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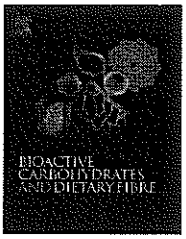

Effects of non-starch polysaccharides on physicochemical properties and in vitro starch digestibility of rice starches

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ABSTRACT

The effects of non-starch polysaccharides (NSPs) on physicochemical properties and starch digestibility of waxy and non-waxy rice starches (WS and NWS) were investigated. The NSPs studied included guar gum (GG), xanthan gum (XG), carboxymethyl cellulose (CMC), tapioca fibre (Tap) and tamarind seed fibre (Tam). They were added to WS and NWS at the levels of 5, 10 and 15 g/100 g dry sample. The mixtures were examined for their in vitro starch digestibility, thermal properties by a DSC and textural properties by a texture analyser. Generally, it was found that all NSPs at the concentrations used in this study had little or no effect on starch digestibility. Glycaemic response parameters slightly decreased in the samples with added NSPs. No obvious effects on thermal properties were obtained. However, the NSPs affected the texture of rice starch gels as evidenced by changes in hardness and adhesiveness values. The textural changes were dependent on the type and concentration of the NSPs.

1. Introduction

As the primary dietary source of carbohydrates in over half of the world's population, rice plays an important role in meeting energy requirements and nutrient intake (Hu, Zhao, Duan, Linlin, & Wu, 2004; Wang et al., 2010). Starch, the major component in rice, undergoes hydrolysis as a result of the activity of amylolytic enzymes in the gastrointestinal tract (also in vitro). Hence it is regarded as a constituent rapidly and completely digested and absorbed in the small intestine in the form of glucose (Leszczyński, 2004). According to the extent and rate of digestion, starch is generally classified as rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS) (Englyst, Kingman, & Cummings, 1992). Overall, the rate of starch digestion and absorption is a determinant of the human metabolic response to a starchy meal (Araya, Contreras, Alvina, Vera, & Pak, 2002). RS has received much attention and is nowadays a focus of research, as it can be considered as functional dietary fibre; RS escapes from digestion in the small intestine and is fermented in the colon, producing short chain fatty acids (SCFAs) (Topping & Clifton, 2001). Due to its properties,

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RS positively influences the functioning of the digestive tract, the microbial flora, the blood cholesterol level, the glycaemic index (GI) and assists in the control of diabetes (Fuentes-Zaragoza, Riquelme-Navarrete, Sánchez-Zapata, & Pérez-Álvarez, 2010). Currently, RS is classified into four groups (RS1–4), according to its physical and chemical properties (Nugent, 2005).

Structurally, fibre can be sub-divided broadly into two forms, RS and non-starch polysaccharide (NSP). While both can be fermented in the colon, the exact site, rate of degradation and the nature of the SCFA produced can vary (Morita, Kasaoka, Hase, & Kiriyama, 1999), all these may affect insulin sensitivity and other metabolic parameters, either directly or indirectly. Indeed, a number of studies have reported that inclusion of fibre in the meal strategy (Giacco et al., 2000) or the use of either acute (Robertson, Currie, Morgan, Jewell, & Frayn, 2003) or chronic (Robertson, Bickerton, Dennis, Vidal, & Frayn, 2005) supplementation with RS does improve blood glucose control following a meal. It is less clear whether NSP is as effective as RS, however, and this is important because the former is the more prevalent form of fibre in Western diets (Lobley et al., 2013).

Physicochemical and metabolic properties of rice starch are influenced by numerous factors. One of these factors is amylose and amylopectin content (Behall, Scholfield, & Canary, 1988; Behall, Scholfield, Yuhaniak & Canary, 1989; Frei, Siddhuraju, & Becker, 2003). It has been well known that high amylose rice exhibits lower starch digestion rate. The amylose content of rice starch usually varies between 10% and 35%, although in high-amylose rice, it may reach even 70%, compared to the so-called "waxy" (high-amylopectin) rice in which amylose occurs in trace amounts (Leszczyński, 2004). Other factors such as granule size, architecture, crystalline pattern, degree of crystallinity, surface pores or channels, post-processing and storage conditions (recrystallisation), physical state and chemical modifications, degree of polymerisation and non-starch components also contribute to the metabolic properties (Biliaderis, 1982; Noda et al., 2008; Seneviratne & Biliaderis, 1991; Tester, Qi, & Karkalas, 2006).

Starch and NSP mixtures are often used to modify the texture of food products. Moreover, the interactions between starch and NSP have a nutritional impact on food products. The potential for altering starch digestibility by blending NSP has been a focus in current research studies, as NSP can modify food structure, texture, and viscosity, resulting in altered accessibility of enzymes to starch granules and processed starch materials (Brennan, 2005; Sasaki & Kohyama, 2011).

In views of the importance of NSP being used widely as food ingredients, the objective of this study was to investigate the effects of five different NSP including derivatives, namely guar gum (GG), xanthan gum (XG), carboxymethyl cellulose (CMC), tapioca fibre (Tap) and tamarind seed fibre (Tam), on the in vitro starch digestibility and physicochemical properties of rice starches.

