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Physicochemical properties, resistant starch content and enzymatic digestibility of unripe banana, edible canna, taro flours and their rice noodle products

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Summary Unripe banana, edible canna and taro flours, which have been reported to contain significant amounts of fibre, were investigated for their physicochemical properties, resistant starch (RS) content and *in vitro* starch digestibility, and compared with commercial high-fibre-modified starches from corn and tapioca. Differential scanning calorimetry showed a single endothermic peak located around 70–83 °C for the samples except the modified starches, which exhibited no transition enthalpy. The samples showed different pasting behaviours in the Rapid Visco-Analyser (RVA) ranging from full to restricted swelling. The RS content varied from 1–26 g per 100 g dry sample, and the estimated glycaemic indices (GIs) of the samples were from 67% to 99%. Generally, samples with high RS were low in GI values. The starches produced acceptable rice noodles but with reduced rate of starch digestion and GI. The effects of the unripe banana, edible canna and taro flours on starch digestibility were either comparable or better than the commercial modified starches. These flours can substitute commercial modified starches to lower GIs of noodles and identical foods.

Keywords Banana flour, canna flour, resistant starch, rice noodle, starch digestibility, taro flour.

Introduction

An emphasis on plant-based foods is driven by the phytochemicals they contain and the desire to increase fibre intake, which is lacking in many diets. There is a general consensus among public health authorities and nutritionists that the inclusion of fibre in human diets provides health benefits (Fernandez-Lopez *et al.*, 2007). Many studies have found that people on diets that are high in dietary fibre have reduced risks of certain diseases such as cancer, coronary heart disease, obesity and possibly diabetes (Buttriss & Stokes, 2008; Viuda-Martos *et al.*, 2010). The Codex Alimentarius Commission Committee on Nutrition and Foods for Special Dietary Uses adopted a new definition of dietary fibre as 'carbohydrate polymers with ten or more monomeric units, which are not hydrolysed by the endogenous enzymes in the small intestine of humans'. Accordingly, RS can be considered a functional dietary fibre by its indigestible nature and beneficial physiological effects (Sajilata *et al.*, 2006; Fuentes-Zaragoza *et al.*, 2010). RS

escapes digestion in the human small intestine and is fermented in the colon with production of metabolically active short chain fatty acids (Topping & Clifton, 2001). According to the Englyst classification, there are four types of RS representing a broad and diverse range of materials that are mostly defined according to physical and chemical characteristics (Englyst *et al.*, 1992; Nugent, 2005).

Unripe banana starch has long been a subject of interest because of its functional properties and health benefits (Kayisu *et al.*, 1981; Langkilde *et al.*, 2002). It has been reported to be rich in starch with total dietary fibre that ranged from 6% to 15% (Suntharalingam & Ravindran, 1993; da Mota *et al.*, 2000; Juarez-Garcia *et al.*, 2006). Canna starch has gained interest because of its high amylose content and large starch granule size (Pérez & Lares, 2005; Cisneros *et al.*, 2009). Hence, native edible canna starch was found to be highly resistant to hydrolysis by amylase enzymes (Hung & Morita, 2005). Taro flour has also been reported to be rich in starch and total dietary fibre (Jane *et al.*, 1992; Tagodoe & Nip, 1994). Consequently, banana, edible canna and taro flour/starch could have the potential to be used as functional ingredients. However, there could

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be varietal/cultivar and location differences. It is also important to understand how newly identified functional ingredients compare with existing or commercial ones. Therefore, this study examined the physicochemical properties and starch digestibility of unripe banana, edible canna and taro flours in comparison with two commercially available high-fibre-modified starches. The nutritional effects on addition of the studied flours/starches into rice noodles were also investigated.

Materials and methods

Materials

Unripe banana, edible canna and taro flours were purchased locally. Banana flour was produced from matured unripe banana (green and/or green trace of yellow peel colour). All the flour samples were processed by wet milling. Modified starch (Brand A), high-fibre-modified corn starch, was purchased from National Starch and Chemical (Thailand) Co., Ltd., Samut Prakan, Thailand. This product was derived from high-amylose corn starch. The supplier labelled a minimum of 60 g per 100 g dry sample total dietary fibre, pH 4.5–7.5 and particle size 10–15 μm . Modified starch (Brand B), high-fibre-modified tapioca starch, was purchased from T-fibre Innovation Co., Ltd. (Nakhon Ratchasima, Thailand). The supplier labelled a minimum of 40 g per 100 g dry sample total dietary fibre. All samples were sieved through 100-mesh screen prior to analysis. This study investigated the flours rather than starches, because apart from the simplicity and ease of flour production, and therefore less expense (da Mota *et al.*, 2000), the interactions of starch with nonstarch components in the flours define the functional properties of the flours.

