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Kinetics of starch digestion in sweetpotato flours from Papua New Guinean and Australian cultivars☆

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ABSTRACT

Twenty-five sweetpotato cultivars from Papua New Guinea (PNG) and Australia were studied for their flour digestibility properties. The cultivars displayed monophasic digestograms, and a modified first-order kinetic model adequately predicted the rate and extent of starch digestion. Flours from all the cultivars had high average glycemic index (GI_{avg}) and glycemic load (GL). This study of starch digestion in a wide range of sweetpotato cultivars demonstrates associations and interactions of non-starch components in the flours, and their effects on starch digestibility. The presence of resistant starch (RS) in some cultivars is highlighted with respect to its potential contribution to human health and nutrition.

1. Introduction

Sweetpotato (*Ipomoea batatas* Lam) is one of the most important root crops in the world, and particularly in tropical and sub-tropical countries. In PNG, where the annual production was estimated at 520,000 metric tonnes (Liu, Sabboh, Kirchoff, & Sopade, 2010), sweetpotato has become a prominent trade commodity in the last decade (Bang & Kanua, 2000). It remains the most important staple food, providing more than 60% of the energy requirements in PNG (Liu et al., 2010). Australia reportedly produced about 40,000 metric tonnes (Maltby, Coleman, & Hughes, 2006), but globally, food and nutrition interests in sweetpotato are increasing because of its phytochemicals (e.g. carotenoids) among other attributes. Sweetpotato has a high carbohydrate (mainly starch) content, and is, therefore, important in food and feed as a source of energy. However, as a food, its high starch content raises health and nutritional concerns.

Starch is classified as either very rapidly digestible starch (VRDS), rapidly digestible starch (RDS), slowly digestible starch (SDS), or resistant starch (RS) depending on the rates and extent of hydrolysis (Englyst, Kingman, & Cummings, 1992; Sopade & Gidley, 2009). The potential health benefits of SDS and RS include diabetes management, stable glucose metabolism, improved mental performance, prevention of colonic cancer, reduction of gallstones and fat accumulation, as well as acting as substrates for the growth of probiotics and increasing mineral absorption (Englyst et al., 1992; Goñi, Garcia-Diz, Manas, & Saura-Calixto, 1996; Goñi, Garcia-Alonso, & Saura-Calixto, 1997; Sajilata, Singhal, & Kulkarni, 2006; Sopade & Gidley, 2009). Studies on digestibility of sweetpotato, (Noda, Takahata, Nagata, & Monma, 1992; Noda et al., 2008; Zhang & Oates, 1999), and other roots and tubers (e.g. canna, potato, yam, and cassava or tapioca) have reported differences in the rates and extent of amylolysis (Hung & Morita, 2005; Noda et al., 2008; Riley, Bahado-Singh, Wheatley, Ahmad, & Asemota, 2008). For example, Hung and Morita (2005) reported that canna starch granules were relatively resistant to amylolysis with high RS, and they attributed this to its high degree of crystalline structure that inhibits starch digestion. High RS has also been measured in banana and potato (Englyst et al., 1992).

Apart from crystalline structure, ease of starch digestibility is reported to be affected by non-starch factors and other starch properties, including granule size, presence of covalently bound phosphates, incomplete swelling and gelatinisation, presence of viscosity-forming materials, amylose content, and starch–protein interactions (Liu & Sopade, 2011; Noda et al., 2008; Zhang & Oates, 1999). The presence of phosphorus esters at C-6 and C-3

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positions of glucan chains of potato starch can impede the transport of enzymes to bypass the phosphorylated glucosyl residue thereby reducing amylolysis (Noda et al., 2008). With sweetpotato starches, cultivar differences possibly due to granule structure, molecular associations, amylose content, and ease of gelatinisation have been reported to affect starch digestibility (Noda et al., 1992; Zhang & Oates, 1999).

Possibly because of their relative abundance and global distribution, more studies have been conducted on starch digestibility in cereals than in roots and tubers. To date, studies of sweetpotato starch digestibility have been conducted on isolated starch (e.g. Noda et al., 1992, 2008; Zhang & Oates, 1999). As food, sweetpotato is mainly consumed as a root crop, containing both starch and non-starch components. While studies on sweetpotato starch have contributed to an understanding of starch digestion, deductions from such studies are limited because the roles of non-starch components are unclear, and may be significant in the context of starch digestibility in food and feed. Hence, utilisation of sweetpotato for global food security would benefit from studies on the whole root crop or its flours. Although some studies have been conducted in our laboratories on starch digestion in sweetpotato flours (Chen, 2009; Chen, Kravchuk, & Sopade, 2009; Liu et al., 2010; Liu & Sopade, 2011; van Ruremonde, 2009), only a limited number of cultivars were investigated, and the selected ones might not represent the wide range of sweetpotato cultivars grown in PNG and Australia.

