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Physicochemical properties and *in vitro* digestibility of starches from different Taiwanese banana cultivars

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Abstract

The physicochemical and digestive properties of starches from Taiwanese bananas (*Musa* AAA Cavendish; Pei Chiao, Tai Chiao No. 5, Tai Chiao No. 7, and *Musa* ABB; Kluai Namwa) were studied. Relationships between properties and banana cultivars were evaluated by principal component analysis (PCA). Results showed that the bananas had high starch (91.11 - 96.24%; dry basis), and low protein (0.16 - 0.31%), fat (not detected), and ash (0.25 - 0.35%) contents. Amylose contents, gelatinisation transition temperature, and gelatinisation enthalpy (ΔH) varied from 25.89 to 33.48%, 63.89 to 86.83°C, and 9.8 to 12.3 J/g, respectively. Banana starch pastes exhibited high peak viscosity (357.92 - 477.69 RVU), low breakdown viscosity (88.69 - 194.31 RVU), and low setback viscosity (37.67 - 147.08 RVU). Swelling power and solubility of all four banana cultivars rapidly increased at 75°C with highest swelling power (21.40 - 33.99 g water/g starch) and solubility (22.92 - 38.62%) values observed at 95°C. *In vitro* digestibility tests of raw banana starches showed 74.09 to 85.88% resistant starch (RS). Kluai Namwa had the highest RS content. After cooking, RS converted to rapidly digestible starch (RDS), and slowly digestible starch (SDS). RS and SDS remained in cooked bananas with lowest and highest combined values being observed in cooked Tai Chiao No. 5 and Kluai Namwa starch, respectively. Combined SDS and RS of the four studied banana cultivars ranged from 24.53 to 46.94%. Relationships of various properties evaluated by PCA showed that the first two components described 88.2% of the total variance.

Introduction

Banana is one of important staple crops in many developing countries, and regarded as the world's fourth highest value crop in terms of gross production income after rice, wheat, and corn (Arias *et al.,* 2003). However, it is a climacteric fruit and highly perishable, leading to serious economic losses during handling, storage, and transportation. Banana is typically consumed at ripe stage, but generally harvested in hard mature unripe green stage; around 10 - 15% of bananas harvested are discarded due to physical defect (Bi *et al.,* 2017). These postharvest wastes can alternatively be used as raw materials for the production of flour, extraction of starch or resistant starch, and other functional ingredients.

In 2018, the global native starch market amounted to 88.2 million tons (MT), and this is expected to increase to 98.2 million tons (MT) by 2024 (Singla *et al.,* 2020). Commercial native starches are mostly obtained from corn and wheat in developed countries, while starches from potato, tapioca (cassava), and taro are found in Africa, India, Brazil, Thailand, The Philippines, and Indonesia as the world's largest exporters (Romano *et al.,* 2016; Singla *et al.,* 2020). Starch has wide-ranging applications. The goal among food scientists currently is to suitably identify new potential starch from unique staple crops for future use in processed food products, to replace imports from other countries, and promote regional economies.

Starch isolated from banana is considered an alternative source of indigestible carbohydrates because of its high dietary fibres and resistant starch which could protect against colon cancer, diarrhoea, intestinal disorders, and control diabetes and obesity (Bi *et al.,* 2017; Dhull *et al.,* 2021). Research on the digestion of banana carbohydrates in the human small intestine showed the amount of indigestible starch to be eight times higher than non-starch polysaccharides, which could be related to banana ripeness (Englyst and Cummings, 1986). Nutritionally, starch digestion is divided into rapidly digestible (RDS), slowly digestible (SDS), and resistant starch (RS) fractions (Dhull *et al.,* 2021). Research on human subjects showed that RDS has a high glycaemic index

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that is purported to increase the likelihood of diabetes/pre-diabetes, cardiovascular disease, and obesity. SDS induces prolonged glucose release over the course of passage through the small intestine that may affect activity level and mental alertness, whereas RS behaves like dietary fibres and is fermented by bacteria in the human colon to short-chain fatty acids, which provide a source of additional energy to the body, and contribute high levels of butyrate that is useful for colon functioning (Ludwig, 2002). Previous studies reported that indigestible starch fraction contents of spaghetti (Hernández-Nava *et al.,* 2009), pasta (Ovando-Martinez *et al.,* 2009), and cookies (Agama-Acevedo *et al.,* 2012) increased significantly when products were made with unripe banana flour.

Banana starch commonly exhibits a restricted swelling pattern, and withstands mechanical and thermal disruption due to lightly cross-linked starch molecules (Kaur *et al.,* 2020; Dhull *et al.,* 2021). The digestibility of different native starches has been attributed to the interplay of several factors including starch source, size, amylose to amylopectin ratio, extent of molecular association, type and degree of crystallinity, amylose chain length, amylopectin structures, and existence of amylose-lipid complexes (Bi *et al.,* 2017; Dhull *et al.,* 2021). Native starch morphology such as specific area, channels, porosity of granules, and physicochemical properties must also be considered in the study of digestibility.