Differential scanning calorimetry (DSC)

The moisture content of the samples (10–14 g per 100 g dry sample) was adjusted to 70 g per 100 g dry sample by adding deionised water prior to DSC (Mettler Toledo DSC 1, equipped with refrigerated cooler). The hydrated samples were kept in airtight containers overnight at room temperature to ensure that they were completely equilibrated. The hydrated samples (20 ± 5 mg) were weighed in the aluminium DSC pans and hermetically sealed. An empty pan was used as the reference, and DSC analysis was done by equilibrating at 30 °C, isothermal for 5 min and ramping at 10 °C per min to 120 °C. The resulting thermograms were analysed using Mettler Toledo Star[®] software (ver. 9.20) for the onset temperature (T_o), peak temperature (T_p), conclusion temperature (T_c) and transition enthalpy. Each sample was analysed in duplicate.

Rapid visco-analysis (RVA)

Pasting properties were investigated using the Rapid Visco-Analyser (RVA-4D; Newport Scientific Pvt Ltd., Warriewood, NSW Australia) following the approved method 61.02 (AACC, 2009). A 13-min RVA profile was used with 3.0 g ground samples (adjusted to 14% moisture content) in 25 mL distilled water. The RVA Thermocline[™] software (ver. 2.6) was used to obtain the RVA profiles and pasting characteristics. Each sample was analysed in duplicate.

Resistant starch content

Resistant starch, non-RS and total starch (TS) fractions were determined using the Megazyme RS assay kit (Megazyme International, Wicklow, Ireland), following the approved AACC method 32–40 (AACC, 2009). Briefly, ground sample (100 ± 5 mg) was accurately weighed into a screw cap tube. Non-RS fraction in the sample was solubilised and hydrolysed to glucose by the combined action of pancreatic α -amylase and amyloglucosidase (AMG) for 16 h at 37 °C in a shaking water bath. The reaction was stopped by the addition of ethanol, and RS was recovered as a pellet by centrifugation. The pellet was dissolved in 2 M KOH by vigorously stirring in an ice water bath. This solution was neutralised with acetate buffer, and the starch was quantitatively hydrolysed to glucose with AMG. Glucose released, which is a measure of RS content and non-RS (solubilised starch), was measured spectrophotometrically at 510 nm with glucose oxidase–peroxidase reagent (GOPOD). TS content was then calculated as the summation of RS and non-RS.

In-vitro starch digestion and modelling of starch digestogram

Time-course starch digestion in the samples was determined using a rapid *in vitro* digestibility assay based on glucometry (Sopade & Gidley, 2009; Mahasukhonthachat *et al.*, 2010). About 0.5 g of ground sample was treated with artificial saliva containing porcine α -amylase (Sigma A-3176 Type VI-B) before pepsin (Sigma P-6887; pH 2.0) was added and incubated at 37 °C for 30 min in a reciprocating water bath (85 rpm). The digesta was neutralised with NaOH before adjusting the pH to 6 (sodium acetate buffer) prior to the addition of pancreatin (Sigma P1750) and AMG (Sigma A-7420). The mixture was incubated for 4 h, during which the glucose concentration in the digesta was measured with an Accu-Check[®] Performa[®] glucometer (Roche Thailand Co., Ltd., Bangkok, Thailand) at specific periods (0, 10, 20, 30, 45, 60, 90, 120, 150, 180, 210 and 240 min). Digested starch per 100 g dry starch (DS) was calculated as in eqn (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^{-1}), V = volume of digesta (mL), 180 = molecular weight of glucose, W = weight of sample (g), S = starch content of sample (g per 100 g sample), M = moisture content of a sample (g per 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, eqn (2), as described earlier (Mahasukhonthachat *et al.*, 2010):

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

where D_t (g per 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 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).

To calculate the glycaemic indices (GIs) of the samples, the areas under the digestograms (AUC_{exp}) were computed with eqn (3), which is the integral form of eqn (1):

$$AUC_{\text{exp}} = \left[D_{\infty}t + \frac{D_{\infty-0}}{K} \exp(-Kt) \right]_0^t \quad (3)$$

The hydrolysis index (HI) of each sample was calculated by dividing (Goni *et al.*, 1997) the area under its digestogram by the area under the digestogram of a fresh white bread, which was calculated to be about 13 000 min g per 100 g dry starch from 0–240 min. (Yong *et al.*, 2010). From the study by Goni *et al.* (1997), single-point measurements of starch digestion at 90 min in the samples were also used to calculate GI (H_{90}). Hence, using the parameters of the modified first-order kinetic model, eqn (2), for both the samples and fresh white bread, GIs of the samples were also calculated, and the average GI (GI_{AVG}) for each sample was defined by eqn (4):

$$GI_{\text{AVG}} = \left[\frac{((39.21 + 0.803H_{90}) + (39.51 + 0.573HI))}{2} \right] \quad (4)$$

