

Elucidating the impact of dual modification with hydroxypropylation and enzymatic hydrolysis on physicochemical properties of corn and sago starch

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Abstract

Enzymatic hydrolysis is one of the most commonly used techniques in starch modification. However, the performance of enzymatic hydrolysis has been restricted by the inherent properties of native starch. In this study, hydroxypropylation with two different concentration levels of propylene oxide (10% and 20%) was carried out on corn and sago starches. The effect of hydroxypropylation on the physico-chemical properties of the enzyme-hydrolyzed starch was investigated. The results showed that the starches treated with 20% propylene oxide had higher molar substitution and dextrose equivalent with greater effects. Scanning electron microscope (SEM) revealed that hydroxypropylation had developed pores and pits on the granular surfaces and subsequently enhanced enzyme penetration. Hydroxypropylation showed no changes in the crystalline pattern, yet a decrease in the amylose content of both corn and sago starches, respectively. Other than that, hydroxypropylation decreased the pasting properties and retrogradation tendency but increased the swelling power of enzyme-hydrolyzed starch significantly. Overall, this work suggested that hydroxypropylation pre-treatment could improve the efficiency of subsequent enzyme hydrolysis and produce modified starch with great potential in food processing applications.

1. Introduction

Starch is a polysaccharide that can be easily obtained from various botanical sources, abundant, inexpensive, biodegradable, non-toxic, and widely used as a thickener, gelling agent, stabilizer for salad dressing, canned food, and baked goods (BeMiller and Whistler, 2009). It consists of two structures namely amylose and amylopectin, which provide a basic source of energy (Alves *et al.*, 2007). Amylose is a linear molecule structure of α -1,4 glycosidic bonds, while amylopectin molecules consist of branches with α -1,4 and α -1,6 glycosidic bonds. The unique properties of starch significantly influence the physicochemical properties such as viscosity, gelatinization temperature, binding capacity and paste clarity. However, native starches have many disadvantages as they display weaknesses such as low shear resistance, easing for retrogradation and low peak viscosity range. Therefore, starch is frequently modified to promote and enhance specific functional properties.

At present, various methods such as physical, enzymatic and chemical have been developed to improve the functionality to meet the specific applications. Among these methods, enzymatic hydrolysis is gaining considerable interest due to its high substrate selectivity, product specificity and mild reaction conditions with respect to the application, safer and healthier for both human consumption and the environment (Bangar *et al.*, 2022). Enzyme hydrolyzed starch in two different ways: α -amylase (endo-acting enzyme) hydrolyzes starch from the outer to the inner part of the granule (exo-corrosion), cleaving α -1,4 glycosidic bonds and creating channels leading to the granule center. Meanwhile, amyloglucosidase is an exo-acting enzyme that hydrolyzes both α -1,4 and α -1,6 linkages from the non-reducing ends of the starch chain resulting in the production of glucose completely as the end-product. The synergistic action of α -amylase and amyloglucosidase could produce starch with thermoresistant and stable adsorbent in food and

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chemical applications (Ashogbon, 2021).

Chemical modification appears to be a promising method that involves the introduction of new functional groups and cleavage of glycosidic linkages, thereby weakening the structure of the starch chains and enhancing enzyme penetrability toward starch (Ashogbon, 2021). Hydroxypropylation is an etherification of native starch with propylene oxide in the presence of an alkaline catalyst (Fu *et al.*, 2019). The introduction of hydroxypropyl groups can disrupt the inter- and intra-molecular hydrogen bonds, thereby reducing the tendency of starch pastes and gels to retrograde. It also preferentially occurred on amylose with higher molar substitution than amylopectin as it is more accessible at the amorphous region. Hydroxypropyl starches resulted in low gelatinization temperature and swelling power, whilst, the viscosity, solubility and paste clarity were increased (Karim *et al.*, 2008; Woggum *et al.*, 2015).

Previously, numerous modification techniques including heat-moisture (Xie *et al.*, 2019), autoclave (Li *et al.*, 2020), and ethanol (Keeratiburana *et al.*, 2020) treatments have been used to enhance the efficiency of enzyme hydrolysis on starch. To the best of our knowledge, no work has been reported on the utilization of hydroxypropylation as a pre-treatment prior to enzymatic modification of starch. Thus, the present work aimed to evaluate the effects of hydroxypropylation pre-treatment on sago and corn starch with different concentrations of propylene oxide (10% and 20%). Through this study, the analysis of the modified starch molar substitution, dextrose equivalent (DE), morphology, crystallinity, amylose content, pasting properties and swelling properties was revealed.

