starch. The increase in percent transmittance may be attributed to greater stability of starch structure in modified starches due to formation of inter and intra molecular bonding. However, cross-linking provided the strength to the swollen starch granules and thus, resulted in reduced transmittance of cross-linked starch as compared to native starch. The paste clarity of native and modified starches decreased during refrigerated storage and it might be due to molecular realignment of solubilized starch chains.

Textural properties

The textural properties of gels made from native and modified starches are shown in Table 1. Dual-modified starch exhibited the highest gumminess, springiness, cohesiveness, resilience and chewiness whereas cross-linked starch gel revealed the highest value of hardness. A similar pattern of texture profile analysis was observed in the case of rice starch (Liu *et al.*, 1999). Oxidized, cross-linked and dual-modified starch pastes showed greater hardness than native starch. The increase in hardness of oxidized starch gel is due to reassociation of the de-polymerized fragments. Similar observations have been reported in the case of oxidized potato starch (Khan *et al.*, 2011). The differences in the textural characteristics of starch pastes are mainly affected by the changes in the rheological properties of starch, the rigidity of starch granules and due to the interactions between the continuous and dispersed phases of the paste. The starches having higher swelling power also had a higher tendency to deformation, which influences the rigidity of the starch paste (Zhou *et al.*, 1998).

Thermal properties

Gelatinization involves irreversible changes that occur when starch granules are heated in presence of water. The gelatinization properties of native and modified starches are shown in Table 2. The oxidized starch had lower onset temperature (T_o= 69.87°C) and peak temperature (T_p=72.8°C) than the native white sorghum starch, which indicated that the oxidized starch had a higher capacity to hydrate and gelatinize (Table 1). Sangseethong *et al.* (2010) reported that after oxidation, the introduction of negatively charged carboxyl groups resulted in greater hydration and gelatinization at a lower temperature. The dual-modified starch also showed lower value for T_o (69.38°C) and T_p (73.22°C) than native starch. Cross-linked starch had higher To and Tp than native, oxidized and dual-modified starches. Cross-linking provided the formation of intra and inter-molecular bonds within the starch granules that strengthened and stabilized the granules (Acquarone and Rao, 2003). The similar results were reported by Choi and Kerr (2004) for cross-linked wheat starch. The enthalpy of gelatinization (ΔH) of oxidized starch remained unchanged. These observations were similar to the results reported by Vanier *et al*. (2012). The cross-linked and dual-modified sorghum starch had a higher value for ΔH than the native starch. The changes in ΔH might be due to the differences in bonding forces within the starch granules.

Pasting properties

The pasting properties of starch are an important parameter to determine the applications of starch in the food products. The data pertaining to

Table 3. Pasting properties of native and modified white sorghum starches

Treatments	$P_{Temp.}$ (°C)	PV (cP)	HPV (cP)	BD(cP)	CPV (cP)	SB(cP)	P_{Time} (Min)
Native	79.1± 1.45 ^{b}	2839± 14.20^{b}	1671± 8.10 ^{c}	1168±10.21 ^{b}	2843± 15.12^{c}	1172± 10.23 ^{c}	5.7±0.23 ^{c}
Oxidized	78.4± 1.25^{ab}	3042± 21.14^{c}	1322± 12.21^{b}	1720± 11.34 ^{c}	2204± 14.23 ^{b}	882± 5.21 ^{b}	4.0±0.12 ^{a}
Cross-linked	87.2± 2.23^{c}	1244± 11.31^{a}	1059± 9.12 ^{a}	185± 2.25 ^{a}	1077± 17.45 ^{a}	18± 0.9.41 ^{a}	6.5±0.51 ^{d}
Dual-modified	76.8± 1.50 ^{a}	3110± 15.42^{d}	1954± 11.34 ^{d}	1156± 6.50 ^{b}	3114± 16.63^{d}	1160± 5.73 ^{c}	4.7±0.36 ^{b}

$P_{Temp.}$= Pasting temperature; PV = Peak viscosity; HPV =Hot paste viscosity; BD = Breakdown; CPV = Cool paste viscosity; SB = Setback; P_{Time} = Pasting time

The values are expressed as the mean ± SD of three independent determinations

The values in a same column having similar superscripts do not differ significantly ($p \leq 0.05$)