Moreover, a review of the literature on sweetpotato digestibility revealed that many previous studies were based on single-point measurements. Those studies that investigated the time-course of starch digestion in sweetpotato starch or flour, however, did not comprehensively model the starch digestograms to describe the digestion kinetics with their quantitative parameters (Zhang & Oates, 1999). Many studies have modelled starch digestograms from cereals, legumes, roots and tubers, and processed products (Goñi et al., 1997; Liu & Sopade, 2011; Mahasukhonthachat, Sopade, & Gidley, 2010a, 2010b; Sopade & Gidley, 2009; Yong, Chan, Garcia, & Sopade, 2011) with a first-order kinetic model. The parameters of the model have been used to estimate glycemic index (GI), and consequently, glycemic load (GL, with the starch content) to gauge potential contributions of these products to health and nutrition. The objectives of the present study, therefore, were to:

- investigate starch digestion in flours from PNG and Australia cultivars of sweetpotato
- assess the digestion behaviours using a modified first-order kinetic model
- evaluate the effects of cultivar differences on the parameters of the model to gauge potential contributions to glycemic response and resistant starch

2. Materials and methods

2.1. Sweetpotato flours

Twenty five Papua New Guinean and Australian cultivars of sweetpotatoes were obtained from the Queensland Department of Employment, Economic Development and Innovation (Primary Industries & Fisheries), Gatton, QLD 4343, and the School of Agriculture & Food Sciences, University of Queensland, St Lucia, QLD 4072, Australia. The pre-harvest growing and weather conditions of the crops have been reported earlier (Waramboi, Dennien, Gidley, & Sopade, 2011). The crops were processed into flours by peeling, dicing, treating with 0.3% metabisulphite, drying (40 °C, 48 h), and hammer milling through a 1-mm retention sieve (Waramboi et al., 2011).

2.2. In vitro starch digestion

In vitro starch digestion was studied based on the glucometry procedure of Sopade and co-workers (Liu et al., 2010; Mahasukhonthachat et al., 2010a, 2010b; Sopade & Gidley, 2009; Srikaeo & Sopade, 2010). About 500 mg sample was digested with artifical saliva (porcine pancreas α-amylase – Sigma A-3176 Type VI-B), before pepsin (gastric porcine mucosa, Sigma P-6887, in 0.02 M HCl, pH 2) was added, and incubated in a reciprocating water bath (85 rpm, 37 °C, 30 min). The digesta was neutralised, adjusted to pH 6 with a 0.2 M sodium acetate buffer, before a mixture of pancreatin (porcine pancreas, Sigma P1750) and amyloglucosidase (*Aspergillus niger*, Sigma A-7420) in the acetate buffer was added. The glucose concentration in the digesta was measured (Accu-Check® Performa®, Roche Diagnostics Australia Pty Ltd., Caste Hill, NSW 2154, Australia), and digested starch per 100 g dry starch was calculated. Starch content of the flours was determined using the Megazyme procedure based on dimethylsulphoxide (DMSO)-α-amylase-amyloglucosidase (Mahasukhonthachat et al., 2010a; Sopade & Gidley, 2009).

2.3. Modelling of starch digestograms

A modified first-order kinetic model (Eq. (1)) was used, and Eq. (2) was used to calculate the area under the digestogram (AUC) between times t_1 and t_2 as described before (Mahasukhonthachat et al., 2010a, 2010b; Sopade & Gidley, 2009; Srikaeo & Sopade, 2010).

$$D_t = D_0 + D_{\infty-0}(1 - \exp(-kt)) \quad (1)$$

$$D_\infty = D_0 + D_{\infty-0}$$

$$\mathrm{AUC} = \left[D_\infty t + \frac{D_{\infty-0}}{K}\exp(-Kt)\right]_{t_1}^{t_2} \quad (2)$$

where D_t = digested starch (g/100 g dry starch) at time t, D_0 = digested starch (g/100 g dry starch) at time $t = 0$, D_∞ = digested starch (g/100 g dry starch) at time $t = \infty$, K = rate of digestion, at selected times (g/100 g dry starch per min).

The hydrolysis index (HI), expressed as the % of the ratio of the AUC of the sample from 0 to 240 min to the AUC of white bread (~13,000 min g/100 g dry starch; Yong et al., 2011) was used in calculating glycemic index using an equation ($GI_{HI} = 39.51 + 0.570HI$) adapted from Goñi et al. (1997). An equation ($GI_{H90} = 39.21 + 0.803D_{90}$) was also obtained from Goñi et al. (1997) to calculate glycemic index (GI_{H90}) using a single-point measurement at 90 min. Consequently, an average glycemic index, GI_{avg}, was defined as $(GI_{HI} + GI_{H90})/2$, while glycemic load, GL (per g solids) was defined as $(GI_{avg}\ S)/100$ (Yong et al., 2011), where S = starch content (g/100 g solids). In modelling the digestograms, and hence calculating GI_{HI}, GI_{H90}, GI_{avg}, and GL, three approaches were adopted:

a. Gastric–pancreatic (GP). This used digested starch as obtained to include salivary-gastric digested starch.
b. Pancreatic (P). This subtracted salivary-gastric digested starch from the time-course values in (a). In addition to removing the actual starch digested during the salivary-gastric stage, this procedure also removes sweetpotato free sugars from the calculations to concentrate on only starch digested during the pancreatic stage.
c. Gastric–pancreatic-enzyme blank (GPEB). An enzyme blank was run by incubating the samples in only the buffers at 37 °C for 60 min. The equivalent starch digested from the solubilised glucose was subtracted from the time-course values in (a). This

was done to remove the likely contributions of sweetpotato-free sugars to the total glucose, from which digested starch was calculated.