2. Materials and methods

2.1 Materials

Corn starch was obtained from the Sim's Company Sdn Bhd (Georgetown, Penang) whereas sago starch was from Thye Huat Chan Sdn Bhd (Bukit Mertajam, Penang, Malaysia). α -amylase from *Aspergillus oryzae* (250 U/mL) and amyloglucosidase from *Aspergillus niger* (800 FAU/g; FAU/g = Amount of the enzyme required to hydrolyses 1 g of starch per hour) and propylene oxide purchased from Sigma-Aldrich Chemical Co. (St, Louis, MO, USA). All reagents used were of analytical grade.

2.2 Hydroxypropylation of starch

Hydroxypropylation was carried out according to Xian *et al.* (2020) with slight modification. Corn and sago starch (50 g, dry basis) were weighed, and 75 mL distilled water was added, followed by 7.5 g of sodium

sulphate (Na_2SO_4). The slurry was incubated (SI-600R, JEIO Tech, Seoul, Korea) at room temperature (25 °C) at 150 rpm for 40 min. pH was adjusted to pH 11 with 1 M sodium hydroxide followed by propylene oxide (10% or 20% based on the starch weight). The reaction was maintained at 40°C for 24 hs at 200 rpm. The starch suspensions were neutralized 0.1 M hydrochloric acid, washed with distilled water until neutral and filtered. The samples were dried at 40°C for 2 days and ground into powder

2.3 Molar substitution

The hydroxypropyl contents were estimated using a spectrophotometric method as proposed by Xian *et al.* (2020) with slight modifications. 100 mg of starch was weighed and completely dissolved in 25 mL of 1 N sulphuric acid by incubating at boiling water until dissolved. Next, 1 mL of solution was transferred to a new 50 mL volumetric flask before 8 mL of concentrated sulphuric acid was added dropwise. The mixture was vortexed and placed in boiling water for 3 mins and immediately cooled down in an ice bath. Then, 0.6 mL of ninhydrin reagent (3 g/100 mL ninhydrin in 5 g/100 mL $\text{Na}_2\text{S}_2\text{O}_5$) was added. The mixture was incubated at 25°C for 100 mins with gentle shaking. After standing for 5 mins, the absorbance was measured at 590 nm by using a spectrophotometer (UV-160A, SHIMADZU, Japan) with the starch blank as a reference. The molar substitution (MS) was calculated using the following equations:

$$W = \frac{C \times 0.7763 \times 10 \times F}{w}$$

Where W is the amount of hydroxypropylated group in 100 mg of dry starch, C is the amount of propylene glycol ($\mu\text{g/mL}$), F is the dilution factor, w is the weight of the sample (mg), and 0.7763 is the conversion factor of glycol to hydroxypropyl group equivalent.

$$MS = \frac{162W}{5800 - 57W}$$

Where MS is the molar substitution and W is the amount of hydroxypropylated group in 100 mg of dry starch.

2.4 Enzymatic hydrolysis

Briefly, 25 g starch (on dry basis) was mixed with 50 mL of sodium acetate buffer (pH 4.5). A combination of α -amylase: glucoamylase (6:1) was added, and then the mixture was incubated at 45°C with 170 rpm (SI-600R, JEIO Tech, Seoul, Korea) for 24 hrs. At 0, 4, 6, 8, 12 and 24 hrs, 1 mL of the hydrolysate was collected and adjusted to the pH of 1.5 – 1.6 with 2 M HCl to inactivate the enzymes and determination of DE. After 24 hrs, the hydrolysis was stopped by adjusting the pH to

1.5 – 1.6 with 2 M HCl. Then, pH was re-adjusted to pH 5 – 6 with distilled water until neutral, filtered, and dried at 40°C for two days.