In Taiwan, banana is an economic crop grown in all regions, mainly for export. The banana production system in the country is well managed; banana fields are replanted annually, harvesting takes place between March and June every year due to the export season, and to minimise the risk of crop losses during the typhoon season (Tang and Hwang, 1994). Banana cultivars in Taiwan mostly are somaclones derived from original Cavendish AAA (Pei Chiao) by tissue culture propagation. The technique of somaclonal breeding was applied into Taiwanese banana cultivation by reason of the attack from race 4 of *Fusarium* wilt on Cavendish in 1967. The outbreak was widespread within 10 years, and threatened banana production throughout the country. In 1984, several tissue-culture plantlets were released to grow in severe pathogen-infested fields to screen the disease-resistant clones (Tang and Hwang, 1994). Tai Chiao No. 5 and No. 7 are two of the developed somaclones from previous survived clones, which are not only resistant against *Fusarium* wilt, but also show superior horticultural traits. These somaclones were commercially accepted by local and export markets. Tai Chiao No. 5 and No. 7 were submitted to the Taiwan intellectual property in 2008 and 2013, whilst Tai Chiao No. 7 is in process of cultivar registration in a few countries (Chao, 2008). Another cultivar, introduced from Thailand, known as Klui Namwa or Pisang Awak or Nan Hwa (ABB) is typically seen in central region of Taiwan. The prominent trait of wind- and disease-resistance makes this cultivar popular to be cultivated in Taiwan, since Taiwan has a long duration of typhoon season (Chao, 2008).

The attentive practice in control and research of banana cultivation in Taiwan leads to high quality production and success in developing several superior banana cultivars. Unfortunately, advanced studies on nutritional benefits and properties of different bananas cultivars have not been done. Therefore, the chemical compositions, physicochemical properties, and *in vitro* starch digestibility of four Taiwanese banana cultivars were investigated in the present work. The relationships among these properties and cultivars were also evaluated in order to contribute knowledge and understanding about the properties of Taiwanese bananas.

Materials and methods

Banana starch isolation

Green (unripe) bananas of four cultivars namely *Musa* AAA Cavendish Var. Pei Chiao (Pei Chiao), *Musa* AAA Cavendish Var. Tai Chiao No. 5 (Tai Chiao No. 5), and *Musa* AAA Cavendish Var. Tai Chiao No. 7 (Tai Chiao No. 7), and *Musa* ABB Kluai "Namwa" (Kluai Namwa) were collected from the Taiwan Banana Research Institute (TBRI), Pingtung, Taiwan. The fruits were gathered immediately after harvest without postharvest treatment. Banana starch was isolated from the fresh fruits according to the method of Vatanasuchart *et al.* (2012).

Chemical composition, amylose content, and total starch content determination

Banana samples were analysed for moisture content, crude protein, and ash by AOAC (1997) methods. Amylose content (AM) was determined according to Williams *et al.* (1970). Total starch content was determined according to Mishra *et al.* (2008). Total starch was determined as glucose × 0.9 in a bulk banana sample (100 mg), gelatinised in dimethyl sulfoxide (2.0 mL, 100°C, 10 min), and digested for 30 min at 37°C after adding 8 mL acetate buffer pH 5.2 containing 0.1 mL of amyloglucosidase (A7095, Sigma). Aliquots of 0.5 mL were transferred into tubes containing 2 mL of ethanol, and mixed thoroughly. The tubes were centrifuged at 1,000 *g* for 2 min (Hitachi CF-15R, Tokyo, Japan), and supernatant was used for sugar reduction analysis. Glucose was measured by a modified DNS colorimetric method. Briefly, 0.05 mL aliquot of glucose standard (10 mg/mL glucose) or the ethanolic sample was added to 0.25 mL of 1% amyloglucosidase in acetate buffer (pH 5.2), and incubated at 30°C for 10 min. Reducing sugars were determined by adding 0.75 mL DNS mixture (containing 1:1:5 mixture of 0.5 mg/mL glucose: 4 M sodium hydroxide: DNS reagent), and heated for 15 min at 95 to 100°C in a water bath. The tubes were cooled, and 4 mL water was added and mixed. Absorbance was measured at 530 nm. All chemical analyses were performed in triplicate.

Physicochemical properties
Swelling power and solubility

Swelling power (SP) and solubility (Sol) were determined according to Utrilla-Coello *et al. (2014).*

Pasting properties

Pasting properties of 10% starch (dry basis) were determined using a rapid viscosity analyser (RVA, Newport Scientific Pty. Ltd., New South Wales, Australia). Banana samples were weighed in an RVA aluminium canister, and distilled water was added to a total weight of 30 g. Sample slurries were held at 50°C for 1 min, heated to 95°C at 6°C/min, held at 95°C for 5.0 min, and cooled to 50°C at 6°C/min (Zhang and Hamaker, 2012). Pasting temperature (PT), peak viscosity (PV), breakdown (BD), final (FV), and setback (SB) viscosities were recorded in triplicate.