2. Materials and methods

2.1. Preparation of samples

Waxy rice starch (WS) and non-waxy rice starch (NWS) were supplied by Cho Heng Rice Vermicelli Factory Co., Ltd. Amylose content of the WS and NWS samples were reported to be 1.48±0.03 and 30.12±0.02 g/100 g dry sample, respectively. Commercial NSPs (GG, XG and CMC) were purchased from Sigma-Aldrich, Singapore. They have been widely used in foods as thickener, stabiliser and emulsifier. GG is primarily the ground endosperm of the seeds from *Cyamopsis tetragonolobus* (L.) Taub., mainly consisting of high molecular weight polysaccharides composed of galactomannans; mannose:galactose ratio is about 2:1. XG is a high molecular weight polysaccharide gum produced by a pure-culture fermentation of a carbohydrate with *Xanthomonas campestris*, purified by recovery with ethanol or isopropanol, dried and milled, it contains D-glucose and D-mannose as the dominant hexose units, along with D-glucuronic acid and pyruvic acid, and is prepared as the sodium, potassium or calcium salt. CMS is the sodium salt of carboxymethyl ether of cellulose and prepared from cellulose by treatment with alkali and monochloro-acetic acid or its sodium salt. "Tap" in dry powder form was supplied by T-fibre Innovation Co., Ltd. It was isolated from the pulp of wet-milled tapioca after the isolation of starch. "Tam" was made from tamarind (*Tamarindus indica* L.) seeds by wet milling and drying at low temperature (50 °C) before use. A crude extract of tamarind seeds, was found to be rich in polysaccharide (~65–72%) (Kumar & Bhattacharya, 2008). These five NSPs were mixed with WS and NWS, each at 5, 10, 15 g/100 g dry sample. All samples were sieved through 100-mesh screen prior to analysis.

2.2. Total starch

Total starch content of the samples was determined enzymatically using the Megazyme assay kit (Megazyme International Ireland), following the approved AACC method 76.13 (AACC, 2009).

2.3. In vitro starch digestion and modelling of starch digestograms

The time-course starch digestion in the samples was determined using a rapid in vitro digestibility assay based on glucometry (Mahasukhonthachat, Sopade, & Gidley, 2010; Sopade & Gidley, 2009). About 0.5 g of ground sample was weighted and mixed with distilled water (1:1.5 w/w) and boiled at 100 °C for 20 min to obtain the gelatinised samples. To avoid the effect of retrogradation, immediately after cooking, the samples were treated with artificial saliva containing porcine α-amylase (Sigma A3176 Type VI-B) before pepsin (Sigma P6887; pH 2.0) was added and incubated at 37 °C for 30 min in a water bath operating under continuous shaking. The digesta was neutralised with NaOH before adjusting the pH to 6.0 (sodium acetate buffer) prior to the addition of pancreatin (Sigma P1750) and AMG (Novozymes AMG 300 L). The mixture was incubated for 2 h, during which the glucose concentration in the digesta was measured with Accu-Check® Performa® glucometer at specific periods (0, 10, 20, 30, 45, 60, 90 and 120 min). Digested starch per 100 g dry starch (DS) was calculated as in Eq. (1).

$$DS = \frac{0.9 \times G_G \times 180 \times V}{W \times S[100 - M]} \quad (1)$$

where G_G=glucometer reading (mM/L), V=volume of digesta (mL), 180=molecular weight of glucose, W=weight of sample (g), S=starch content of sample (g/100 g sample), M=moisture content of a sample (g/100 g sample), and 0.9=stoichiometric constant for starch from glucose contents.

The digestogram (digested starch at a specific time period) of each sample was modelled using a modified first-order kinetic model, Eq. (2), as described before (Mahasukhonthachat et al., 2010).

$$D_t = D_0 + D_{\infty-0}(1-\exp[-Kt]) \quad (2)$$

where D_t (g/100 g dry starch) is the digested starch at time t, D_0 is the digested starch at time t=0, D_∞ is the digestion at infinite time (D_0+$D_{\infty-0}$), and K is the apparent rate constant (min^{-1}).

The Microsoft Excel Solver® was used to compute the parameters of the model by minimising the sum of squares of residuals (SUMSQ) and constraining $D_\infty \leq 100$ g per 100 g dry starch, and $D_0 \geq 0$ g per 100 g dry starch. In addition to the coefficient of determination (r^2), the predictive ability of the models was assessed with the mean relative deviation modulus (MRDM) as described elsewhere (Mahasukhonthachat et al., 2010).

In order to calculate the estimated GIs of the samples, the areas under the digestograms (AUC_{exp}) were computed with Eq. (3)

$$AUC_{exp} = \left[D_\infty t + \frac{D_{\infty-0}}{K}\exp(-Kt)\right]_{t_1}^{t_2} \quad (3)$$

The hydrolysis index (HI) and starch digestion at 45 min (H_{45}) of each sample were calculated by dividing the area under its digestogram by the area under the digestogram of a fresh white bread (Goñi, García-Alonso, & Saura-Calixto, 1997) which was calculated to be about 11,000 min g/100 g dry starch. Using the parameters of the modified first-order kinetic model for both the samples and fresh white bread, estimated GIs of the samples were also calculated, and the average GI (GI_{AVG}) for each sample was defined as Eq. (4)

$$GI_{AVG} = \left[\frac{((39.51 + 0.803H_{45}) + (39.51 + 0.803HI))}{2}\right]. \quad (4)$$

2.4. Differential scanning calorimetry (DSC)

The moisture content of the samples was adjusted to 70 g/100 g dry sample by adding distilled water prior to DSC, which was carried out in a Mettler Toledo DSC 1 equipped with a refrigerated cooler. The hydrated samples were weighted (25±5 mg) into aluminium DSC pans (120 μL) and hermetically sealed. The DSC analysis was run by scanning from 30 to 100 °C, ramping at 10 °C/min and a hermetically sealed empty pan was used as a reference. Nitrogen was used as a purging gas. The software used for the analysis of the resulting thermograms was Star^e software (Mettler Toledo). The onset temperature (T_0), peak temperature (T_p), conclusion temperature (T_c) and transition enthalpy (ΔH) were determined. Each sample was analysed in duplicate.