2.5 Dextrose equivalent

The reducing sugar value was measured using the dinitrosalicylic acid (DNS) method from Miller (1959) to determine the dextrose equivalent (DE). Approximately 1 mL of starch slurry hydrolyzed for 2, 4, 6, 8, 12, 24 h were placed in separate test tubes. Then, 4 mL of 3,5-dinitrosalicylic acid reagent (DNS) was added into the test tubes, vortexed and heated in boiling water for 5 min. After cooling to room temperature, the absorbance was measured at 540 nm by using a spectrophotometer (UV-160A, Shimadzu, Kyoto, Japan) and the percentage of reducing sugar was determined.

$$DE = \frac{m_r}{m_s} \times 100\%$$

where DE is the dextrose equivalent, m_r is the mass of reducing sugar, and m_s is the mass of dry starch.

2.6 Scanning electron microscope

The microstructure of starch granules was studied using a field emission scanning electron microscope (FESEM Leo Supra 50VP, Carl-Zeiss SMT, Oberkochen, Germany). Starch granules were stuck on an aluminum specimen stub with double-sided adhesive tape and sputtered with gold. The accelerating voltage of the SEM is 5kV.

2.7 X-ray diffraction analysis

The X-ray diffraction pattern and relative crystallinity of the starch samples were evaluated by an X-ray diffractometer (XRD) with Cu K α -radiation. The XRD measurements were adopted at 40 kV and 40 mA with scanning rate of 0.05°/s. The powders were added to the depression of the test holder, and scanning was done at 4 – 40°.

2.8 Apparent amylose content

The amylose content of starch was determined according to Xian et al. (2020). An amount of 100 mg of starch samples was dispersed in dimethyl sulfoxide (DMSO) in a water bath at 85°C for 15 mins. The starch solution was transferred and diluted into a volumetric flask (25 mL) with deionized water. Then, the starch solution (1 mL) was 5 mL of iodine solution (0.0025 mol/L in potassium iodide 0.0065 mol/L) and diluted with 50 mL deionized water and allowed to stand for 20 min. The standard mixture (amylose and amylopectin) and samples were measured at 600 nm by using a spectrophotometer (UV-160A, SHIMADZU, Japan).

2.9 Pasting properties

Pasting properties of starch were determined using a Rapid Visco Analyzer RVA Series 4 (Newport Scientific, Warriewood, Australia). Weight of 2 g starch with corrected 14% moisture content and 25 mL of distilled water were thoroughly mixed in a canister. The starch suspension was heated from 50°C to 95°C at the rate of 12°C/min, held at 95°C for 2.5 mins, then reduced to 50°C. The rotating speed was held at 960 rpm for the first 10 s and maintained at 160 rpm for the remaining process. The parameters such as peak viscosity (PV), final viscosity (FV), holding strength or trough viscosity (TV), breakdown viscosity (BDV), setback viscosity (SBV) and pasting temperature (PT) were determined.

2.10 Swelling and solubility properties

The swelling and solubility of starch were evaluated by the method of Schoch (1964). The 100 mg starch powdered samples were dispersed in distilled water, mixed thoroughly, and heated at the peak temperature for 30 mins. The solution was centrifuged for 15 mins at 3000 rpm. The supernatant was poured into a weighed petri dish, dried in a hot air oven overnight and the final weight was recorded. Wet residue was weighed to determine the swelling power. The solubility and swelling power were calculated from the equation below:

$$\text{Solubility} = \frac{W_d}{W_s}$$

Where W_d is the weight of dry supernatant and W_s is the initial weight of dry starch.

$$\text{Swelling power} = \frac{W_w}{W_s}$$

Where W_w is the weight of wet sediment and W_s is the initial weight of dry starch.

2.11 Statistical analysis

All experimental data were the average of triplicate observations and conveyed in terms of mean \pm standard deviation (SD) at the significant difference of $p < 0.05$ of taken samples. A comparison of the means was evaluated by Duncan's test ($p < 0.05$) using analysis of variance by using SPSS Statistical Software, version 16.0, for Windows (SPSS Inc., USA).