Thermal properties

Thermal properties of starches were determined according to Zhang and Hamaker (2012) with slight modification using a differential scanning calorimeter (DSC, TA Q200 DSC, PerkinElmer Pyris 6, England). Starch (3 mg) was weighed into a DSC aluminium pan, and distilled water was added to each pan using an Eppendorf pipette at starch:water ratio of 1:4. The pans were hermetically sealed and equilibrated for 1 h before analysis. Each sample pan was positioned in the colorimeter, and heated from 0 to 120°C at 10°C/min. An empty pan was used as a reference. The instrument was calibrated using indium as a standard. Endothermal curves exhibited onset, peak, and end temperatures as well as melting enthalpy (J/g of the sample weight on a dry basis) of triplicate samples.

In vitro starch digestibility determination

Starch digestibility was determined according to the *in vitro* digestion method of Mishra *et al.* (2008) with slight modifications. Banana samples (0.5 g; dry basis) were mixed with water (5 mL) in 50 mL polypropylene centrifuge tubes. The tubes were covered and vortexed for 2 min. Each sample was left uncooked or cooked in a boiling water bath for 10 min. The tubes were then cooled to room temperature, and placed in the water bath at 37°C. Next, 20 mL of water and 0.8 mL of 1 M HCl were added to all the sample tubes to obtain a pH of 2.5 ± 0.2, followed by the addition of 1 mL of 10% pepsin dissolved in 0.05 M HCl. The mixture was shaken at 37°C for 30 min. Samples were neutralised using 2 mL of 1 M $NaHCO_3$ and 5 mL of 0.2 M maleate buffer (pH 6.0, 0.2% sodium azide, 1 mM $CaCl_2$), followed by the addition of 1 mL of 2% pancreatin solution in 0.1 M maleate buffer (pH 6.0, 0.2% sodium azide, 1 mM $CaCl_2$) and 0.1 mL of amyloglucosidase. Digestion was timed following the addition of pancreatin, and 0.5 mL aliquots were removed from all tubes at 0, 10, 20 30, 60, 90, 120, and 180 min, transferred into tubes containing 2 mL of 50% ethanol, and mixed thoroughly. The tubes were centrifuged at 1,000 *g* for 2 min (Hitachi CF-15R, Tokyo, Japan), and supernatant was used for the reducing sugar analysis.

Sugars released during digestion were measured as glucose. Rapidly digestible starch (RDS) was determined as the reducing sugar measured after 20 min. Slowly digestible starch (SDS) was calculated as the reduction of sugar released after 120 min (RDS+SDS) minus the RDS. Resistant starch (RS) was estimated as the difference between RDS + SDS and total starch. Starch fractions were expressed as mg of glucose × 0.9.

Statistical analysis

All analyses were performed in triplicate. Statistical analyses were conducted by Duncan's multiple range test ($p < 0.05$) using SPSS statistical software version 19 (SPSS Institute Inc., Cary, NC, USA).

Results and discussion

Chemical composition, total starch content, and amylose content

The chemical compositions of banana starch from different cultivars are shown in Table 1. Moisture contents ranged from 10.36 to 12.80%, and

Table 1. Chemical composition, swelling power, solubility, and *in vitro* starch digestibility of banana starch of different cultivars (dry basis).

Parameter	Banana cultivar			
	Pei Chiao	**Tai Chiao No. 5**	**Tai Chiao No. 7**	**Kluai Namwa**
Moisture (%)	12.80 ± 0.32^{a}	10.96 ± 0.38^{b}	10.68 ± 0.46^{b}	10.36 ± 0.17^{b}
Ash (%)	0.25 ± 0.03^{b}	0.26 ± 0.01^{b}	0.33 ± 0.01^{a}	0.35 ± 0.01^{a}
Protein (%)	0.18 ± 0.01^{c}	0.16 ± 0.01^{c}	0.28 ± 0.08^{b}	0.31 ± 0.08^{a}
Fat (%)	ND	ND	ND	ND
Total starch (%)	95.70 ± 3.48^{a}	91.11 ± 1.09^{c}	92.62 ± 1.77^{b}	96.24 ± 1.57^{a}
Amylose (%)	25.89 ± 0.49^{c}	26.40 ± 0.57^{bc}	27.03 ± 0.86^{b}	33.48 ± 0.57^{a}
Swelling power (g/g)				
55°C^{ns}	7.12 ± 0.46	7.32 ± 0.35	7.45 ± 0.51	7.44 ± 0.24
65°C^{ns}	8.26 ± 0.84	8.00 ± 0.84	8.97 ± 0.46	8.83 ± 0.91
75°C	16.23 ± 1.23^{cd}	18.37 ± 1.22^{ab}	19.17 ± 1.04^{a}	17.20 ± 0.86^{bc}
85°C	20.20 ± 1.18^{cde}	22.27 ± 2.12^{bc}	22.82 ± 1.73^{b}	34.08 ± 1.45^{a}
95°C	21.40 ± 1.28^{b}	22.06 ± 1.37^{b}	22.54 ± 1.49^{b}	33.99 ± 1.35^{a}
Solubility (%)				
55°C^{ns}	7.54 ± 0.41	7.65 ± 0.54	7.51 ± 0.34	7.81 ± 0.61
65°C^{ns}	8.30 ± 0.56	8.02 ± 0.41	8.98 ± 0.41	8.63 ± 1.03
75°C	15.40 ± 1.64^{bc}	22.48 ± 1.50^{a}	21.60 ± 1.62^{a}	22.11 ± 1.65^{a}