2.5. Textural properties

The samples were mixed with distilled water to prepare 30 g of paste (30% w/w) in a 50 mL cylindrical glass jar, followed by 30-min heating under continuous stirring using a magnetic stirrer for gelatinisation and then cooling at 4 °C for another 30 min. To avoid the effects of starch retrogradation, the samples were immediately measured for textural properties (Lu et al., 2011) using a Texture Analyzer (TA-XT2, Stable Micro Systems, England) equipped with a 5 mm diameter cylinder probe and compression platens. The parameters were set as follows: pretest speed 2.0 mm/s, test speed 1.0 mm/s, post test speed 2.0 mm/s, trigger force 15 g, distance 5 mm. The resulting force–time curves were then analysed with the Exponent software (Stable Micro Systems, England) for sample texture characteristics including hardness and adhesiveness. Hardness was defined as the maximum compressive force that displays substantial resistance to deformation. Adhesiveness was defined as the negative force area after the first compression, representing the work necessary to pull the compressing plunger away from the sample. At least 10 measurements were conducted for each sample.

2.6. Statistical analysis

Analysis of variance (ANOVA), test of significance and comparison of means, using the Tukey's test were performed using Minitab® ver. 16 with confidence level of 95%. The samples were randomised for all the analyses described above.

3. Results and discussion

3.1. Total starch

Table 1 shows the total starch content of all samples. The rice starches used in this study had considerably high total starch content. As expected, the higher the amount of NSP, the lower the total starch content.

3.2. In vitro starch digestion

Tables 2 and 3 show the digestion data of WS and NWS mixtures respectively. The modified first-order kinetic model proved suitable in describing the digestograms (WS samples: r^2=0.90–0.99; MRDM=2.7–13.3%; SUMSQ=80–699 and NWS samples: r^2=0.90–0.99; MRDM=0.9–18.4%; SUMSQ=0.5–103). In general, NWS exhibited lower GI values than WS samples. This is due to the higher level of amylose content in NWS samples. It has been well established that amylose exhibits a slower rate of enzyme degradation, resulting in the reduction of GI values (Hu et al., 2004; Zhu, Liu, Wilson, Gu, & Shi, 2011).

Comparing among all the NSPs in WS mixtures, statistically, only GG, XG and Tam provided better digestion parameters (lower K, HI and GI values than those of the control). However, at the levels of NSP used in this study (5, 10 and 15 g/100 g dry sample) there was no significant effect, giving similar results for all the NSPs (Table 2). In terms of NWS

Table 1 – Total starch content of waxy and non-waxy rice starch samples.[1]

Samples	Total starch (g/100 g dry sample)	Samples	Total starch (g/100 g dry sample)
WS	93.78±5.35^{a}	NWS	94.12±2.95^{a}
WS+GG(5)	86.36±4.71^{abc}	NWS+GG(5)	89.23±3.68^{ab}
WS+GG(10)	81.60±1.05^{bc}	NWS+GG(10)	85.54±0.08^{bc}
WS+GG(15)	78.76±0.66^{bc}	NWS+GG(15)	81.16±0.44^{c}
WS+XG(5)	88.00±0.65^{abc}	NWS+XG(5)	88.57±0.49^{ab}
WS+XG(10)	83.44±5.07^{abc}	NWS+XG(10)	86.63±0.22^{bc}
WS+XG(15)	77.15±0.29^{c}	NWS+XG(15)	83.00±0.06^{bc}
WS+CMC(5)	87.55±0.84^{abc}	NWS+CMC(5)	89.52±2.73^{ab}
WS+CMC(10)	84.04±1.09^{abc}	NWS+CMC(10)	83.77±1.00^{bc}
WS+CMC(15)	79.28±3.04^{bc}	NWS+CMC(15)	80.72±2.19^{c}
WS+Tap(5)	89.70±0.48^{ab}	NWS+Tap(5)	88.93±0.56^{ab}
WS+Tap(10)	85.12±1.88^{abc}	NWS+Tap(10)	83.63±3.50^{bc}
WS+Tap(15)	79.21±0.25^{bc}	NWS+Tap(15)	81.02±0.73^{c}
WS+Tam(5)	88.06±3.55^{abc}	NWS+Tam(5)	89.18±0.28^{ab}
WS+Tam(10)	81.03±4.43^{bc}	NWS+Tam(10)	85.54±1.34^{bc}
WS+Tam(15)	78.29±4.19^{bc}	NWS+Tam(15)	83.38±0.39^{bc}

For each parameter (column), values with the same letters are not significantly different ($p > 0.05$).
Abbreviations: WS, waxy rice starch; NWS, non-waxy rice starch; GG, guar gum; XG, xanthan gum; CMC, carboxymethyl celullose; Tap, tapioca fibre; Tam, tamarind seed fibre; (5) (10) (15), 5, 10 and 15 g/100 g dry sample addition of NSP to the starch samples, respectively.
[1] Values are means±standard deviations (triplicate).