2.4. Statistical analysis

All analyses were randomised and duplicated. The Minitab® ver16 software (Minitab Inc., USA) was used for analysis of variance (ANOVA), test of significance ($p < 0.05$), and correlation. The parameters were also subjected to Principal Component Analysis (PCA), and the eigenvalues, percentage variances and correlation coefficients of the variables loaded on the respective principal components were calculated. The parameters of the digestion model were computed using Microsoft Excel Solver® by minimising the residual sums of squares (SSQ), and constraining digested starch at infinite time (maximum), $D_\infty \leq 100$ g/100 g dry starch, and initial digested starch, $D_0 \geq 0$ g/100 g dry starch. The coefficient of determination (r^2), and mean relative deviation modulus (MRDM), were also calculated to assess the predictive ability of the model (Mahasukhonthachat et al., 2010a, 2010b; Srikaeo & Sopade, 2010).

3. Results

3.1. In vitro starch digestion

Fig. 1 shows representative digestograms of the sweetpotato flours. Irrespective of the RVA pasting classes (Waramboi et al., 2011) and cultivar, they all displayed monophasic digestion behaviour. The digestograms are similar to those reported by Chen et al. (2009), who studied the *Beauregard* cultivar of sweetpotato, a commercially important cultivar in Australia. Zhang and Oates (1999) also obtained monophasic digestograms for sweetpotato starch from six cultivars. However, biphasic digestograms have been reported for flours of six sweetpotato cultivars from PNG which were grown by different farmers at different locations in the country (Liu et al., 2010; Liu & Sopade, 2011). Although there were differences in the equipment used in sample preparation, the sweetpotato cultivars from the earlier study were dried (~40 °C, 48 h) and milled (hammer mill, 1 mm retention sieve) using the same conditions as the present study. The biphasic (earlier study) and monophasic (present study) behaviours of the *Wanmun* cultivar, for example, could be due to genetic and environmental ($G \times E$) factors, which will be subject of future studies in our laboratories. While monophasic digestograms might indicate negligible initial restrictions or impediments to amylolysis, biphasic digestograms have been suggested to be due to restricted amylolysis or transport of digestion products from the cells by the presence of cell walls in the sweetpotato flour (Sopade, Mahasukhonthachat, Liu, Sabboh, & Gidley, 2008). For both monophasic and biphasic digestograms, modelling of the digestograms is required to derive more quantitative information on digestibility properties, including cultivar differences.

3.2. Modelling of starch digestion kinetics

Irrespective of the approach (gastric–pancreatic, GP; pancreatic, P; gastric–pancreatic-enzyme blank, GPEB) used in analysing the kinetics of starch digestion in the sweetpotato flours, the first-order kinetic model (Eq. (1)) was suitable ($r^2 = 0.992$; SSQ = 76; MRDM = 13) in describing the experimental data (Fig. 1). Table 1 shows the parameters of the model, as well as the calculated glycemic parameters (GI and GL) for the sweetpotato flours. From Table 1, D_0, which is a measure of the very rapidly digested starch (VRDS) in starch-only systems, ranged from 2.3 to 20.6 g/100 g dry