3. Results and discussion

3.1 Molar substitution

The MS refers to the average number of hydroxypropyl groups that are substituted per glucosyl unit in the starch molecule. In this study, the MS values of hydroxypropylated corn and sago starch at different levels of propylene oxide concentration are shown in Table 1. The result demonstrates that both corn and sago

starch increased significantly ($p < 0.05$) with increasing concentrations of propylene oxide. The MS of hydroxypropylated corn starches ranged from 0.138 (10%) to 0.314 (20%) and were higher than hydroxypropylated sago starch. The increase in MS was due to a greater collision between starch and propylene oxide, resulting in more hydroxypropyl groups being substituted on starch (Xian *et al.*, 2020). It was also reported that starch with higher amylose content achieved a higher MS value. After enzymatic hydrolysis, the amorphous regions of corn starch increased and became more accessible for etherification with propylene oxide compared to the crystalline domains, thus resulting in a higher MS (Shen *et al.*, 2019).

Table 1. Molar substitution (MS) of hydroxypropylated corn and sago starch with 10% and 20% propylene oxide concentration.

Type of Starch	Concentration of Propylene Oxide Used (%)	
	10	20
Corn	0.138±0.025 ^{ab}	0.314±0.018 ^c
Sago	0.112±0.019 ^a	0.149±0.011 ^b

Values are presented as mean±SD (N = 3). Values with different superscripts within the same column are statistically significantly different ($p < 0.05$).

3.2 Dextrose equivalent

The hydrolysis of starch granules involves breaking down the starch molecules into simpler sugars and the process can be monitored by measuring the reaction of starches with enzymes such as α -amylase and glucoamylase at specific time intervals. As shown in Table 2, after 24 hrs of hydrolysis at 45°C, DE of corn and sago starches increased significantly in the range of 4.37 – 28.12%, respectively. Hydroxypropylated corn starch exhibited higher DE compared to sago starch due to the naturally present pinholes and internal cavities that allow the enzyme to penetrate the granules (Uthumporn *et al.*, 2010). Moreover, treating both starches with propylene oxide reduced the DE significantly ($p < 0.05$). The presence of this bulky functional group sterically hinders the binding of the subsite of enzyme on the glucose chains and promotes the enzyme inhibitory effect by blocking the subsite and preventing the

formation of the enzyme-substrate complex (MacGregor, 1988).

3.3 Scanning electron microscope

The microstructure of enzyme-hydrolyzed and hydroxypropylated-enzyme-hydrolyzed starches was observed using a scanning electron microscope (SEM) (Figure 1). Based on the SEM micrographs, visible pores were randomly distributed, and pits were observed on the surface of enzyme-hydrolyzed corn starch granules. Meanwhile, hydrolyzed-sago starch granules showed a smooth surface oval shape and some shallow indentation. This indicated the corn starch was more extensively hydrolyzed by the enzymes compared to sago starch. During enzymatic hydrolysis, α -amylase enlarged the pinholes, thus providing physical access to the interior of the granules (Matsubara *et al.*, 2004). This similar finding has been reported in earlier work by Uthumporn *et al.* (2010). During hydroxypropylation of corn starch, propylene oxide entered through the pits and pinholes, creating a steric hindrance and blocking the channel for the enzyme to enlarge the pore. Thus, hydroxypropylated -enzyme-hydrolyzed corn and sago starch showed smaller and lesser porosity compared to un-pretreated enzyme-hydrolyzed starches. The pre-treatment of hydroxypropylation reduced the efficiency of the subsequent enzymatic hydrolysis process in starch. The substituted hydroxypropyl groups had sterically blocked the subsequent enzymatic attack through the formation of atypical linkages (Tupa *et al.*, 2018). However, corn

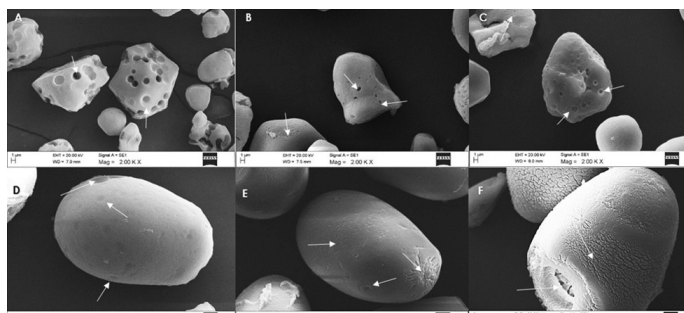


Figure 1. Scanning electron microscope (SEM) of native and hydroxypropylated starches (A) native corn starch (B), corn 10% hydroxypropylated, (C) corn 20% hydroxypropylated, (D) native sago starch, (E) sago 10% hydroxypropylated, and (F) sago 20% hydroxypropylated.