Means in the same row with different superscript lowercases differ significantly ($p < 0.05$); ns: not significant ($p \geq 0.05$); ND: not detected.

protein contents ranged from 0.16 to 0.31%, consistent with Kayisu *et al.* (1981) at 10.8% moisture content and 0.2% protein content. Ssonko and Muranga (2017) reported that the moisture content of starch from east African highland banana (EAHB) cultivars ranged from 11.12 to 12.83%, and protein content was 0.1%. Lipids were not detected using the standard method (AOAC, 1997). Low fat content in banana starch indicated that the starch had potential to be used in various food industries with less chance of turning rancid. Ash values ranged 0.25 to 0.35%, less than previously mentioned by Utrilla-Coello *et al.* (2014) at 1.11 to 1.43%, and Bello-Pérez *et al.* (1999) at 0.43 to 1.3%. However, Ssonko and Muranga (2017) recorded 0.23 to 0.47%, and de Barros Mesquita *et al.* (2016) recorded 0.26 to 0.34% for Prata bananas. Bello-Pérez *et al.* (1999) reported higher results of protein (1.95 - 2.03%), fat (2.2 - 2.3%), and ash (0.43 - 1.43%) for banana starch. Lower values of protein, fat, and ash in banana starch observed in the present work indicated that pure starch could be obtained by the isolation method (Peissari *et al.,* 2012). Differences in chemical compositions of banana samples may be due to different techniques for starch isolation, banana cultivar, regional climate condition, and harvesting period.

Total starch content ranged between 91.1 and 96.2% in banana starches (Table 1), consistent with previously reported values (92.7 - 99.6%) by Enano, Valery, and Macho bananas (Utrilla-Coello *et al.,* 2014), but higher for Thai banana cultivars (82.7 - 88.9%) (Vatanasuchart *et al.,* 2012).

Amylose content affects the functional and physicochemical properties of starches because the amorphous fractions of starch granules are primarily comprised of amylose (Bello-Pérez *et al.,* 1999; Peissari *et al.,* 2012). Amylose of banana starches ranged from 25.9 to 33.5% (Table 1), with highest and lowest values obtained from Kluai Namwa and Pei Chiao bananas, respectively. Banana starch is also known to contain various levels of amylose:

17 - 19.5% in the Cavendish cultivar (Eggleston *et al.,* 1992), and 13.4 - 43.8% in Thai banana cultivars (Vatanasuchart *et al.,* 2012). Different values of amylose may be due to diverse starch preparation, ripeness, and cultivation conditions (Li *et al.,* 2016).

Swelling and solubility

Values of swelling power (SP) of the banana samples are shown in Table 1. Lowest values of SP (< 10 g water/g starch) were shown in banana samples at temperatures below 75°C. There were no significant differences ($p > 0.05$) in SP values among banana samples (Table 1). Lowest SP values in this temperature range were representative of the thermal stability of starch granules at temperatures below starch gelatinisation for the different banana samples. Rapid increase in SP occurred from 75 to 85°C for all banana starches, with SP values of 20.20, 22.27, 22.82, and 34.08 g water/g starch for Pei Chiao, Tai Chiao No. 5, Tai Chiao No. 7, and Kluai Namwa starch, respectively. Significant differences ($p < 0.05$) in SP values among samples were shown for temperature range 75 - 95°C. The SP results at temperatures above 75°C were consistent with Agama-Acevedo *et al.* (2015). The increase observed at this temperature range indicated that gelatinisation occurred gradually. All starches had highest SP values at 95°C (21.40 - 34.08 g water/g starch), higher than starch from Prata bananas (~ 15 g water/g starch) (de Barros Mesquita *et al.,* 2016) and EAHB cultivars (12.41 - 14.27 g water/g starch) (Ssonko and Muranga, 2017).