Table 2 – Model parameters, hydrolysis index (HI) and glycaemic index (GI) of the waxy rice starch mixtures.[1]

Samples	D_0 (g/100 g dry starch)	$K \times 10^{-3}$ (min^{-1})	HI	GI_{AVG}
WS	4.48±0.22^{d}	27.54±0.88^{abc}	78.71±0.92^{ab}	100.15±0.84^{ab}
WS+GG(5)	13.98±0.27^{ab}	15.32±0.47^{g}	66.15±1.00^{d}	88.88±0.83^{d}
WS+GG(10)	14.09±3.26^{a}	14.99±0.42^{g}	65.59±2.43^{d}	88.41±1.97^{d}
WS+GG(15)	13.47±1.04^{ab}	14.81±0.06^{g}	64.96±1.17^{d}	87.90±0.94^{d}
WS+XG(5)	13.00±0.10^{ab}	16.50±1.62^{fg}	67.69±2.83^{d}	90.19±2.37^{d}
WS+XG(10)	11.12±0.24^{abc}	14.73±0.56^{g}	63.59±1.23^{d}	86.80±1.01^{d}
WS+XG(15)	8.34±4.43^{abcd}	15.37±1.14^{g}	63.46±0.01^{d}	86.72±0.06^{d}
WS+CMC(5)	13.70±0.19^{ab}	23.73±0.02^{cd}	77.93±0.05^{abc}	99.03±0.04^{abc}
WS+CMC(10)	13.42±0.58^{ab}	24.80±1.11^{bcd}	78.96±0.93^{ab}	99.97±0.86^{ab}
WS+CMC(15)	12.52±1.98^{ab}	24.83±0.38^{bcd}	78.68±1.08^{ab}	99.75±0.89^{ab}
WS+Tap(5)	4.12±1.47^{d}	27.96±0.53^{ab}	79.00±0.04^{ab}	100.44±0.11^{ab}
WS+Tap(10)	5.84±0.09^{cd}	29.30±0.58^{a}	80.74±0.53^{a}	101.96±0.49^{a}
WS+Tap(15)	7.43±1.00^{bcd}	24.70±2.52^{bcd}	76.69±2.42^{abc}	98.19±2.23^{abc}
WS+Tam(5)	9.83±0.34^{abcd}	22.16±0.34^{de}	74.68±0.56^{bc}	96.29±0.48^{bc}
WS+Tam(10)	10.07±0.64^{abcd}	22.60±1.01^{de}	75.30±0.99^{bc}	96.83±0.90^{bc}
WS+Tam(15)	13.60±0.50^{ab}	19.83±0.06^{ef}	73.15±0.12^{c}	94.82±0.09^{c}

For each parameter (column), values with the same letters are not significantly different ($p > 0.05$).
Abbreviations: WS, waxy rice starch; NWS, non-waxy rice starch; GG, guar gum; XG, xanthan gum; CMC, carboxymethyl celullose; Tap, tapioca fibre; Tam, tamarind seed fibre; (5) (10) (15), 5, 10 and 15 g/100 g dry sample addition of NSP to the starch samples, respectively.
[1] Values are means±standard deviations (triplicate).

mixtures, most of the results showed no significant effects; e.g. all the studied NSPs provided similar digestion results. Only for the Tam samples, the GI values were slightly reduced. In addition, the NSP levels used in this study had little effect on starch digestibility.

Metabolic health improvement based on lowering either the rate or amount of glucose absorbed from a meal has been suggested (Wolever et al., 2008). This may involve substitution of some of the easily digested carbohydrates with fermentable carbohydrates, often grouped under the term fibre, that are either partially or completely degraded in the large intestine to short chain fatty acids (SCFA). Absorbed SCFA may also have direct effects on mechanisms linked to insulin sensitivity, either by substitution of gluconeogenic

Table 3 – Model parameters, hydrolysis index (HI) and glycaemic index (GI) of the non-waxy rice starch mixtures.[1]

Samples	D_0 (g/100 g dry starch)	$K \times 10^{-3}$ (min^{-1})	HI	GI_{AVG}
NWS	9.79 ± 0.16^{abcd}	4.09 ± 0.09^{b}	31.30 ± 0.52^{ab}	61.94 ± 0.38^{bcd}
NWS+GG(5)	8.87 ± 1.25^{bcd}	7.07 ± 4.27^{b}	31.68 ± 0.77^{ab}	62.42 ± 0.85^{abc}
NWS+GG(10)	7.46 ± 0.82^{d}	10.43 ± 2.02^{ab}	31.51 ± 0.44^{ab}	62.51 ± 0.45^{abc}
NWS+GG(15)	9.42 ± 1.29^{abcd}	7.03 ± 3.36^{b}	32.15 ± 2.78^{a}	62.76 ± 1.75^{abc}
NWS+XG(5)	11.21 ± 0.71^{abcd}	9.75 ± 3.48^{ab}	34.38 ± 3.16^{a}	64.69 ± 1.94^{ab}
NWS+XG(10)	11.79 ± 0.74^{abcd}	4.76 ± 0.07^{b}	35.76 ± 0.90^{a}	65.27 ± 0.69^{ab}
NWS+XG(15)	12.98 ± 0.38^{ab}	6.82 ± 3.65^{b}	34.92 ± 0.62^{a}	64.96 ± 0.78^{ab}
NWS+CMC(5)	13.04 ± 2.99^{ab}	3.56 ± 0.10^{b}	35.40 ± 1.82^{a}	65.85 ± 2.20^{ab}
NWS+CMC(10)	12.48 ± 2.97^{abc}	2.86 ± 1.21^{b}	34.42 ± 0.73^{a}	65.04 ± 1.32^{ab}
NWS+CMC(15)	13.86 ± 0.62^{a}	3.78 ± 0.05^{b}	33.53 ± 0.34^{a}	63.79 ± 0.28^{ab}
NWS+Tap(5)	7.54 ± 0.27^{cd}	6.57 ± 2.02^{b}	34.05 ± 0.51^{a}	63.95 ± 0.60^{ab}
NWS+Tap(10)	8.02 ± 0.38^{cd}	10.39 ± 0.64^{ab}	36.08 ± 0.16^{a}	65.83 ± 0.16^{ab}
NWS+Tap(15)	7.29 ± 0.77^{d}	17.96 ± 6.47^{a}	35.86 ± 1.75^{a}	66.30 ± 0.80^{a}
NWS+Tam(5)	9.33 ± 0.09^{abcd}	3.18 ± 0.12^{b}	26.85 ± 0.45^{bc}	58.74 ± 0.31^{cde}
NWS+Tam(10)	9.18 ± 0.56^{abcd}	3.01 ± 0.11^{b}	25.93 ± 0.12^{c}	58.07 ± 0.03^{de}
NWS+Tam(15)	9.52 ± 0.35^{abcd}	2.73 ± 0.05^{b}	24.94 ± 0.08^{c}	57.40 ± 0.08^{e}