Addition of the investigated flours/starches in rice noodles

Trials in our laboratory found that 20% of the investigated flours/modified starches could be added to

normal rice noodle formula without significant effects on taste and textural properties of the noodles as indicated by sensory evaluations (data not shown). Hence, normal rice noodle formula was added with unripe banana, edible canna, taro flours and two modified starches, each at the same level of 20 g per 100 g dry ingredient. The mixtures were used to produce dry rice noodles under a commercial noodle plant environment by wet milling, slurry ageing, spreading to sheets and steaming, ageing of steamed noodle sheets, cutting to the size of $\sim 0.5 \times 30$ cm and drying. The samples were analysed for TS, RS and starch digestibility as described previously. Normal rice noodle formula produced from 100% medium amylose rice was used as the control sample.

Statistical analysis

Analysis of variance (ANOVA) and test of significance were performed using SPSS[®] ver. 17 (SPSS (Thailand) Co., Ltd., Bangkok, Thailand) with confidence level of 95%. The samples were randomised for all the analysed described earlier.

Results and discussion

Physicochemical and starch digestibility properties of the flour and modified starch samples

Table 1 summarises the physicochemical and starch digestibility properties of the unripe banana, edible canna and taro flours including the two modified starches (Brands A and B). In terms of the gelatinisation behaviours, banana, edible canna and taro flours exhibited a single endothermic peak. Notably, both the commercial modified starches (A and B) did not show any transition energy change. This suggests changes in starch granule molecular order and structures by the modification process. According to the manufacturer, Brand A is a high-amylose starch, which generally gelatinises at high temperatures. In this study, the gelatinisation temperatures and enthalpy of the unripe banana flour were found to be higher than those of the taro and edible canna flours. Gelatinisation temperatures of the banana, edible canna and taro flours can vary because of factors that include genetic origin, environmental conditions and age of the parent plant (Jane *et al.*, 1992; da Mota *et al.*, 2000; Moorthy, 2002; Hung & Morita, 2005). High-amylose starches with longer average chain have been reported to exhibit higher transition temperatures (Jane *et al.*, 1992).

Figure S1 (see Supporting Information available online) shows the RVA profile of the samples. Modified starch A did not swell, and as highlighted earlier, the modification process appeared to have completely altered the native starch characteristics. Alternatively,

Table 1 Physicochemical and digestibility properties of the flour and modified starch samples*

Parameters	Unripe banana flour	Edible canna flour	Taro flour	Brand A	Brand B
Starch property (g per 100 g solids)					
TS	30.4 ^d ± 0.42	34.0 ^c ± 1.99	28.3 ^d ± 0.90	74.2 ^a ± 1.51	43.7 ^b ± 1.46
RS	12.5 ^c ± 0.49	18.6 ^b ± 0.45	12.0 ^c ± 0.09	26.1 ^a ± 0.31	0.8 ^d ± 0.01
Non-RS	17.9 ^c ± 0.08	15.4 ^c ± 1.70	16.3 ^c ± 0.91	48.1 ^a ± 1.41	42.9 ^b ± 2.46
DSC property (°C, J g ⁻¹)					
Onset	79.28 ^a ± 0.34	67.18 ^b ± 0.43	67.09 ^b ± 0.09	nd	nd
Peak	83.15 ^a ± 0.75	70.67 ^b ± 0.06	70.25 ^b ± 0.15	nd	nd
Conclusion	88.52 ^a ± 2.12	75.11 ^b ± 0.67	74.17 ^b ± 0.14	nd	nd
Enthalpy (sample)	19.25 ^a ± 1.26	11.58 ^b ± 1.27	12.96 ^b ± 1.12	nd	nd
Pasting property (°C, RVU)					
Pasting temperature	83.82 ^b ± 0.31	75.97 ^c ± 0.24	88.37 ^a ± 0.03	nd	73.25 ^d ± 0.21
Peak viscosity	348.95 ^b ± 4.30	430.00 ^a ± 1.17	80.12 ^d ± 1.11	nd	125.37 ^c ± 1.70
Trough viscosity	254.87 ^b ± 1.94	261.00 ^a ± 0.82	75.20 ^d ± 1.47	nd	83.75 ^c ± 0.11
Final viscosity	381.50 ^a ± 3.53	354.54 ^b ± 5.48	109.66 ^c ± 3.41	nd	113.29 ^c ± 0.64
In vitro starch digestion property (g per 100 g dry starch; min ⁻¹ ; %)					
Gastric-pancreatic					
D ₀	47.1 ^b ± 0.31	46.4 ^b ± 1.75	61.0 ^a ± 4.24	22.4 ^d ± 0.43	33.2 ^c ± 0.32
D _∞	94.6 ^{ab} ± 7.71	100.0 ^a ± 0.00	84.0 ^b ± 6.37	62.7 ^c ± 0.79	100.0 ^a ± 0.00
K × 10 ⁻³	2.8 ^b ± 0.62	1.3 ^b ± 0.08	14.1 ^a ± 4.19	9.4 ^a ± 0.06	9.2 ^a ± 1.04
GI _{H90}	85 ^c ± 0.5	81 ^c ± 1.5	101 ^a ± 2.6	76 ^d ± 0.4	96 ^b ± 2.3
GI _{HI}	101 ^b ± 0.4	96 ^b ± 2.0	119 ^a ± 4.1	88 ^c ± 0.6	115 ^a ± 2.4
GI _{AVG}	93 ^b ± 0.5	88 ^b ± 1.8	110 ^a ± 3.4	82 ^c ± 0.5	105 ^a ± 2.4
Pancreatic					
D ₀	44.9 ^b ± 7.03	75.0 ^a ± 2.64	25.2 ^c ± 1.21	40.4 ^b ± 0.34	79.4 ^a ± 7.22
K × 10 ⁻³	3.1 ^{cd} ± 0.65	1.0 ^d ± 0.10	25.9 ^a ± 3.42	11.3 ^b ± 0.12	6.8 ^c ± 0.75
GI _{H90}	48 ^d ± 0.2	44 ^a ± 0.3	57 ^c ± 0.3	60 ^b ± 0.1	68 ^a ± 0.3
GI _{HI}	53 ^d ± 0.1	48 ^a ± 0.5	61 ^c ± 0.5	67 ^b ± 0.1	81 ^a ± 1.0
GI _{AVG}	50 ^d ± 0.2	46 ^a ± 0.4	59 ^c ± 0.4	63 ^b ± 0.3	74 ^a ± 0.7