Table 1 also shows the solubility (Sol) behaviours for the four banana cultivars at temperatures between 55 and 95°C. Results indicated that Sol of all samples slightly increased from 7.51 to 8.98% in the range of 55 to 65°C, whereas above 65°C, Sol of all banana cultivars increased rapidly (15.40 - 38.62%). Kluai Namwa starch showed the highest Sol (38.62%) at 95°C, while that of Pei Chiao, Tai Chiao No. 5, and Tai Chiao No. 7 starches were 22.92, 24.73, and 25.65%, respectively; these were significantly different. These results were higher than those reported by Ssonko and Muranga (2017) for starches from EAHB cultivars at temperatures between 50 and 90°C (0.65 - 14.19%), and lower than those reported by Utrilla-Coello **et al.** (2014) between 50 to 90°C (10% - 65%). Swelling power at 85°C (SP_{85}) and solubility at 85°C (Sol_{85}) were positively correlated to amylose content ($r = 0.997$ and $r = 0.995$, $p < 0.01$) (Table 4).

In vitro starch digestibility

The contents of rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) are presented in Table 1. Raw banana starches can resist enzyme hydrolysis (Zhang and Hamaker, 2012). Digestion of cooked banana starch is of great importance in the food industry because the consumption of cooked starch by humans is much more common than raw starch. Table 1 shows that the heat treatment on banana starch slurries increased starch digestibility over the native samples.

The RDS, SDS, and RS contents of raw banana starch ranged from 4.92 to 7.82%, 1.91 to 11.13%, and 74.09 to 85.88%, respectively. Among native banana starches, Kluai Namwa showed the highest RS content (85.88%), whereas Tai Chiao No. 5 showed the lowest (74.09%). The digestibility of native starch was influenced by starch source, granule size, amylose/amylopectin ratio, crystallinity, and amylopectin molecular structure (Chung *et al.,* 2012). Lower digestibility of Kluai Namwa starch may reflect higher amylose (Table 1) and higher gelatinisation enthalpy (ΔH) (Table 3). Moreover, there were significant differences in the gelatinised samples. After cooking, the resistant digestion property decreased, with increase in RDS and SDS. These results concurred with a previous study on red banana, Pisang Awak banana, and Cavendish banana (Bi *et al.,* 2017). Thus, gelatinisation of these banana starches increased the RDS and SDS fractions with combined total contents of 24.53 - 46.94%, higher than in cooked potato and corn starches, and consistent with the findings of Zhang and Hamaker (2012). Gelatinised Tai Chiao No. 5 starch had the lowest value with the highest in gelatinised Kluai Namwa starch. It is well known that both SDS and RS have a positive impact on health by reducing the glycaemic index value, while the RS content is decreased by gelatinisation that can be controlled in low moisture foods such as cookies (Chávez-Salazar *et al.,* 2017). Raw banana starch can be effectively used as an ingredient to manufacture low moisture foods with dry heat cooking such as baking, roasting, and extrusion (Chávez-Salazar *et al.,* 2017; Pandey *et al.,* 2021). No significant correlation was observed among the digestive properties of raw banana starch (Table 4). RDS_{gel} was positively related to SDS_{raw} ($r = 0.953$, $p < 0.05$), while RS_{raw} was positively related to amylose ($r = 0.990$, $p < 0.01$), Sol_{85} ($r = 0.989$, $p < 0.05$), SP85 ($r = 0.979$, $p < 0.05$), SB ($r = 0.951$, $p < 0.05$), and FV ($r = 0.963$, $p < 0.05$). A negative relationship was shown between RS_{raw} and BD ($r = -0.961$, $p < 0.05$).

Physicochemical properties

Pasting properties

When heated in the presence of water, starch undergoes a phase transition known as gelatinisation that involves breaking down the intermolecular bonds. Starch paste attributes are affected by amylose, lipids, phosphorus constituents, and by the distribution of lengths of amylopectin (Tester and Morrison, 1990).

Pasting behaviours play an important role in selecting starch variety for utilisation as a thickener and binder (Santos *et al.,* 2016). Differences in pasting properties of banana starches were observed among the tested cultivars (Table 2). Pasting temperature (PT) ranged from 71.89 to 76.98°C. Peak viscosity (PV) represents the water-holding capacity or degree of granule swelling of starch (Kong *et al.,* 2015). Breakdown viscosity (BD) is the difference between PV and hold viscosity (HV), while setback viscosity (SB) is the tendency of starch paste to retrograde after gelatinisation and cooling with re-association of amylose (Kong *et al.,* 2015). PV, BD, SB, and final viscosity (FV) of banana starches ranged from 357.92 to 477.69, 88.69 to 194.31, 37.67 to 147.08, and 315.56 to 416.31 RVU, respectively. PV of Kluai Namwa was lower than the other three cultivars, while Kluai Namwa exhibited a lower BD but higher SB and FV. The pattern determined for Kluai Namwa starch indicated that when the starch paste was produced at 95°C, the swollen granules resisted the shear stress during cooking. Higher ΔH and amylose decreased the PV of Kluai Namwa. Lower BD but higher SB and FV might be attributable to higher amylose in this starch. When compared with corn starch, banana starch exhibited lower PT (~ 79°C) and higher PV (~ 86 RVU) (Sandhu and Sinh, 2007). Banana starches also showed a slight BD and SB that is convenient for the development of food products requiring thermolabile and stable viscosity. Interrelations among pasting parameters were also observed. SB was positively correlated to FV ($r = 0.960$, $p < 0.05$), while PV and BD were negatively correlated to amylose ($r = -0.958$ and $r = -0.987$, $p < 0.05$), and PT was positively correlated to ΔH ($r = 0.981$, $p < 0.05$) (Table 4).