For each parameter (column), values with the same letters are not significantly different ($p > 0.05$).
Abbreviations: WS, waxy rice starch; NWS, non-waxy rice starch; GG, guar gum; XG, xanthan gum; CMC, carboxymethyl celullose; Tap, tapioca fibre; Tam, tamarind seed fibre; (5) (10) (15), 5, 10 and 15 g/100 g dry sample addition of NSP to the starch samples, respectively.
[1] Values are means ± standard deviations (triplicate).

demands or by enhancing glucose uptake by muscle and adipose tissue (Robertson, 2007). Soluble forms of fibre also slow the rate of glucose absorption from the small intestine and thus lower glycaemic excursion in the post-prandial state (Wursch & Pi-Sunyer, 1997). Processing techniques such as extrusion could also contribute to the product glycaemic responses (Brennan, Derbyshire, Brennan, & Tiwari, 2012; Brennan, Derbyshire, Tiwari, & Brennan, 2013). In this study, the addition of various NSP at the concentration of 5–15 g/100 g dry sample in rice starches had little or no impact on improving starch digestibility properties as determined by the in vitro method.

However, Sasaki and Kohyama (2011) evaluated the influence of some NSPs (agar, xanthan gum, and konjac glucomannan) on the in vitro digestibility and rheological properties of concentrated rice starch gel and found that the added NSPs suppressed starch hydrolysis in the gels. The suppressive effect of NSP on starch digestibility in starch gels is related to a number of factors and is not only due to the rheological properties of the gel. These authors also studied the effects of several NSPs on starch digestibility in starch suspensions (Sasaki & Kohyama, 2012). They concluded that the effects of NSPs on starch digestion were dependent on various factors, and not only affected by the higher viscosity and decreased diffusivities in the mixed NSP–starch dispersions. XG was found to exert the most pronounced suppressive effect on starch digestibility.

When NSPs were used in the starch–water system specifically at around the gelatinisation temperatures, the extent of starch hydrolysis by α-amylase was characteristically reduced compared to NSP free starch–water systems. Reductions in the extent of hydrolysis were always greater as the concentration of NSPs increased and were more marked at higher starch to water ratios. At 80 °C, however, inhibition of starch hydrolysis by the addition of most of the NSPs/concentrations was masked due to extensive hydrolysis of the gelatinised material (Tester & Sommerville, 2003). The results from Tester and Sommerville (2003) also indicated that the limitation of water availability as a consequence of soluble NSP hydration could restrict gelatinisation and hence hydrolysis with enzymes. In a true three-phase system (starch, NSP and water) there would potentially be a more dynamic interchange of water molecules between the different polymers and not the relatively "artificial" exclusion of the different polymers from each other.

The nutritional impact of the interaction between starch and NSP has become a vital issue in improving the nutritional benefit of starch and cereal-based foods in relation to their ability to alter the rate and amount of starch hydrolysis. Mechanisms on how NSP could lower starch digestion rate are essential. Soluble fibres may reduce starch digestibility by changing the microstructure of food products (Brennan, Blake, Ellis, & Schofield, 1996; Cleary & Brennan, 2006; Tudorica, Kuri, & Brennan, 2002) or by limiting water availability as a consequence of soluble NSP hydration which, in turn, restricts starch gelatinisation (Banchathanakij & Suphantharika, 2009; Cleary & Brennan, 2006). In addition, they could alter the rate of glucose absorption in the small intestine. The in vitro starch digestion method is a measure of glucose released from starch by the digestive enzymes. Hence, it may not be suitable to evaluate the starch–NSP system if the mechanism is based on the glucose absorption in the small intestine. Moreover, the starch digestibility was reduced to different degrees in food products with the same soluble fibre source indicating that the ability of the fibre to reduce starch digestibility in foods may be process and product dependent (Brennan, 2005). With in vivo studies, Lobley et al. (2013) found that additional RS or NSP above

the amounts currently recommended resulted in little or no improvement in glycaemic control of obese male volunteers. There is still a need for further research on the effects of NSP on starch digestion on the underlying physicochemical and physiological mechanisms.