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

nd, not detectable; DSC, Differential scanning calorimetry; GI, glycaemic indices; HI, hydrolysis index; RS, resistant starch; TS, total starch.

*Values are means ± standard deviations.

the pasting behaviours of Brand A resemble those of high-amylose starches. The modified tapioca starch (Brand B) swelled during the RVA heating process. This is surprising because while the pasting behaviours of this sample appear to suggest the presence of native starch granules, there was no evidence of starch gelatinisation in the DSC. However, although both the RVA and DSC measure different properties of starch in excess water, it is expected that native starch granules that pasted in the RVA would be gelatinised with an enthalpy change in the DSC. In view of its pasting properties, it is unlikely that Brand B is a high-amylose starch. The unripe banana and edible canna flours gave higher peak and final viscosities than those of taro, while their pasting temperatures were essentially identical (Table 1). Although both the unripe banana and edible canna flours can be said to have higher water binding capacity than the taro flour, the latter was more resistant to shear, more stable during cooling and retrograded less as indicated by lower breakdown and setback viscosities. The pasting behaviours of the unripe banana, edible canna and taro flours (Table 1) are generally in agreement with published studies (Jane

et al., 1992; da Mota *et al.*, 2000; Piyachomkwan *et al.*, 2002; Thitipraphunkul *et al.*, 2003; Aboubakar *et al.*, 2008; Haslinda *et al.*, 2009). In addition, the entanglement and interaction between amylose and amylopectin molecules and entrapped incompletely disrupted granules are also responsible for the viscosity characteristics of starch pastes and gels (Debet & Gidley, 2007).

For RS, non-RS and TS, the data are also summarised in Table 1; non-RS or digestible starch is the difference between total and resistant starches. The samples contained significant amounts of RS except the modified tapioca starch (Brand B), which contained about 1 g per 100 g dry sample. As expected, the modified maize starch (Brand A) contained the highest amount of RS because of its high-amylose content. Unripe banana is considered the RS-richest nonprocessed food with more than 10% RS, which could vary with genotype and environment (Juarez-Garcia *et al.*, 2006; Fuentes-Zaragoza *et al.*, 2010). Unripe or green banana could represent an alternative source of indigestible carbohydrates. Edible canna and taro flours were also reported to contain high RS (Aboubakar *et al.*, 2009; Zhang *et al.*, 2009). Probably because of

their large starch granules or presence of starch–protein interactions, tubers and legumes generally tend to have high RS, but plant sources can vary (0–80%) in their RS contents (Giczewska & Borowska, 2003; Chen *et al.*, 2010). Moreover, hydrothermal processing can cause an increase or decrease in the RS fraction depending on the process conditions and postprocess handling (Giczewska & Borowska, 2003).