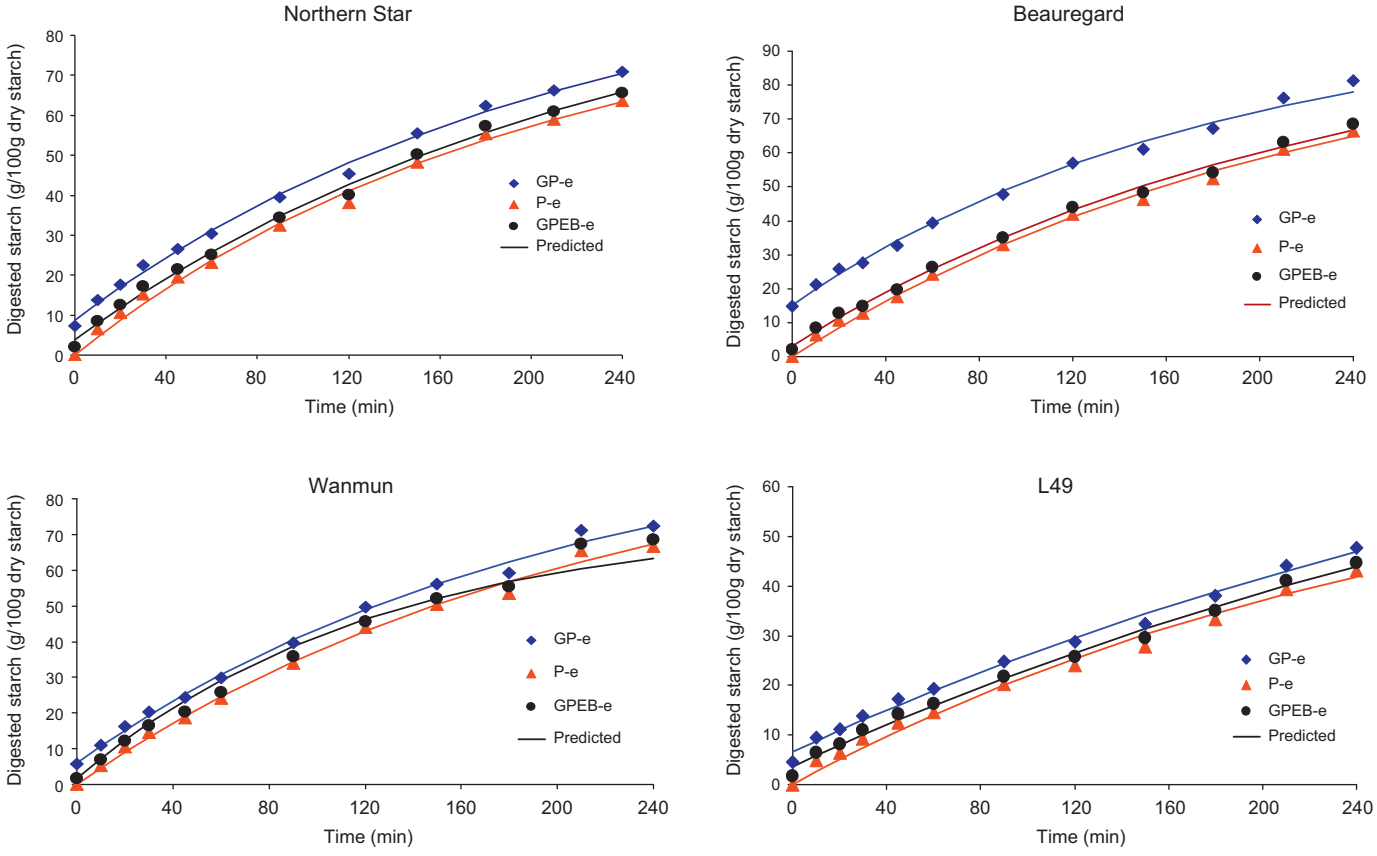

Fig. 1. Digestograms of the sweetpotato cultivars showing the experimental (e) and predicted (—) values for the GP, P and GPEB digestion approaches.

Table 1
Digestibility and glycemic parameters of the modified first-order kinetic model for the sweetpotato cultivars (g/100 g dry starch).

Cultivar[a]	Gastric–pancreatic (GP)							Pancreatic (P)						Gastric–pancreatic-enzyme blank (GPEB)						
	D_0	D_∞	$K(\times 10^{-3})$	GI_{H90}	GI_{HI}	GI_{avg}	GL	D_∞	$K(\times 10^{-3})$	GI_{H90}	GI_{HI}	GI_{avg}	GL	D_0	D_∞	$K(\times 10^{-3})$	GI_{H90}	GI_{HI}	GI_{avg}	GL
Beauregard	14.7	100.0	7.1	83	100	92	44	96.9	5.5	69	84	77	37	2.9	97.9	5.8	72	87	79	38
Beauregard II	14.2	100.0	10.6	92	110	101	43	91.7	8.5	79	94	86	37	1.6	93.8	8.6	81	96	88	38
Beerwah gold	7.7	100.0	5.8	76	91	83	44	98.1	5.4	69	84	77	40	3.4	100.0	5.3	71	86	79	42
Beerwah gold II	7.4	100.0	15.4	86	102	94	28	100.0	11.4	90	107	99	29	0.5	100.0	12.6	94	110	102	30
Honey gold	15.5	100.0	6.5	82	99	90	35	89.1	6.5	71	85	78	31	5.6	91.5	5.6	73	88	80	32
Kestle	7.4	100.0	4.6	70	85	78	28	100.0	4.4	65	79	72	26	4.3	95.7	4.3	68	82	75	27
L11	6.4	86.7	5.3	68	82	75	28	81.8	5.7	64	76	70	26	3.2	81.8	5.2	65	78	72	26
L135	15.4	91.2	6.4	77	92	85	49	76.0	6.9	66	78	72	42	5.0	80.8	5.9	68	81	75	43
L18	14.7	94.6	3.7	69	82	76	40	70.9	4.9	59	69	64	34	3.3	81.8	3.9	60	71	65	34
L3	7.0	80.4	5.4	68	80	74	39	63.5	8.4	65	75	70	37	2.4	71.0	5.8	64	76	70	37
L46	6.3	86.7	4.8	66	79	73	41	74.2	5.8	63	74	69	38	3.6	80.4	4.8	64	76	70	39
L49	5.9	83.9	3.8	61	71	66	34	65.7	4.9	58	67	62	32	3.0	79.4	3.8	58	68	63	33
Magenta gold	20.6	100.0	5.7	81	98	90	43	78.5	6.4	67	79	73	35	4.2	84.7	5.1	68	81	74	35
Meriken	15.9	100.0	11.9	96	114	105	38	100.0	7.4	78	95	87	31	0.0	100.0	8.0	80	97	89	32
NG 7570	6.9	93.3	4.9	69	83	76	42	88.6	5.0	65	77	71	39	3.4	88.1	4.8	66	80	73	40
Northern star	8.1	99.2	5.5	74	90	82	43	89.5	6.0	69	83	76	40	3.0	92.1	5.5	70	84	77	41
Northern star II	2.3	100.0	8.2	82	98	90	41	100.0	7.1	77	93	85	39	0.0	100.0	7.7	79	95	87	40
Orange delight	16.9	99.4	8.0	87	104	96	46	86.4	7.2	72	86	79	38	2.0	85.9	7.3	74	88	81	39
O/Beauregard	12.0	100.0	7.1	82	99	91	39	97.1	6.2	72	87	80	34	3.9	95.3	6.0	74	90	82	35
Purple custard	4.7	87.9	3.7	62	73	68	39	76.0	4.5	59	70	65	37	0.8	71.3	5.0	61	71	66	38
Rocky gold	17.1	97.2	6.6	81	98	90	43	84.9	6.4	68	81	75	36	4.4	86.3	6.1	71	84	77	37
Rusty	7.5	94.2	6.1	74	89	82	41	88.0	6.1	68	82	75	38	2.6	88.4	6.0	70	84	77	39
Snow white	15.5	100.0	7.9	86	103	94	46	90.8	7.0	73	88	81	39	3.3	92.2	6.6	75	90	83	40
Wanmun	6.3	98.8	4.9	71	86	78	42	92.6	5.1	66	80	73	39	2.2	81.5	6.4	69	82	75	41
WSPF	6.4	97.9	5.8	74	90	82	41	94.2	5.6	69	83	76	38	0.0	93.2	6.1	70	85	78	38
LSD values	0.64	3.99	0.00	2.68	3.01	2.84	1.12	4.53	0.00	1.78	2.14	1.95	0.91	0.57	5.68	0.00	1.83	2.18	2.00	0.93