3.3. *Thermal analysis*

The DSC results showed that starch gelatinisation peak temperatures are around 77–83 °C in case of NWS and 68–76 °C for WS samples. Differences in gelatinisation temperatures of WS and NWS seemed to be influenced by the different amylose content of the starches. Generally, gelatinisation temperatures increased with the increase of apparent amylose content (Chung, Liu, Lee, & Wei, 2011; Rojas, Rosell, & Benedito de Barber, 1999). All the DSC parameters are shown in Tables 4 and 5. Generally, there was apparently little effect of the added NSPs on gelatinisation temperatures in both WS and NWS mixtures. This trend was observed in the transition enthalpy as well. No significant differences were noted among the WS mixtures, whereas a slight decrease in the apparent gelatinisation enthalpy values was found in NWS mixtures. Gelatinisation of granular starch dispersions represents a composite effect of starch crystallite melting (endothermic effect) and amylose-lipid complex formation (exothermic effect). Both processes take place simultaneously upon heating aqueous granular starch dispersions; complex formation obviously takes place only in the case of NWS and therefore it exhibits lower gelatinisation enthalpy as compared with the WS (Biliaderis, Page, Maurice, & Juliano, 1986). There are huge variations on the published data regarding to the effects of NSP on gelatinisation temperatures. The presence of NSPs tended to elevate gelatinisation temperatures, in particular T_c. With respect to the gelatinisation enthalpy, the presence of NSPs tended to cause a reduction when the starch content was relatively high (Tester & Sommerville, 2003). GG and XG were the NSPs which have been studied extensively. The findings for the thermal properties of GG–starch mixtures were rather inconsistent. Sudhakar, Singhal, and Kulkarni (1996) found a decrease in T_c, while the opposite result was found by Kim and Wang (1999). In terms of enthalpy, both an increase (Biliaderis, Arvanitoyannis, Izydorczyk, & Prokopowich, 1997; Ferrero, Martino, & Zaritzky, 1996) and a decrease (Rojas et al., 1999) were reported. For XG–starch mixture, Biliaderis et al. (1997) and Rojas et al. (1999) reported no effect on T_c. It should be noted that not only there are variations in terms of conditions used between different studies, but also in terms of parameters studied. More in-depth studies are necessary in this context.

3.4. *Textural properties*

It is well known that the addition of NSP strongly influences the texture or rheological properties of starch based foods. Starch and NSP mixtures are often used to modify the texture of food products. The addition of NSPs to rice starches (both WS and NWS) affected the textural properties as observed by hardness and adhesiveness in this study (Figs. 1 and 2).

Differences in results between WS and NWS are influenced by the amylose content in the starch samples. It has been reported that hardness increases with the increase of amylose, whereas there was a decrease in the adhesiveness (Lu, Sasaki, Yoshihashi, Li, & Kohyama, 2009; Yu, Ma, & Sun, 2009).

Previous studies suggested that the addition of NSP resulted in an increase of hardness values (Huang, Kennedy, Li, Xu, & Xie, 2007). In the present study, generally the increasing hardness was observed in WS mixtures containing

Table 4 – DSC parameters of the waxy rice starch mixtures.[1]

Samples	T_o (°C)	T_p (°C)	T_c (°C)	ΔH (J/g dry sample)
WS	61.87 ± 0.38^{c}	68.77 ± 0.49^{g}	77.35 ± 0.39^{e}	8.27 ± 0.22^{a}
WS+GG(5)	61.76 ± 0.11^{c}	69.77 ± 0.28^{defg}	79.20 ± 0.12^{cde}	8.25 ± 0.05^{a}
WS+GG(10)	62.73 ± 0.68^{c}	71.37 ± 0.84^{cd}	80.25 ± 0.97^{bcd}	6.95 ± 1.49^{a}
WS+GG(15)	62.15 ± 0.59^{c}	70.77 ± 0.88^{cde}	79.34 ± 1.85^{bcde}	6.86 ± 0.87^{a}
WS+XG(5)	62.15 ± 0.09^{c}	69.97 ± 0.37^{defg}	78.25 ± 0.32^{de}	7.27 ± 0.52^{a}
WS+XG(10)	62.58 ± 0.25^{c}	70.94 ± 0.04^{cde}	79.91 ± 0.73^{bcde}	7.64 ± 1.40^{a}
WS+XG(15)	63.41 ± 0.57^{bc}	72.20 ± 0.62^{bc}	81.67 ± 1.13^{abc}	7.73 ± 0.02^{a}
WS+CMC(5)	63.00 ± 0.01^{bc}	70.64 ± 0.01^{cdef}	78.61 ± 0.17^{de}	7.46 ± 0.32^{a}
WS+CMC(10)	64.87 ± 0.56^{b}	73.26 ± 0.42^{b}	81.98 ± 0.64^{ab}	7.17 ± 0.05^{a}
WS+CMC(15)	67.36 ± 0.04^{a}	75.70 ± 0.29^{a}	83.95 ± 0.27^{a}	6.83 ± 0.51^{a}
WS+Tap(5)	62.14 ± 0.24^{c}	68.99 ± 0.11^{fg}	77.32 ± 0.49^{e}	8.26 ± 0.71^{a}
WS+Tap(10)	63.74 ± 1.53^{bc}	69.59 ± 0.26^{efg}	78.41 ± 0.20^{de}	8.14 ± 0.31^{a}
WS+Tap(15)	62.78 ± 0.18^{c}	69.74 ± 0.15^{defg}	78.64 ± 0.50^{de}	7.88 ± 0.48^{a}
WS+Tam(5)	62.50 ± 0.13^{c}	69.57 ± 0.28^{efg}	77.81 ± 0.40^{de}	8.27 ± 0.02^{a}
WS+Tam(10)	62.66 ± 0.09^{c}	69.63 ± 0.18^{efg}	77.65 ± 0.21^{de}	7.25 ± 0.74^{a}
WS+Tam(15)	63.10 ± 0.21^{bc}	70.15 ± 0.12^{defg}	78.18 ± 0.21^{de}	6.50 ± 0.24^{a}

For each parameter (column), values with the same letters are not significantly different ($p > 0.05$).