Figure S2 shows the starch digestograms of the samples. Figure S2a depicts the gastric–pancreatic data, while the pancreatic data, obtained by subtracting the gastric data, are plotted in Figure S2b. The modified first-order kinetic model, eqn (2), was suitable ($r^2 = 0.869$ – 0.993 ; MRDM = 1–18%; SUMSQ = 5–141) in describing the digestograms from both approaches. All the samples exhibited high D_0 (gastric digestion), a measure of the very rapidly digested starch (VRDS). Despite having high-amylose content, Brand A showed a higher rate of digestion (K) than the unripe banana and edible canna flours. However, Brand A had more or less the lowest maximum digested starch (D_∞). The estimated GI of the samples was higher than 50% (Table 1). Generally, Brand A would have the lowest GI, while taro flour and Brand B would give the highest GI. The higher resistant starch content was reported to reduce starch digestion rate in various food systems (Choi *et al.*, 2010; Yadav *et al.*, 2010). Among the flours, the unripe banana and edible canna appeared to be potential valuable ingredients for low-GI foods and might prove better than the modified tapioca starch (Brand B). The GI of foods depends upon various factors such as starch granule morphology, amylose to amylopectin ratio, molecular structure, degree of branching in terms of steric hindrance and consequently mass transfer resistance (Fuentes-Zaragoza *et al.*, 2010; Singh *et al.*, 2010). Starchy foods that are rich in amylose content are associated with lower blood glucose levels and slower emptying of human gastrointestinal tract compared to those with low levels of amylose (Behall *et al.*, 1988, 1989). Amylose content was reported to have an obvious impact on GI values and RS content. The contents of RS were increased with the increasing amylose as studied in rice (Hu *et al.*, 2004). Edible canna and banana starches were reported to contain substantial amount of amylose, ranging from 19% to 23% in edible canna (Thitipraphunkul *et al.*, 2003; Hung & Morita, 2005) and 16–20% in unripe banana (Zhang *et al.*, 2005). Both intrinsic resistance and encapsulation of starch granules in edible canna and unripe banana flour samples could contribute to low digestibility found in this study. The large amount of resistant starch in edible canna and unripe banana starches was considered to relate with B-type crystal structure (Hung & Morita, 2005). Taro starches were reported to contain about 21–23% amylose (Aboubakar *et al.*, 2008). However, because of the small sizes of its

starch granules, taro is highly digestible (Jane *et al.*, 1992). It is widely recognised that low-GI foods are valuable for use in controlled glucose release applications and in lowering insulin response, and greater access to the use of stored fat is expected (Nugent, 2005; Sajilata *et al.*, 2006). This is important for diabetes and its dietary management.

The present study showed native or regular unripe banana and edible canna flours can have similar or better functional properties as obtained from commercial modified starches. This appears to support the conclusions of Moorthy (2002) that some tropical tuber and root crop starches have the potential to be used in low-GI foods.

Starch content and digestibility of rice noodles

Rice noodles, which are usually produced from medium amylose broken rice, were used as the study model as it is among the popular rice products in tropical countries where banana, edible canna and taro flours are abundant. Noodles are also particularly a notable dietary item in Asia. Table 2 summarises the properties of the rice noodles with and without the flours and starches. The rice noodles are rich in TS, and the addition of the flours/starches significantly increased RS content in the final products. In this study, TS of rice noodles ranged from about 65 to 79 g per 100 g dry sample (Table 2). As expected, modified starch A provided the highest RS content because it is a high-amylose starch with a high RS content. Among all the flours, the edible canna and unripe banana flours were proved to be the promising source of indigestible carbohydrates, providing significant amounts of RS in the processed product as speculated earlier.

Figure S3 shows the starch digestograms of the noodles. As with the flours and starches, the modified first-order kinetic model, eqn (2), was suitable ($r^2 = 0.982$ – 0.996 ; MRDM = 2–11%; SUMSQ = 16–86) in describing the digestograms. All the noodles exhibited high D_0 (VRDS), which is not surprising because of the gelatinising effects of the heat–moisture treatments during the noodle manufacture. This could also be partly responsible for the reduction in the RS content of the noodles in comparison with the flours and starches (Table 1). The presence of the flours and starches reduced (14–68%) the rate of starch digestion in the noodles to show the beneficial effects of the substitution. This also translates to reduced GI values in the substituted rice noodles even though, irrespective of the modelling approach (gastric–pancreatic or pancreatic), GI values were higher than 55%, being the upper limit for low-GI foods. In terms of their GI values, foods are classified as high (70% and above), medium (56–69%) and low (55% and under). Although the substituted noodles still gave high GI values, the noodles

Table 2 Starch content and digestibility properties of the noodles added with high-fibre flours or modified starch samples