[a] Cultivars with II of the same cultivar were supplied by the QDPI&F, Gatton; WSPF = White Skin Purple Flesh; O/Beauregard = Original Beauregard; and these apply to all other tables where they appear.

starch using the GP approach, and significantly ($p < 0.05$) differed among the cultivars. However, the equivalent D_0 using the GPEB approach was less than 6 g/100 g dry starch, suggesting the presence of variable amounts of soluble glucose between the cultivars, which contributed to the high values from the GP approach.

The three approaches (GP, P and GPEB) revealed significant differences ($p < 0.05$) in the maximum digested starch (D_∞), and Table 1 shows that the raw starch in some of the cultivars could be completely digested (D_∞ = 100 g/100 g dry starch), while resistant starch could be up to about 30% (dry basis) in some cultivars using the GPEB method that disregards endogenous soluble sugars. Since the sweetpotato flours were not heat-moisture-treated in any form, the indicated resistant starch would be of type 1 (encapsulated starch), type 2 (uncooked starch) or mixtures of both using the Englyst classification (Englyst et al., 1992). Resistant starch levels similar to the ones found here have been measured or calculated in non-processed foods including sweetpotato (e.g. Benmoussa, Suhendra, Aboubacar, & Hamaker, 2006; Chanvrier et al., 2007; Liu & Sopade, 2011). Hence, the predicted RS levels for some of the 25 cultivars are consistent with published studies.

Although ANOVA ($p < 0.05$) revealed no significant differences in the rates of digestion (K), nominal differences existed among cultivars. Cultivar Beerwah Gold II had the highest K values compared to all other cultivars irrespective of the modelling approach used (Table 1). Its relatively higher K value in the GP (15.4×10^{-3}) than in the P (11.4×10^{-3}) and GPEB (12.6×10^{-3}) g/100 g dry starch approaches suggests that, soluble sugars, as discussed above, could have played a part particularly in the GP approach. In the GP approach, cultivars Meriken and Beauregard II also had higher K (>10 g/100 g dry starch) values, while the K was relatively similar in other cultivars. The marginal differences in the K may affect digestibility in the absence of inhibitory factors, for example, starch–protein interactions in sorghum (Mahasukhonthachat et al., 2010a), resulting in increased GI. Rates of starch digestion differ among food types, and are also affected by the inherent properties of the material (e.g. cell walls) and transit time in the gastro-intestinal tract (e.g. presence of viscosity-forming ingredients).

Table 1 also shows the predicted glycemic properties of the samples which were significantly different ($p < 0.05$) among the cultivars. All cultivars had high HI (not shown), GI_{HI} and GI_{H90}, with values >60% (60 g/100 g dry starch) irrespective of the modelling approach used. Although many parameters were used to define the predicted glycemic properties, the discussion here will be based on the GI_{avg} and the GL because of their expected contribution to blood sugar and metabolic diseases that affect human health. Sugars, present as natural constituents of the food, or due to actions of naturally occurring α-amylase (van Hal, 2000) or from exogenous forms (those hydrolysed by added *in vitro* enzymes) are expected to be readily soluble at the initial stages of digestion (e.g. salivary-gastric). This will lead to an increase in the GI and blood glucose concentration after consumption of meals. As shown in Table 1, the sweetpotato cultivars studied here can be considered as high GI_{avg} (~70%) and high GL (~40%) foods. Moreover, it can also be seen in Table 1 that the higher the D_∞ and K, the higher the GI_{avg}. This is expected in high-starch containing foods such as sweetpotato, and in the absence of compounding factors such as rigid cell walls and enzyme inhibitors, sugars will positively affect glycemia.

Food materials with GI values >70, 56–69 and <55 are classified as high, medium and low GI foods respectively, while those with a GL >25 are considered as high GL foods (Anonymous, 2011; Atkinson, Foster-Powell, & Brand-Miller, 2008). Consumption of starchy foods (e.g. rice, potato, and sweetpotato), which are often low in protein and dietary fibre, have been associated with increases in metabolic diseases such as diabetes, obesity and hypolipidermia (Goñi et al., 1997). Studies have shown that starches that are digested and absorbed slowly in the human body, i.e. high SDS and RS fractions, tend to result in lower levels of blood glucose and insulin responses in the body (Goñi et al., 1997; Riley et al., 2008), thus potentially reducing the risk of the diseases mentioned above.

The digestibility properties of the sweetpotato cultivars studied here are diverse, and have implications for processing, bioavailability, human health and nutrition. These differences are expected to be affected by many factors including starch and non-starch components, for example, phosphates in potato, and starch–protein interactions in sorghum (Mahasukhonthachat et al., 2010a; Noda et al., 1992, 2008; Thompson, 1993; Zhang & Oates, 1999). Some of these factors are examined below to help understand their possible effects on digestibility in the sweetpotato cultivars.