Abbreviations: WS, waxy rice starch; NWS, non-waxy rice starch; GG, guar gum; XG, xanthan gum; CMC, carboxymethyl celullose; Tap, tapioca fibre; Tam, tamarind seed fibre; (5) (10) (15), 5, 10 and 15 g/100 g dry sample addition of NSP to the starch samples, respectively.

[1] Values are means ± standard deviations (triplicate).

Table 5 – DSC parameters of the non-waxy rice starch mixtures.[1]

Samples	T_o (°C)	T_p (°C)	T_c (°C)	ΔH (J/g dry sample)
NWS	73.40 ± 0.08^{d}	77.57 ± 0.13^{e}	82.37 ± 0.57^{d}	6.40 ± 0.56^{a}
NWS+GG(5)	74.59 ± 1.38^{cd}	78.97 ± 1.46^{cde}	85.14 ± 2.48^{bcd}	4.19 ± 0.27^{def}
NWS+GG(10)	75.61 ± 0.08^{abcd}	80.47 ± 0.06^{abcd}	86.74 ± 0.22^{abc}	3.36 ± 0.59^{ef}
NWS+GG(15)	77.20 ± 0.98^{ab}	82.47 ± 1.29^{ab}	89.55 ± 1.99^{a}	3.33 ± 0.17^{f}
NWS+XG(5)	74.55 ± 0.24^{cd}	78.94 ± 0.26^{cde}	85.05 ± 0.23^{bcd}	5.34 ± 0.63^{abcd}
NWS+XG(10)	75.25 ± 0.88^{abcd}	79.88 ± 1.28^{bcde}	85.92 ± 1.99^{abcd}	4.24 ± 0.15^{def}
NWS+XG(15)	74.98 ± 0.18^{bcd}	79.53 ± 0.12^{cde}	85.39 ± 0.06^{bcd}	4.55 ± 0.63^{cdef}
NWS+CMC(5)	75.30 ± 0.74^{abcd}	79.83 ± 0.87^{bcde}	85.20 ± 0.91^{bcd}	5.29 ± 0.46^{abcd}
NWS+CMC(10)	76.67 ± 0.95^{abc}	80.82 ± 0.36^{abc}	86.16 ± 0.16^{abcd}	5.76 ± 0.37^{abc}
NWS+CMC(15)	77.78 ± 0.55^{a}	82.76 ± 0.67^{a}	88.88 ± 1.07^{ab}	4.84 ± 0.17^{bcde}
NWS+Tap(5)	73.30 ± 0.39^{d}	77.76 ± 0.32^{de}	82.57 ± 0.35^{d}	6.18 ± 0.37^{ab}
NWS+Tap(10)	74.30 ± 0.33^{cd}	78.54 ± 0.62^{cde}	83.44 ± 0.50^{cd}	4.66 ± 0.05^{cdef}
NWS+Tap(15)	73.74 ± 0.11^{d}	78.02 ± 0.06^{de}	82.95 ± 0.01^{cd}	4.60 ± 0.37^{cdef}
NWS+Tam(5)	74.25 ± 0.76^{cd}	77.94 ± 0.14^{de}	82.59 ± 0.18^{cd}	5.94 ± 0.05^{abc}
NWS+Tam(10)	74.18 ± 0.07^{cd}	78.31 ± 0.25^{cde}	83.14 ± 0.24^{cd}	5.55 ± 0.00^{abcd}
NWS+Tam(15)	74.75 ± 0.47^{bcd}	78.77 ± 0.53^{cde}	83.70 ± 0.45^{cd}	4.88 ± 0.14^{bcd}

For each parameter (column), values with the same letters are not significantly different ($p > 0.05$).
Abbreviations: WS, waxy rice starch; NWS, non-waxy rice starch; GG, guar gum; XG, xanthan gum; CMC, carboxymethyl celullose; Tap, tapioca fibre; Tam, tamarind seed fibre; (5) (10) (15), 5, 10 and 15 g/100 g dry sample addition of NSP to the starch samples, respectively.
[1] Values are means ± standard deviations (triplicate).