Parameters	Control	Noodle with unripe banana flour	Noodle with edible canna flour	Noodle with taro flour	Noodle with modified starch A	Noodle with modified starch B
Starch property (g per 100 g solids)						
TS	74.7 ^a ± 1.87	73.9 ^a ± 2.44	72.8 ^a ± 5.37	78.5 ^a ± 5.31	78.5 ^a ± 4.35	64.8 ^b ± 0.61
RS	1.00 ^a ± 0.24	2.47 ^c ± 0.12	3.64 ^b ± 0.07	1.16 ^{de} ± 0.15	8.77 ^a ± 0.01	1.40 ^d ± 0.06
Non-RS	73.7 ^{ab} ± 1.81	71.4 ^{ab} ± 2.56	69.2 ^{bc} ± 5.37	77.34 ^a ± 5.43	69.7 ^{bc} ± 4.42	63.4 ^d ± 0.64
In vitro starch digestion property (g per 100 g dry starch; min ⁻¹ ; %)						
Gastric-pancreatic						
D ₀	31.5 ^a ± 3.79	29.5 ^a ± 0.09	29.1 ^a ± 0.71	28.2 ^a ± 0.14	30.9 ^a ± 1.18	32.0 ^a ± 0.57
D ₁	99.2 ^a ± 1.16	100.0 ^a ± 0.00	100.0 ^a ± 0.00	93.1 ^{ab} ± 0.46	89.3 ^b ± 6.65	97.9 ^a ± 1.75
K × 10 ⁻³	14.9 ^a ± 2.87	7.4 ^b ± 0.10	6.5 ^{cd} ± 0.61	12.8 ^a ± 0.00	8.2 ^b ± 1.57	11.8 ^a ± 0.00
GI _{H90}	104 ^a ± 3.8	90 ^c ± 0.3	88 ^c ± 2.0	98 ^b ± 0.3	88 ^c ± 0.0	100 ^b ± 1.1
GI _{HI}	123 ^a ± 3.5	109 ^c ± 0.3	106 ^c ± 2.4	115 ^b ± 0.4	105 ^c ± 0.9	118 ^{ab} ± 1.4
GI _{AVG}	113 ^a ± 3.7	99 ^c ± 0.3	97 ^c ± 2.2	106 ^b ± 0.3	97 ^c ± 0.5	109 ^b ± 1.2
Pancreatic						
D ₀	69.0 ^b ± 3.43	77.7 ^a ± 0.52	84.5 ^a ± 3.05	64.6 ^{bc} ± 0.32	59.1 ^c ± 6.31	65.6 ^{bc} ± 1.17
K × 10 ⁻³	14.6 ^a ± 3.37	6.2 ^c ± 0.02	4.7 ^c ± 0.00	12.4 ^a ± 0.00	7.6 ^{bc} ± 1.69	11.4 ^{ab} ± 0.00
GI _{H90}	79 ^a ± 2.9	67 ^c ± 0.1	62 ^d ± 0.8	74 ^b ± 0.2	62 ^d ± 1.1	73 ^b ± 0.6
GI _{HI}	91 ^a ± 2.0	79 ^c ± 0.2	74 ^d ± 1.3	85 ^b ± 0.2	72 ^d ± 0.6	84 ^b ± 0.8
GI _{AVG}	85 ^a ± 2.5	73 ^c ± 0.2	68 ^d ± 1.1	80 ^b ± 0.2	67 ^d ± 0.9	79 ^b ± 0.7

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

GI, glycaemic indices; HI, hydrolysis index; RS, resistant starch; TS, total starch.

from the edible canna and unripe banana flours gave the lowest reduction in GI compared with the control, lower GI than the noodle from the modified starch B and essentially the same GI as the noodle from the modified starch A. Banana flours were reported to successfully enhance the nutritional properties in noodles products (Ramli *et al.*, 2009; Choo & Aziz, 2010), and the results obtained in the present study are consistent with the general trend. The results are also remarkable because banana and edible canna are locally available in Thailand, and their flours can be easily produced. This will not only save cost, but it will provide local taste to a popular food product (noodles).

Conclusions

Resistant starch has received much attention for both its health and nutritional benefits. The functional properties of unripe banana, edible canna and taro flours were investigated in comparison with two commercial modified high-fibre starches. All the investigated flours, specifically unripe banana and edible canna flours, contained significant amount of RS. They also showed the potential to be used as functional ingredients for lowering GIs in starchy food products, rice noodle as an example in this study. The inherent characteristics of these flours can help in value addition of these crops and contribute to well-being and food security in the tropical and subtropical regions, where these crops are abundantly grown.