3.3. General discussion

This is probably the first study to report on the digestibility properties of a wide range of sweetpotato cultivars from PNG and Australia. The digestibility parameters showed differences between cultivars that may have been due to interactions and/or associations between starch and non-starch components in the flours. In an earlier study (Waramboi et al., 2011), the physicochemical and functional properties of the 25 sweetpotato cultivars were reported. Here we further examine these properties to help understand the digestion behaviours using Pearson correlation analysis.

The cultivars were significantly different in the starch (30–58 g/100 g solids) and amylose (20–33%) contents (Waramboi et al., 2011), and it is expected that materials with high starch generally would have high GL (Tables 1 and 2). However, the significant ($p < 0.05$) and inverse relationship between starch and the D_∞, K and GI_{avg} parameters, irrespective of the approach (GP, P and GPEB), is unusual. This could suggest that non-starch components in the flours affected digestibility. Free glucose and maltose in the flours will contribute directly to glucometer readings (Sopade & Gidley, 2009), and any maltose would be expected to be converted to glucose by the digestive enzymes. With the GP approach, the inverse relationship between starch content and digestion parameters could be a reflection of a stronger positive relationship between the free sugars and digestion parameters (Table 2) as increasing starch is probably associated with decreasing free sugars. However, it is doubtful if the presence of free sugars can fully explain the inverse relationship between starch and digestion parameters. This is because when the sugars were subtracted in the P and GPEB approaches in order to understand the contributions of only the starch component (Sopade & Gidley, 2009), the inverse relationship was maintained (Table 2). Hence, both free sugars and non-sugar components of the sweetpotato cultivars define the digestion behaviours of the cultivars.

Although sugar contents in the digesta were not measured, total sugar (fructose, glucose, sucrose, and maltose) of the flours ranged from 0 to 8 g/100 g solids (Waramboi et al., 2011). Table 2 shows a highly significant ($p < 0.001$) positive relationship between the sugars and digestion parameters for the GP and GPEB approaches, while a negative relationship was obtained with the P approach (D_∞, -0.548^{**}; K, -0.575^{**}; GI_{avg}, -0.730^{***}). The positive relationship, which was more significant with the GP approach, suggests that sugars present either as natural constituents in sweetpotato or as products of starch hydrolysis, are solubilised mainly in the salivary-gastric stage. After a rapid release of free sugars in the salivary-gastric stage, the inverse relationship between starch and digestion parameters, discussed above, was maintained during the pancreatic digestion (P approach). It is worth mentioning that although the sugar effects were subtracted in the GPEB approach (a positive sugar–digestion relationship), this approach included the salivary-gastric digestion, and the sugar effects during the initial

Table 2
Pearson correlation coefficients between the properties of the sweetpotato cultivars.

Parameter	D_0	D_∞	K	GI_{avg}	GL
Total starch	−0.365	−0.547**	−0.738***	−0.685***	0.239
	(NA)	(−0.548*)	(−0.575**)	(−0.730***)	(0.371)
	[0.007]	[−0.637***]	[−0.636***]	[−0.747***]	[0.353]
Amylose	0.235	−0.370	−0.408*	−0.269	0.326
	(NA)	(−0.452*)	(−0.336)	(−0.512)	(0.256)
	[0.429*]	[−0.417*]	[−0.464*]	[−0.496*]	[0.256]
Protein	0.565**	0.330	0.218	0.358	0.019
	(NA)	(0.088)	(0.285)	(0.239)	(−0.157)
	[0.610**]	[0.284]	[0.165]	[0.267]	[−0.144]
Total sugar	0.887***	0.595**	0.499*	0.784***	0.228
	(NA)	(−0.548**)	(−0.575**)	(−0.730***)	(0.371)
	[0.109]	[0.397*]	[0.356]	[0.463*]	[−0.128]
Glucose	0.937***	0.409*	0.274	0.643**	0.406*
	(NA)	(−0.011)	(0.223)	(0.204)	(0.052)
	[0.173]	[0.134]	[0.131]	[0.200]	[0.019]
Maltose	0.390	0.670***	0.576**	0.675***	0.044
	(NA)	(0.465*)	(0.506**)	(0.667***)	(−0.064)
	[−0.082]	[0.660***]	[0.514**]	[0.669***]	[−0.076]
Phosphorus	0.235	0.175	0.240	0.253	0.005
	(NA)	(0.060)	(0.408*)	(0.284)	(−0.044)
	[0.349]	[0.254]	[0.234]	[0.292]	[−0.035]
Sulphur	0.638**	0.348	0.494*	0.609**	0.132
	(NA)	(0.165)	(0.463*)	(0.431*)	(−0.090)
	[0.289]	[0.365]	[0.370]	[0.449*]	[−0.084]
WAI	0.591**	0.569**	0.527	0.674***	−0.013
	(NA)	(0.424**)	(0.291)	(0.488**)	(−0.258)
	[0.074]	[0.588**]	[0.325]	[0.501**]	[−0.245]
WSI	0.804***	0.550**	0.484*	0.708***	0.044
	(NA)	(0.275)	(0.385)	(0.453*)	(−0.267)
	[0.333]	[0.516**]	[0.313]	[0.468*]	[−0.272]
Enthalpy	−0.259	−0.442*	−0.146	−0.329	−0.199
	(NA)	(−0.264)	(0.015)	(−0.187)	(−0.086)
	[0.280]	[−0.178]	[−0.104]	[−0.174]	[−0.076]
Peak temperature	−0.006	−0.451*	−0.410*	−0.513	−0.255
	(NA)	(−0.517**)	(−0.287)	(−0.525**)	(−0.253)
	[0.446*]	[−0.504*]	[−0.381]	[−0.511**]	[−0.241]
Initial viscosity	0.346	0.401*	0.654***	0.631**	0.042
	(NA)	(0.328)	(0.520**)	(0.584**)	(−0.100)
	[−0.282]	[0.376]	[0.586**]	[0.586**]	[−0.099]
Peak viscosity	−0.517	−0.703***	−0.514	−0.691***	−0.013
	(NA)	(−0.512**)	(−0.408*)	(−0.611***)	(0.157)
	[−0.217]	[−0.743***]	[−0.394]	[−0.624**]	[0.157]
Trough viscosity	−0.291	−0.748***	−0.509	−0.669***	−0.046
	(NA)	(−0.642**)	(−0.371)	(−0.662***)	(0.042)
	[0.043]	[−0.771***]	[−0.441*]	[−0.670***]	[0.044]
Final viscosity	−0.235	−0.729***	−0.503*	−0.641**	0.003
	(NA)	(−0.641**)	(−0.370)	(−0.659***)	(0.073)
	[0.087]	[−0.767***]	[−0.440*]	[−0.665***]	[0.077]
Pasting temperature	−0.059	−0.594**	−0.600**	−0.654***	−0.073
	(NA)	(−0.738***)	(−0.393*)	(−0.719***)	(−0.057)
	[0.374]	[−0.729***]	[−0.551**]	[−0.726***]	[−0.058]