Thermal properties

The thermal properties of banana starches measured by a differential scanning calorimeter (DSC) showed significant differences. Endothermic peaks in gelation for starches from different banana cultivars appeared between 63.89 and 86.83°C. Transition temperatures (T_o: onset gelatinisation temperature; T_p: peak gelatinisation temperature; T_c: conclusion gelatinisation temperature), R (T_c - T_o), and gelatinisation enthalpy (ΔH) of banana starches are presented in Table 3.

The T_o, T_p, and T_c values from different gelatinised banana starches ranged from 63.9 to 73.3°C, 70.3 to 77.4°C and 80.4 to 86.8°C, respectively. Starch of Pei Chiao showed the highest T_o, T_p, and T_c values, whereas Tai Chiao No. 5

Table 2. Pasting properties of banana starch of different cultivars.

Banana cultivar	Pasting temperature (°C)	Peak viscosity (RVU)	Breakdown viscosity (RVU)	Setback viscosity (RVU)	Final viscosity (RVU)
Pei Chiao	71.89 ± 1.82^{c}	477.69 ± 18.77^{a}	194.31 ± 27.01^{a}	67.11 ± 0.50^{b}	350.50 ± 13.17^{b}
Tai Chiao No. 5	74.02 ± 0.04^{b}	446.44 ± 11.04^{b}	170.72 ± 4.98^{ab}	39.83 ± 0.60^{c}	315.56 ± 3.04^{c}
Tai Chiao No. 7	75 .11± 1.02^{b}	476.25 ± 8.01^{a}	168.08 ± 5.04^{ab}	37.67 ± 0.90^{c}	343.89 ± 2.04^{b}
Kluai Namwa	76.98 ± 1.04^{a}	357.92 ± 5.21^{c}	88.69 ± 21.14^{c}	147.08 ± 0.64^{a}	416.31 ± 15.41^{a}

Means in the same column with different superscript lowercases differ significantly ($p < 0.05$).

Table 3. Thermal properties of banana starch of different cultivars.

Banana cultivar	T_o (°C)	T_p (°C)	T_c (°C)	R (°C)	ΔH (J/g)
Pei Chiao	73.3 ± 0.4^{a}	77.4 ± 0.0^{a}	86.8 ± 1.6^{a}	13.5 ± 0.1^{c}	9.8 ± 0.9^{c}
Tai Chiao No.5	63.9 ± 0.3^{d}	70.3 ± 0.2^{d}	80.4 ± 1.0^{c}	16.5 ± 0.2^{b}	10.4 ± 1.0^{b}
Tai Chiao No.7	64.8 ± 0.0^{c}	71.5 ± 0.1^{c}	82.9 ± 1.1^{b}	18.1 ± 0.1^{a}	11.2 ±0.5^{b}
Kluai Namwa	67.6 ± 0.1^{b}	73.8 ± 0.2^{b}	85.6 ± 2.2^{a}	18.0 ± 0.4^{a}	12.3 ± 0.7^{a}

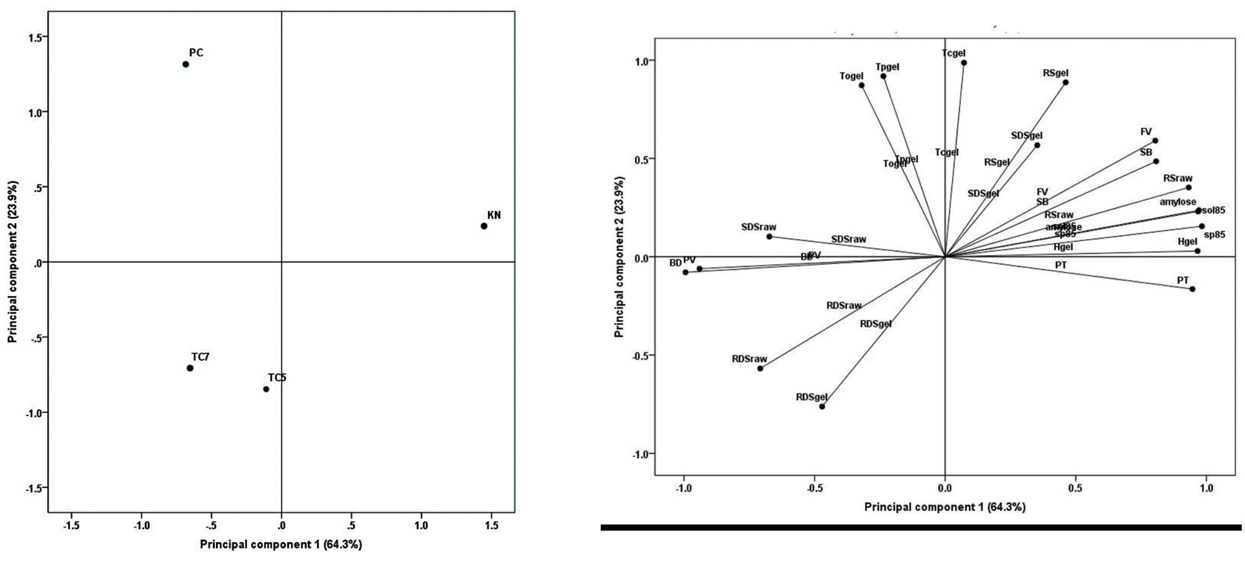
Means in the same column with different superscript lowercases differ significantly ($p < 0.05$).