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References

- AACC (2009). *AACC International Approved Methods of Analysis* (Method 32-40, 61-02), 11th edn. St. Paul MN: AACC International.
- Aoubakar, Njintang, Y.N., Scher, J. & Mbofung, C.M.F. (2008). Physicochemical, thermal properties and microstructure of six varieties of taro (*Colocasia esculenta* L. Schott) flours and starches. *Journal of Food Engineering*, **86**, 294–305.
- Aoubakar, Njintang, Y.N., Scher, J. & Mbofung, C.M.F. (2009). Texture, microstructure and physicochemical characteristics of taro (*Colocasia esculenta*) as influenced by cooking conditions. *Journal of Food Engineering*, **91**, 373–379.
- Behall, K.M., Scholfield, D.J. & Canary, J. (1988). Effect of starch structure on glucose and insulin responses in adults. *American Journal of Clinical Nutrition*, **47**, 428–432.
- Behall, K.M., Scholfield, D.J., Yuhaniak, I. & Canary, J. (1989). Diets containing high amylose vs amylopectin starch: effects on metabolic variables in human subjects. *American Journal of Clinical Nutrition*, **49**, 337–344.
- Buttriss, J.L. & Stokes, C.S. (2008). Dietary fibre and health: an overview. *British Nutrition Foundation, Nutrition Bulletin*, **33**, 186–200.
- Chen, L.Y., Liu, R.P., Qin, C.Y. *et al.* (2010). Sources and intake of resistant starch in the Chinese diet. *Asia Pacific Journal of Clinical Nutrition*, **19**, 274–282.
- Choi, H.J., Lee, C.J., Cho, E.J., Choi, S.J. & Moon, T.W. (2010). Preparation, digestibility, and glucose response in mice of rice