Table 2. Dextrose Equivalent (DE) value of control and porous hydroxypropylated starches after 24 hours of hydrolysis.

Hydrolysis time (hrs)	Type of Starch					
	Corn			Sago		
	Native	10%	20%	Native	10%	20%
0	0.24±0.05 ^{ab}	1.48±0.04 ^d	4.39±0.12 ^g	0.49±0.02 ^{ab}	0.11±0.01 ^a	1.04±0.02 ^c
4	12.78±0.18 ^f	6.17±0.34 ⁱ	11.94±0.43 ^p	3.11±0.07 ^f	0.57±0.03 ^b	2.20±0.65 ^c
8	16.07±0.08 ^u	8.66±0.06 ^o	13.27±0.10 ^s	5.16±0.07 ^h	1.86±0.06 ^{de}	5.19±0.49 ^h
12	24.57±0.47 ^x	12.26±0.22 ^q	17.11±0.44 ^v	7.56±0.19 ^k	3.23±0.10 ^f	6.26±0.08 ^{ij}
24	28.12±0.18 ^y	14.66±0.32 ^t	18.23±0.40 ^w	11.27±0.03 ^p	4.37±0.11 ^g	6.63±0.09 ^j

Values are presented as mean±SD (N = 3). Values with different superscripts within the same column are statistically significantly different ($p < 0.05$).

starch treated with 20% propylene oxide had higher porosity compared to 10%. This may be due to the presence of more hydroxypropyl groups which disrupted the intermolecular structure and led to swelling of the starch (Choi and Kerr, 2003; Hoover and Zhou, 2003). The granular surface of both treated sago starch had no pore or indentation observed, however, 20% of the treated sago starch showed crates on the surface of the granules.

3.4 X-ray diffraction

Starches can be classified into A-, B-, and C-type crystals based on the sharp peak of crystalline structure. In this study, the XRD patterns of native and modified starches are presented in Figure 2. The modified corn starches showed strong reflection at 15.26°, 17.20°, 18.20°, and 23.30°, indicating an A-type crystalline pattern, which is similar to the study reported by Rahaman *et al.* (2021). All modified sago starch exhibited C-type, characterized by diffraction peaks at 15.26°, 17.3°, and 23.2° (Du *et al.*, 2020). After hydroxypropylation, no obvious changes were observed in the crystalline pattern of corn and sago starches, but the crystallinity decreased significantly as the concentration of propylene oxide used increased. Results suggested that the hydroxypropyl groups formed in the amorphous regions inhibited the interchain association and crystallization and disrupted the crystalline structure of enzyme-hydrolyzed starch (Woggum *et al.*, 2015). There were also additional diffraction peaks at 20°,

which was reported to be the diffraction peak of the amylose-lipid complex (Man *et al.*, 2012). While starch with A-type crystallite was more susceptible to enzymatic hydrolysis compared to the C-type crystallite pattern owing to its smaller blocklet size (Govindaraju *et al.*, 2021), native and hydroxypropylated corn starches had relatively higher DE value than sago starches (Table 2).

3.5 Apparent amylose content

Apparent amylose content is one of the crucial determinants playing important roles in starch properties and applications. In this study, the amylose content for the enzyme-hydrolyzed and pre-treated enzyme-hydrolyzed starches was determined by the iodine-binding method and displayed in Figure 3. The apparent amylose content of the enzyme-hydrolyzed corn and sago starches pretreated with 10% and 20% propylene oxide decreased significantly ($p < 0.05$) after hydroxypropylation. Hydroxypropylation has been reported to occur in the amorphous region of starch. The hydroxyl groups disrupted the hydrogen bonding of adjacent starch chains, promoted the amylose to leach from the starch granules, contributed to lower iodine binding capacity, and hence, resulting in smaller values of apparent amylose content (Xian *et al.*, 2020). Higher propylene oxide concentration also lowered the value of amylose content. Amylopectin was less susceptible to hydroxypropylation due to its high degree of order, and therefore, the bulky group of hydroxypropyl group is mostly found on amylose or the amorphous region (Kaur, Singh and Singh, 2004).