NA = not applicable; GP = gastric pancreatic, *P* = pancreatic and GPEB = gastric-pancreatic-enzyme blank. Values with no brackets represent GP, while values in () and [] represent P and GPEB digestion approaches, respectively (WAI, WSI = water absorption and solubility indices; Enthalpy, Peak temperature = enthalpy and peak temperature of gelatinisation in the Differential Scanning Calorimeter; Initial, Peak, Trough and Final viscosities, and Pasting temperature in the Rapid Visco-Analyser (Waramboi et al., 2011)).

* Significance level: $p < 0.05$.
** Significance level: $p < 0.01$.
*** Significance level: $p < 0.001$.

stages of digestion could have been responsible for the relationship measured with the GPEB approach.

With special reference to glucose and maltose, the two sugars that will directly influence starch digestion parameters, Fig. 2 shows the trends with digestibility parameters for the three (GP, P and GPEB) approaches. Irrespective of the approach, both sugars effectively show significant positive relationship with the digestion parameters (Table 2), with maltose correlating better with the digestion parameters than glucose. This could be because, while glucose will be solubilised directly during digestion, maltose will both be solubilised and digested by amylolytic enzymes. As mentioned above, the total sugars inversely or negatively correlated with the digestion parameters in the P approach. The positive or direct correlation with glucose and maltose for the same approach could be due to the effects of other sugars (e.g. fructose and sucrose).

A small effect of amylose content on starch digestion in the cultivars is manifested by inverse relationships, statistically significant for the *K* value. Although most cultivars had <30% amylose contents (Waramboi et al., 2011), it is well recognised that high amylose can restrict digestibility (Sang, Bean, Seib, Pedersen, & Shi, 2008) due to the ability of the linear amylose to form condensed enzyme-resistant materials. Proteins can either increase or decrease starch digestion in foods. Addition of exo-proteins in whey fortified starch extrudates (Yong et al., 2011) has been shown to increase digestibility while endo-proteins (e.g. starch–protein interactions in sorghum, Mahasukhonthachat et al., 2010a, 2010b)