starch showed the lowest. Different gelatinisation temperatures might reflect differences in amylose, amylopectin fine structure, granule size, form and distribution of starch granules, and the presence of minor components such as proteins and lipids (Srichuwong and Jane, 2007). The ΔH values for all starches ranged from 9.8 to 12.3 (J/g). Different ΔH values indicated amylopectin crystallite melting. Variations in ΔH between the samples indicated differences in bonding forces between the double helices forming the amylopectin crystallites, resulting in variation in the alignment of the hydrogen bonds within the starch molecules (McPherson and Jane, 1999). The highest ΔH value of Kluai Namwa suggested that the largest amount of energy was required for starch gelatinisation. Gelatinisation temperature range (R) relates to the degree of heterogeneity of the crystals within the starch granules. Tai Chiao No. 7 and Kluai Namwa showed higher heterogeneity of their crystalline region as compared to the other cultivars. These results concurred with other studies (Bello-Pérez *et al.,* 2000; Núñez-Santiago *et al.,* 2004). Positive correlation between T_o and T_p (r = 0.994, p < 0.01) was also observed (Table 4).

Principal component analysis

The principal component analysis (PCA) was used to describe the relationships between physicochemical properties and *in vitro* digestibility of starches from different banana cultivars. The eigenvalues of the first two principal components described 88.2% of all the variances. The first principal component (PC1) was mainly contributed by the pasting parameters such as PT, SB, FV, BD, and PV, while SP_{85}, Sol_{85}, AM, ΔH, RS_{raw}, and RDS_{raw} also showed high significance, and described 64.3% of the total variance. The second principal component (PC2) mainly included thermal properties such as T_o, T_p, and T_c and also RS_{gel}, and RDS_{gel}, and described 23.9% of the total variance.

The PCA plots revealed an overview of the similarities and differences between the four banana cultivars (Figure 1a). Locations of the banana cultivars impacted their physicochemical properties and starch digestibility. Kluai Namwa (KN) had higher amylose content and exhibited on the top right-hand side of PC1 with high RS*raw*, SP_{85}, Sol_{85}, (Table 1), FV, PT, SB (Table 2), and ΔH (Table 3), but low RDS_{raw} content (Table 1), BD, and PV (Table 2). On the other hand, lower amylose content of Pei Chiao (PC) was located at a differentiable distance from PC1 to the left-hand side due to high BD and PV. Pei Chiao gave positive scores of PC2 as a result of its high gelatinisation temperature (T_o, T_p, and T_c) (Table 3). Starches from Tai Chiao No. 5



(a) (b)

Figure 1. Principal component analysis (PCA) (a) score plot and (b) loading plot of PC1 - PC2 banana starch. PC: Pei Chiao; TC5: Tai Chiao No. 5; TC7: Tai Chiao No. 7; KN: Kluai Namwa; sp85: swelling power at 85°C; sol85: solubility at 85°C; T_o: onset gelatinisation temperature; T_p: peak gelatinisation temperature; T_c: conclusion gelatinisation temperature; H: ΔH gelatinisation enthalpy; PT: pasting temperature; PV: peak viscosity; BD: breakdown viscosity; FV: final viscosity; SB: setback viscosity; RDS_{raw}; rapidly digestible raw banana starch; SDS_{raw}: slowly digestible raw banana starch; RS_{raw}: resistant raw banana starch; RDS_{gel}; rapidly digestible gelatinised banana starch; SDS_{gel}: slowly digestible gelatinised banana starch; RS_{gel}: resistant gelatinised banana starch.

Table 4. Pearson correlation coefficients (r) among various properties of banana starches.