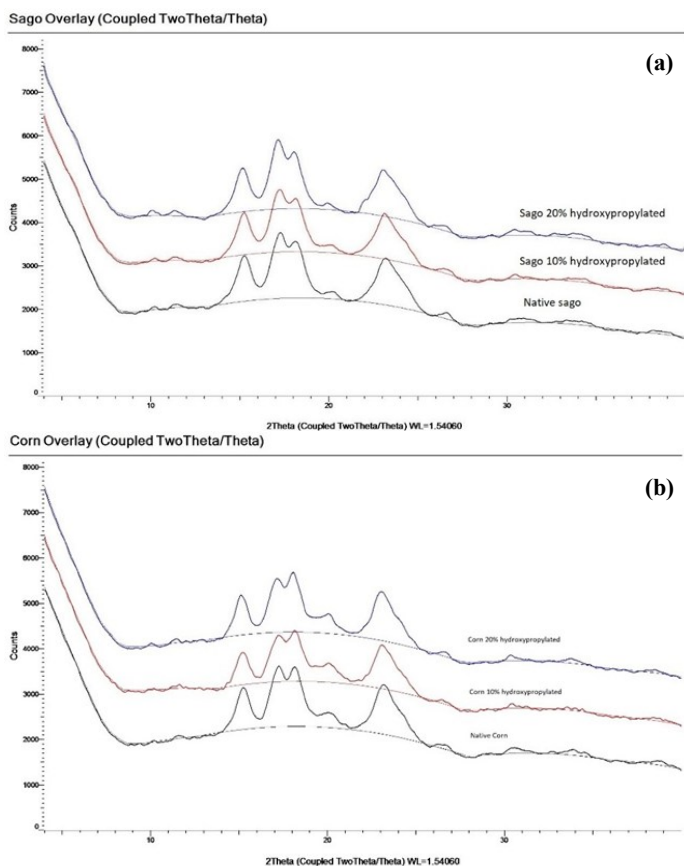


Figure 2. XRD patterns of native and modified starches (A) XRD pattern of corn starch (B) XRD pattern of sago starch.

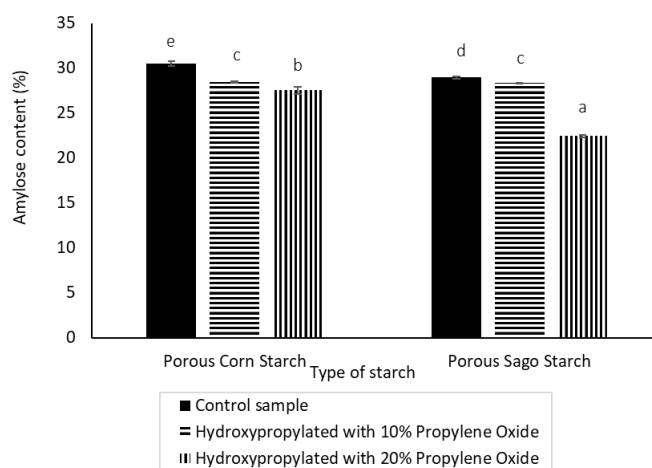


Figure 3. The amylose content for native and modified starches. Bars with different notations are statistically significantly different ($p < 0.05$).

3.6 Pasting properties

Pasting properties refer to the changes that occur in swollen starch granules when they are heated in the presence of excess water and these properties are crucial

for determining the cooking characteristics and overall quality of starch. In this study, the pasting properties of both corn and sago starches were significantly ($p < 0.05$) affected by hydroxypropylation (Table 3).

Table 3. Pasting properties of control and porous hydroxypropylated starches.

Type of Starch	Pasting Temperature (°C)	Viscosity (cP)		
		Peak	Setback	
Corn Starch	Native	77.15±0.48 ^c	986±6 ^c	336±19 ^c
	10%	69.67±0.51 ^c	736±24 ^b	169±4 ^c
	20%	66.38±0.49 ^a	562±5 ^a	99±6 ^a
Sago Starch	Native	76.73±0.13 ^c	1774±50 ^c	364±10 ^f
	10%	72.10±0.44 ^d	1478±54 ^d	258±13 ^d
	20%	68.80±0.45 ^b	1029±20 ^c	154±3 ^b

Values are presented as mean±SD (N = 3). Values with different superscripts within the same column are statistically significantly different ($p < 0.05$).