pasting properties of native and modified starches is presented in Table 3 and Figure 2a depicts the pasting profiles of the starches. The value of pasting temperature varied from 76.8 to 87.2°C. A reduction in pasting temperature was observed after oxidation and dual-modification of white sorghum starch. This might be due to the incorporation of bulky functional groups that interfered with the binding forces within the starch molecules and thus weakened the starch granule. However, the pasting temperature of the cross-linked starch was higher (87.2°C) than the native starch (79.1°C). The cross-linking of the molecular chains strengthens the starch granules and therefore, more energy would be required. Detduangchan *et al.* (2014) also reported similar findings for cross-linked rice starch. The pasting time reduced after oxidation and dual-modification helping easy passage of water into starch granules which resulted in decrease peak viscosity. The cross-linked starch showed the lowest value (1244 cp) whereas dual-modified starch showed highest value (3110 cp) for peak viscosity. The reduction in peak viscosity of cross-linked starch might be due to the presence of the cross-linking groups which may have interfered with the association of starch molecules with water. The oxidation of starch led to increased peak viscosity (3042 cp). The increase in peak viscosity after oxidation would result from the presence of carbonyl and carboxyl groups which improve the integrity of starch. Guerra-Della *et al.* (2008) also found an increase in PV of oxidized starch. Hot paste viscosity varied from 1059 to 1954 cp, lowest for cross-linked and highest for dual-modified white sorghum starch. Ali and Hasnain (2013) also observed a reduction in HPV after chemical modification of white sorghum starch. The oxidized and cross-linked starches showed lower value whereas dual-modified starch showed a higher value for cold paste viscosity as compared to native starch. The presence of functional groups in oxidized and cross-linked starches reduces the tendency of reassociation of starch polymers. The decrease in setback viscosity of the chemically modified starches suggested that oxidation, cross-linking and dual- modification reduced the tendency

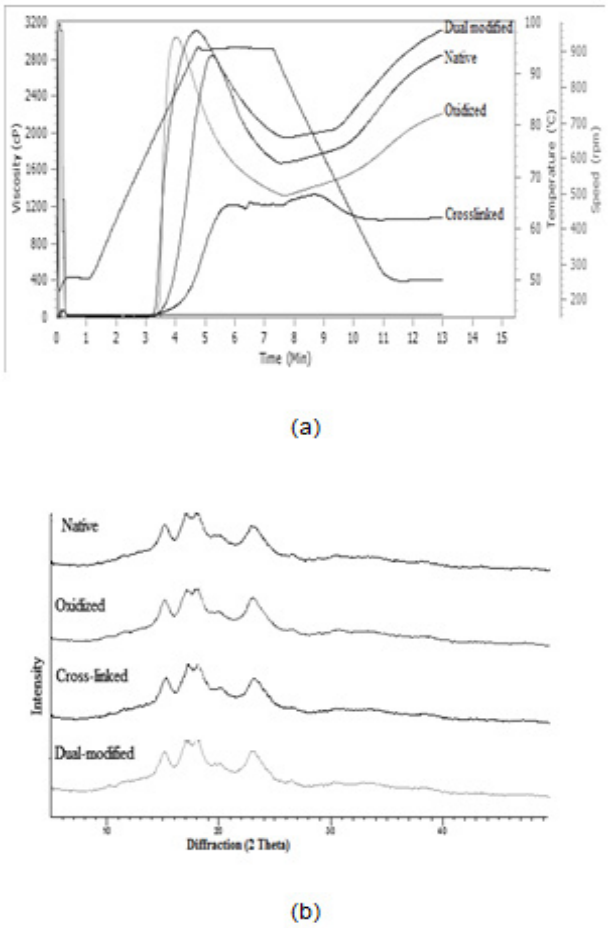

Figure 2. (a) Viscosity profiles (b) X-ray diffractograms of native and modified White sorghum starches

of starch to retrograde. Oxidation increased the breakdown viscosity of starch compared to native starch. Adebowale and Lawal (2003) also reported an increase in breakdown viscosity of oxidized starch.

X-ray diffraction studies

The X-ray diffractograms of the native and modified starches are shown in Figure 2b. All starches showed A-type diffraction pattern. The major diffraction peaks of native starch were reported at 2ɵ = 14.9, 17.2 and 22.9 and weak diffraction at 2ɵ = 11.4 and 26.7. The modified starches had their stronger peaks at 2ɵ = 15.2, 17.2 and 23.0 and weak diffraction peaks at 11.2 and 26.7 (Table 2). The results are in agreement with the results reported by

Xiao *et al.* (2012) that A-type pattern is characterized by a well-defined peak at 16.9-17.5 (2ɵ). The increase in % crystallinity of all modified starches was observed in comparison to native starch. Percent crystallinity of oxidized (22.11%), cross-linked (29.76%) and dual modified starches (16.52%) was observed to be higher than native white sorghum starch (13.43%). A similar increase in crystallinity of corn starch was observed after oxidation with 0.8% sodium hypochlorite (Kuakpetoon and Wang, 2006). The introduction of functional group after chemical modification was mainly found in the amorphous region of starch granule with the degradation of starch molecules, which might have increased the relative crystallinity of starch.

Conclusion

Chemical modification significantly affected the amylose content of the starch. Cross-linked white sorghum starch showed the highest value for gelatinization temperature whereas oxidized starch showed lowest value for onset and peak temperature. Therefore, the oxidized starch had a greater capacity to hydrate and gelatinize and it can be used in applications where low gelatinization property is required. The oxidation and dual-modification also improved the paste clarity of white sorghum starch. The decreased setback viscosity after chemical modification presented the reduced tendency of the starch to retrograde. Relative crystallinity of modified starches was reported higher than native starch. The study concluded that employing chemical modifications including cross-linking, oxidation and dual-modification, the functional properties of white sorghum starch having implications in starch-based food formulations, can be altered desirably for specific food applications.

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