	AM	**Sol_{85}**	**SP_{85}**	**PT**	**PV**	**BD**	**SB**	**FV**	**T_o**	**T_p**	**T_c**	**ΔH**	**RDS_{raw}**	**SDS_{raw}**	**RS_{raw}**	**RDS_{gel}**	**SDS_{gel}**	**RS_{gel}**
AM	1																	
Sol_{85}	0.995**	1																
SP_{85}	0.997**	0.991	1															
PT	0.851	0.882	0.877	1														
PV	-0.958*	-0.927	-0.967	-0.788	1													
BD	-0.987*	-0.984	-0.997	-0.908	0.964	1												
SB	0.927	0.898	0.903	0.592	-0.901	-0.866	1											
FV	0.921	0.921	0.888	0.647	-0.813	-0.851	0.960*	1										
T_o	-0.072	-0.106	-0.142	-0.549	0.124	0.222	0.289	0.281	1									
T_p	0.014	-0.014	-0.058	-0.463	0.061	0.139	0.361	0.372	0.994**	1								
T_c	0.311	0.303	0.238	-0.134	-0.176	-0.160	0.586	0.650	0.891	0.935	1							
ΔH	0.916	0.947	0.928	0.981*	-0.825	-0.944	0.709	0.778	-0.379	-0.283	0.061	1						
RDS_{raw}	-0.775	-0.824	-0.742	-0.693	0.561	0.718	-0.708	-0.879	-0.114	-0.222	-0.551	-0.808	1					
SDS_{raw}	-0.701	-0.627	-0.719	-0.451	0.872	0.715	-0.739	-0.527	0.034	0.022	-0.053	-0.460	0.112	1				
RS_{raw}	0.990**	0.989*	0.979*	0.802	-0.926	-0.961*	0.951*	0.963*	0.039	0.129	0.427	0.890	-0.826	-0.651	1			
RDS_{gel}	-0.587	-0.640	-0.536	-0.444	0.341	0.496	-0.601	-0.801	-0.349	-0.447	-0.721	-0.591	0.953*	-0.087	-0.671	1		
SDS_{gel}	0.398	0.480	0.360	0.447	-0.117	-0.341	0.311	0.572	0.106	0.202	0.477	0.548	-0.884	0.366	0.467	-0.929	1	
RS_{gel}	0.649	0.658	0.589	0.295	-0.483	-0.528	0.798	0.894	0.620	0.701	0.906	0.475	-0.837	-0.208	0.741	-0.900	0.677	1

* and ** indicate that correlations are significantly different at $p < 0.05$, and $p < 0.01$, respectively; AM: amylose content; Sol_{85}: solubility at 85°C; SP_{85}: swelling power at 85°C; PT: pasting temperature; PV: peak viscosity; BD: breakdown viscosity; FV: final viscosity; SB: setback viscosity; T_o: onset gelatinisation temperature; T_p: peak gelatinisation temperature; T_c: conclusion gelatinisation temperature; H: ΔH gelatinisation enthalpy; RDS_{raw}; rapidly digestible raw banana starch; SDS_{raw}: slowly digestible raw banana starch; RS_{raw}: resistant raw banana starch; RDS_{gel}; rapidly digestible gelatinised banana starch; SDS_{gel}: slowly digestible gelatinised banana starch; and RS_{gel}: resistant gelatinised banana starch.

(TC5) and Tai Chiao No. 7 (TC7) were close to each other in both negative score plots, thus representing the similarity in their physicochemical properties and digestibility of raw starch. These results suggest that crop genetics could be an important factor impacting the variation in physicochemical properties and digestibility.

Loading plots of PC1-PC2 were conducted to identify the correlations between physicochemical properties and digestibility (Figure 1b). Pair-wise parameters with small angles showed a positive correlation. Angles close to 90° and 180° had neutral and negative relationships, respectively. RS_{raw}, Sol_{85}, SP_{85}, AM, FV, PT, SB, and ΔH were clustered together on the right-hand side of PC1, and these parameters were affected by AM. Other parameters such as gelatinisation temperature (T_o, T_p, and T_c) and SDS_{gel} showed as positive in PC2, whereas RDS_{gel} was negative, probably due to the effect of other factors such as the structure of amylopectin. For PCA, PC1, and PC2 represented 88.2% of the total variance and distribution of banana cultivars. Amylose content and amylopectin structure were shown to affect physicochemical properties and starch digestibility.

Conclusion

Amylose played an important role on physicochemical properties and *in vitro* digestibility of Taiwanese banana starches. Other parameters such as solubility, swelling power, peak viscosity, breakdown, and resistant starch (RS) content were strongly correlated. Extracted banana starches showed high amount of resistant starch; the level remained significantly high even after been cooked. This indicated a good trait of an alternative source of nutraceutical ingredient. On their thermal and pasting properties, using them as thermal resistant thickening and binding agents is recommended. Combination of these distinctive features is a strong point that attracts low-glycaemic food consumers who could tolerate excessive processing. The significant similarities and differences in physicochemical properties and *in vitro* digestibility were observed in banana starches of different cultivars from Taiwan, thus demonstrating their specific potential uses. To foster understanding of banana starches in Taiwan in a sustainable way, it is expected that an effort towards banana cultivation research can provide the opportunities to create novel banana starches for multiple utilisation in the future.

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