The pasting temperature (PT) of the unpretreated enzyme-hydrolyzed corn and sago starches was significantly ($p < 0.05$) higher than those pre-treated with hydroxypropylation. The PT of hydroxypropylated-enzyme-hydrolyzed corn and sago starches was gradually decreased as MS increased. The inclusion of hydroxypropyl groups disrupted the starch granular structure, subsequently facilitating the penetration of water into the starch granules, thus allowing the starch to swell (Shen *et al.*, 2019). Similar observations were also reported by Hazarika and Sit (2016) and Arueya *et al.* (2019).

Peak viscosity (PV) is the maximum viscosity that is attained by starch while heating. Hydroxypropylated-enzyme-hydrolyzed corn and sago starches had significantly ($p < 0.05$) lower PV compared to their unpretreated counterparts. The decrease in PV was observed to be higher in the hydroxypropylated starches treated with 20% of propylene oxide. The incorporation of the hydroxypropyl group reduced the attractive forces between hydroxyl groups of the starch molecules, lowering the hydration capacity of starch and thus, resulting in lower PV (Arueya *et al.*, 2019). Cai *et al.* (2020) also reported a decrement in the PV of starch after hydroxypropylation.

Setback viscosity (SB) is the measure of the degree of reassociation of amylose chains upon cooling after gelatinization and is also an indication of the stability of starch during swelling (Karim, Sufha and Zaidul, 2008). The SB of hydroxypropylated-enzyme-hydrolyzed starches was found to be lower ($p < 0.05$) compared to the enzyme-hydrolyzed starches. The reduced SB could be due to the inclusion of the hydroxypropyl group which hinders the reassociation of leached amylose molecules

after gelatinization. The elimination of hydrogen bonding of hydroxyl groups affected the associative tendency on the cooling of starch paste (Hazarika and Sit, 2016; Arueya *et al.*, 2019).

3.7 Swelling properties

Swelling power is an indicator of the extent of interaction between starch chains within the amorphous and crystalline region of starch granules which reflects the water absorption into the inner space of starch granules (Hazarika and Sit, 2016). Table 4 shows the swelling power of the enzyme-hydrolyzed and pre-treated enzyme-hydrolyzed starches. The swelling power of enzyme-hydrolyzed corn and sago starches pre-treated with propylene oxide was in the range of 9.11 – 10.93 g/g and 9.40 – 10.01 g/g, respectively, were higher than those of unpretreated (7.03 – 8.84 g/g) and increased with an increase in MS. The results implied that the swelling power of enzyme-hydrolyzed starches had increased by the pre-treatment of hydroxypropylation. The incorporation of hydroxypropyl groups disrupted the inter and intramolecular hydrogen bonds in the starch chains, thereby weakening the granular structure of starch and increasing the accessibility of the starch granules to water. Shen *et al.* (2019) also reported that hydroxypropylation could increase the swelling power of starch.

Table 4. Swelling and solubility of control and porous hydroxypropylated starches.

Type of Starch	Swelling Power (g/g)	
Corn Starch	Native	8.84±0.63 ^b
	10%	9.11±0.77 ^{bc}
	20%	10.93±0.44 ^d
Sago Starch	Native	7.03±0.09 ^a
	10%	9.40±0.10 ^{bc}
	20%	10.01±0.83 ^{cd}

Values are presented as mean±SD (N = 3). Values with different superscripts within the same column are statistically significantly different ($p < 0.05$).

4. Conclusion

Hydroxypropylated starches with different molar substitutions were produced by using different concentrations of propylene oxide (10% and 20%). This study showed that 20% propylene oxide was the most effective in improving the subsequent enzyme hydrolysis. The substitution of the bulky hydroxypropyl group blocked the enzyme adsorption site and sterically hindered the enzymatic attack. However, when more hydroxypropyl groups were introduced, the intermolecular structure of starch was disrupted consequently, allowing the starch granules to swell and increase accessible areas for enzymatic attack. Besides

that, the hydroxypropylated-enzyme-hydrolyzed starches also had greater potential to be used as food ingredients owing to their relatively lower pasting temperature, retrogradation tendency, and higher swelling power.

Conflict of interest

The authors declare no conflict of interest.

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