- coated with resistant starch type 4 using locust bean gum and agar. *International Journal of Food Science & Technology*, 45, 2612–2621.
- Choo, C.L. & Aziz, N.A.A. (2010). Effects of banana flour and beta-glucan on the nutritional and sensory evaluation of noodles. *Food Chemistry*, 119, 34–40.
- Cisneros, F.H., Zevillanos, R. & Cisneros-Zevallos, L. (2009). Characterization of Starch from two Ecotypes of Andean Achira Roots (*Canna edulis*). *Journal of Agricultural and Food Chemistry*, 57, 7363–7368.
- Debet, M.R. & Gidley, M.J. (2007). Why do gelatinized starch granules not dissolve completely? Roles for amylose, protein, and lipid in granule “ghost” integrity. *Journal of Agricultural and Food Chemistry*, 55, 4752–4760.
- Englyst, H.N., Kingman, S.M. & Cummings, J.H. (1992). Classification and measurement of nutritionally important starch fractions. *European Journal of Clinical Nutrition*, 46, 3–50.
- Fernandez-Lopez, J., Viuda-Martos, M., Sendra, E., Sayas-Barbera, E., Navarro, C. & Perez-Alvarez, J.A. (2007). Orange fibre as potential functional ingredient for dry-cured sausages. *European Food Research and Technology*, 226, 1–6.
- Fuentes-Zaragoza, E., Riquelme-Navarrete, M.J., Sanchez-Zapata, E. & Perez-Alvarez, J.A. (2010). Resistant starch as functional ingredient: a review. *Food Research International*, 43, 931–942.
- Giczewska, A. & Borowska, J. (2003). Nutritional value of broad bean seeds. Part I: starch and fibre. *Nahrung-Food*, 47, 95–97.
- Goni, L., Garcia-Alonso, A. & Saura-Calixto, F. (1997). A starch hydrolysis procedure to estimate glycemic index. *Nutrition Research*, 17, 427–437.
- Haslinda, W.H., Cheng, L.H., Chong, L.C. & Aziah, A.A.N. (2009). Chemical composition and physicochemical properties of green banana (*Musa acuminata* x *balbisiana* Colla cv. Awak) flour. *International Journal of Food Sciences and Nutrition*, 60, 232–239.
- Hu, P., Zhao, H., Duan, Z., Linlin, Z. & Wu, D. (2004). Starch digestibility and the estimated glycemic score of different types of rice differing in amylose contents. *Journal of Cereal Science*, 40, 231–237.
- Hung, P.V. & Morita, N. (2005). Physicochemical properties and enzymatic digestibility of starch from edible canna (*Canna edulis*) grown in Vietnam. *Carbohydrate Polymers*, 61, 314.
- Jane, J., Shen, L., Chen, J., Lim, S., Kasemsuwan, T. & Nip, W.K. (1992). Physical and chemical studies of taro starches and flours. *Cereal Chemistry*, 69, 528–535.
- Juarez-Garcia, E., Agama-Acevedo, E., Sáyago-Ayerdi, S.G., Rodriguez-Ambroz, S.L. & Bello-Pérez, L.A. (2006). Composition, digestibility and application in breadmaking of banana flour. *Plant Foods for Human Nutrition*, 61, 131–137.
- Kayisu, K., Hood, L.F. & Vanzoest, P.J. (1981). Characterization of starch and fiber of banana fruit. *Journal of Food Science*, 46, 1885–1890.
- Langkilde, A.M., Champ, M. & Andersson, H. (2002). Effects of high-resistant-starch banana flour (RS2) on in vitro fermentation and the small-bowel excretion of energy, nutrients, and sterols: an ileostomy study. *American Journal of Clinical Nutrition*, 75, 104–111.
- Mahasukhonthachai, K., Sopade, P.A. & Gidley, M.J. (2010). Kinetics of starch digestion in sorghum as affected by particle size. *Journal of Food Engineering*, 96, 18–28.
- Moorthy, S.N. (2002). Physicochemical and functional properties of tropical tuber starches: a review. *Starch-Stärke*, 54, 559–592.
- da Mota, R.V., Lajolo, F.M., Cordenunsi, B.R. & Ciacco, C. (2000). Composition and functional properties of banana flour from different varieties. *Starch – Stärke*, 52, 63–68.
- Nugent, A.P. (2005). Health properties of resistant starch. *British Nutrition Foundation, Nutrition Bulletin*, 30, 27–54.
- Pérez, E. & Lures, M. (2005). Chemical composition, mineral profile, and functional properties of canna (*Canna edulis*) and arrowroot (*Maranta spp.*) starches. *Plant Foods for Human Nutrition*, 60, 113–116.
- Piyachomkwan, K., Chotinceranat, S., Kijhunasatian, C. et al. (2002). Edible canna (*Canna edulis*) as a complementary starch source to cassava for the starch industry. *Industrial Crops and Products*, 16, 11.
- Ramli, S., Alkarkhi, A.F.M., Yong, Y.S., Min-Tze, L. & Easa, A.M. (2009). Effect of banana pulp and peel flour on physicochemical properties and in vitro starch digestibility of yellow alkaline noodles. *International Journal of Food Sciences and Nutrition*, 60, 326–340.
- Sajilata, M.G., Singhal, R.S. & Kulkarni, P.R. (2006). Resistant starch – A review. *Comprehensive Reviews in Food Science and Food Safety*, 5, 1–17.
- Singh, J., Dartois, A. & Kaur, L. (2010). Starch digestibility in food matrix: a review. *Trends in Food Science & Technology*, 21, 168–180.
- Sopade, P.A. & Gidley, M.J. (2009). A rapid in-vitro digestibility assay based on glucometry for investigating kinetics of starch digestion. *Starch-Stärke*, 61, 245–255.
- Suntharalingam, S. & Ravindran, G. (1993). Physical and biochemical properties of green banana flour. *Plant Foods for Human Nutrition*, 43, 19–27.
- Tagodoe, A. & Nip, W.K. (1994). Functional properties of raw and precooked taro (*Colocasia esculenta*) flours. *International Journal of Food Science & Technology*, 29, 457–462.
- Thitipraphunkul, K., Uttapap, D., Piyachomkwan, K. & Takeda, Y. (2003). A comparative study of edible canna (*Canna edulis*) starch from different cultivars. Part I. Chemical composition and physicochemical properties. *Carbohydrate Polymers*, 53, 317.
- Topping, D.L. & Clifton, P.M. (2001). Short-chain fatty acids and human colonic function: roles of resistant starch and nonstarch polysaccharides. *Physiological Reviews*, 81, 1031–1064.
- Viuda-Martos, M., López-Marcos, M.C., Fernández-López, J., Sendra, E., López-Vargas, J.H. & Pérez-Alvarez, J.A. (2010). Role of fiber in cardiovascular diseases: a review. *Comprehensive Reviews in Food Science and Food Safety*, 9, 240–258.
- Yadav, B.S., Sharma, A. & Yadav, R.B. (2010). Effect of storage on resistant starch content and in vitro starch digestibility of some pressure-cooked cereals and legumes commonly used in India. *International Journal of Food Science & Technology*, 45, 2449–2455.
- Yong, L.-Z., Chan, C.H., Garcia, C. & Sopade, P.A. (2010). Weighing up whey fortification of foods: implications for kinetics of starch digestion and estimated glycemic index of model high-protein-low-carbohydrate food systems. *Carbohydrate Polymers*, 84, 162–172.
- Zhang, P., Whistler, R.L., BeMiller, J.N. & Hamaker, B.R. (2005). Banana starch: production, physicochemical properties, and digestibility—a review. *Carbohydrate Polymers*, 59, 443–458.
- Zhang, J., Wang, Z.W. & Shi, X.M. (2009). Effect of microwave heat/moisture treatment on physicochemical properties of *Canna edulis* Kerstarch. *Journal of the Science of Food and Agriculture*, 89, 653–664.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Pasting rapid visco-analysis behaviours of the of unripe banana, edible canna, taro flours and two modified starches (Brand A and B).

Figure S2. Gastric–pancreatic (a) and pancreatic digestograms (b) of banana flour (♦), edible canna flour (▲), taro flour (■), modified starch A (+) and modified starch B (●).

Figure S3. Gastric–pancreatic (a) and pancreatic digestograms (b) of noodle samples; control (♦), with added banana flour (▲), with added canna flour (■), with added taro flour (+), with added modified starch A (●) and with added modified starch B (□).

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