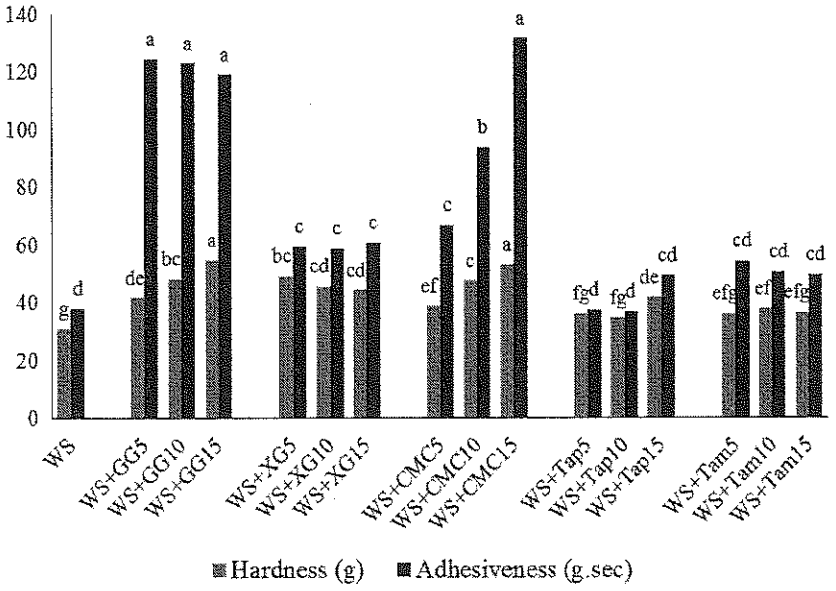

Fig. 1 – Average hardness and adhesiveness values of the waxy starch and NSP gel dispersions. For each parameter, bars with the same letters are not significantly different ($p > 0.05$). WS, waxy rice starch; NWS, non-waxy rice starch; GG, guar gum; XG, xanthan gum; CMC, carboxymethyl celullose; Tap, tapioca fibre; Tam, tamarind seed fibre; (5) (10) (15), 5, 10 and 15 g/100 g dry sample addition of NSP to the starch samples, respectively.

GG or CMC. Smaller increases were noted in the case of XG, Tam and Tap mixtures. In contrast, inconsistent results were obtained for NWS mixtures. The NWS mixtures containing GG, Tam and Tap showed increasing hardness, while XG and CMC mixtures exhibited decreasing hardness. With the increase in NSP concentration, the interaction between helices of NSP increases and the flexible chains become shorter, which could be attributed to a harder and more brittle gel (Barrangou, Daubert, & Foegeding, 2006).

In terms of adhesiveness, this probably is more of a surface characteristic and depends on a combined effect of adhesive and cohesive forces, including viscosity effects as well (Adhikari, Howes, Bhandari, & Truong, 2001). Generally, the adhesiveness increased in the presence of NSPs. The

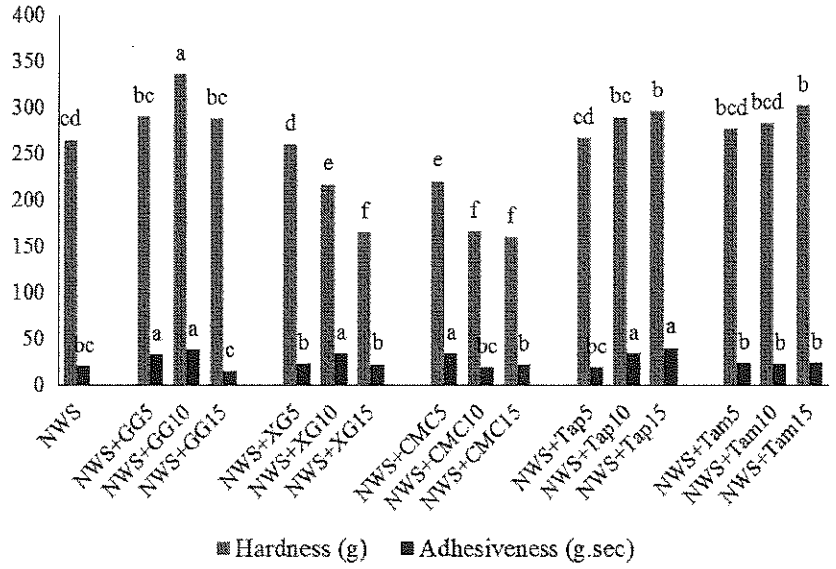

Fig. 2 – Average hardness and adhesiveness values of the non-waxy starch and NSP gel dispersions. For each parameter, bars with the same letters are not significantly different ($p > 0.05$). WS, waxy rice starch; NWS, non-waxy rice starch; GG, guar gum; XG, xanthan gum; CMC, carboxymethyl celullose; Tap, tapioca fibre; Tam, tamarind seed fibre; (5) (10) (15), 5, 10 and 15 g/100 g dry sample addition of NSP to the starch samples, respectively.

results were more obvious in WS samples than those in NWS samples. The high amylose in NWS could interfere and contribute to the changes in texture, and it might have more pronounced effect than NSPs. The textures seem to depend on the type of NSPs. In this study, XG, Tap and Tam were found to have a smaller impact on the texture of rice starches, maintaining the texture profile similar to the control samples.

4. Conclusions

Starch and NSP mixtures are often used to modify the texture of starch based foods. The interaction between starch and NSP has an impact on physicochemical and also nutritional qualities. The potential for altering starch digestibility by blending NSP with starches has been another objective of this work. This paper examined the effects of five NSPs (GG, XG, CMC, Tap and Tam) at a concentration of 5–15 g/100 g dry sample and found that they only had little or no effect on starch digestibility and the physicochemical properties of the starch–NSP mixtures. In general, the GI values slightly decreased as the concentration of NSPs increased. No pronounced changes were found in the thermal properties of the mixtures, as assessed by DSC. However, the non-starch polysaccharides contributed to the modification of the gel textures, resulting in higher hardness and adhesiveness values, especially for the GG and CMC containing mixtures of the WS gel dispersions.

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