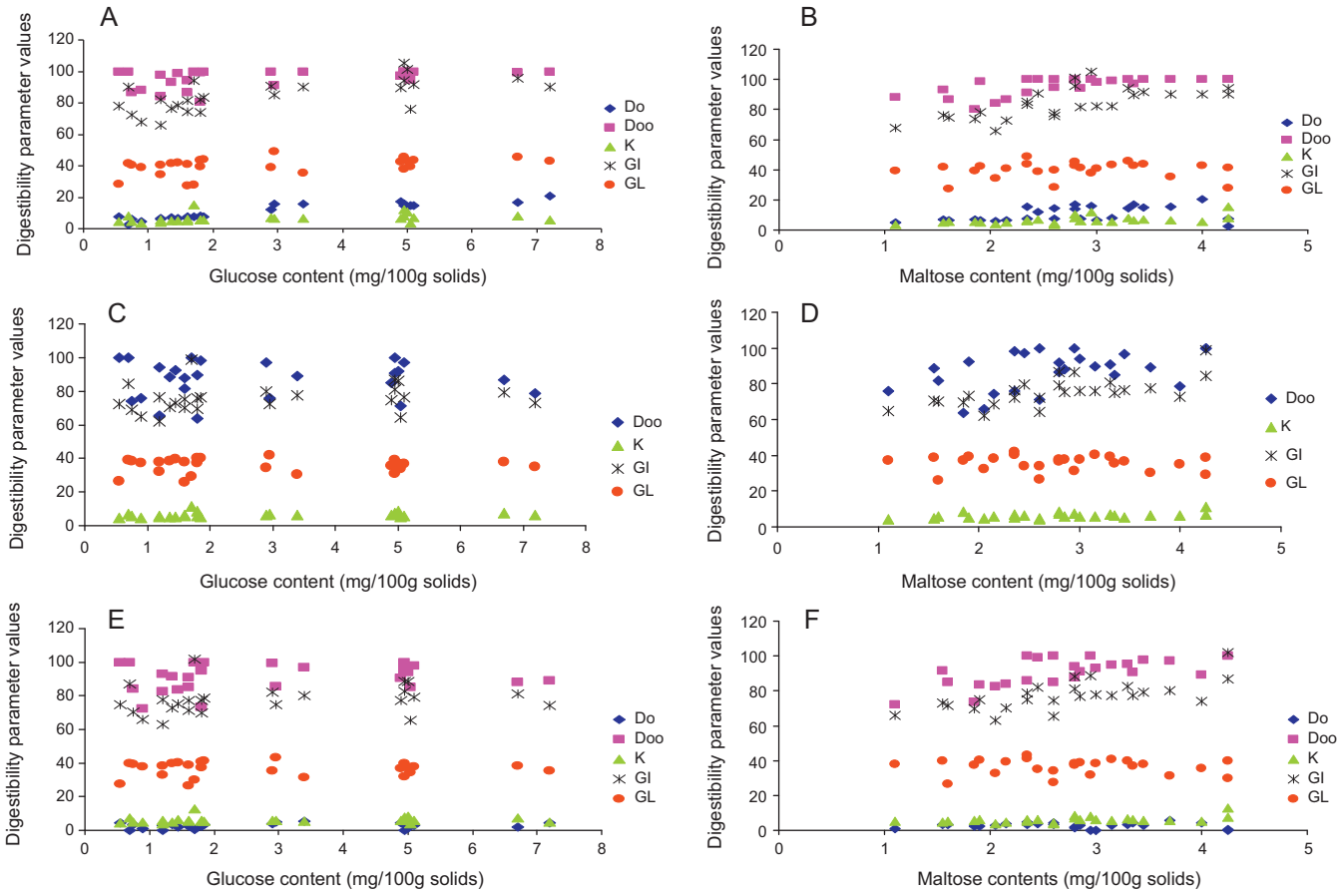

Fig. 2. Plot of sugars against digestibility parameters for the GP (A and B), P (C and D) and GPEB (E and F) digestion modelling approaches.

have been found to reduce starch digestion. In the present study, the protein contents in the sweetpotato cultivars were generally low at <8%, and the protein contents decreased as starch contents increased (Waramboi et al., 2011). Although it is not known how proteins affect starch digestion in sweetpotato, the relationship between proteins and D_0 (Table 2) suggests the sweetpotato proteins enhanced starch digestion. This possibly implies that the sweetpotato starch was not encapsulated by the protein bodies as in sorghum, for example (Mahasukhonthachat et al., 2010a). Furthermore, the scanning electron micrographs from Osundahunsi, Fagbemi, Kesselman, and Shimoni (2003) on red and white Nigerian sweetpotato, and Waramboi et al. (2011) on the present cultivars, did not reveal substantial presence of protein bodies surrounding starch granules as seen with sorghum (Mahasukhonthachat et al., 2010a). The direct relationship between proteins and starch digestion in the present study could also be due to an indirect effect based on the inverse starch–protein (and therefore direct protein–free sugar) relationship in the cultivars.

The presence of phosphate ester substituents in starches can affect starch properties, including digestibility. Noda et al. (2008) studied the effects of phosphorus on digestion (hydrolysis rate) of potato, sweetpotato, cassava and yam starches. Although these authors reported a significant inverse relationship across the 31 starches, there was no specific data presented on sweetpotato. The phosphorus content of sweetpotato cultivars was correlated (Liu & Sopade, 2011) with starch digestion parameters. These authors also obtained a significant inverse relationship, but the relationship was more at phosphorus content below 130 mg/100 g solids. In the present study, the phosphorus content of the cultivars were slightly higher than those (10–112 mg/100 g solids) reported by Noda et al. (2008), and ranged from 110 to 267 mg/100 g solids, and a few cultivars like L135 had significantly high phosphorus content (Waramboi et al., 2011). Table 2 suggests a direct relationship between phosphorus and digestion parameters. In view of an inverse relationship reported by other studies for starches and sweetpotato flours (Noda et al., 2008; Liu & Sopade, 2011), the present observation was considered unusual and inconsistent with theory. However, the relationship is not significant and would suggest that phosphorus did not materially affect starch digestion in the sweetpotato cultivars. Moreover, Noda et al. (2008) obtained a direct non-significant relationship between digestion properties and phosphorus content of potato. Hence, while phosphorus might affect starch properties, it is probable that with some starches or flours, it has no effect.

Similarly, the positive correlation of sulphur particularly with the D_0, K and glycemic parameters (Table 2) is at first sight surprising. However, similarity with protein effects suggests that sulphur content is a reflection of sulphur-containing amino acids in the proteins, and that this could have been responsible for this behaviour. Besides chemical properties, structural and functional properties of food materials like particle size (e.g. Mahasukhonthachat et al., 2010a), gelatinisation (Zhang & Oates, 1999), pasting (Srikaeo & Sopade, 2010), water absorption (WAI) and water solubility (WSI) (Mahasukhonthachat et al., 2010a) properties were also shown to affect digestibility. Table 2 shows very strong positive relationships ($p < 0.001$) between the WAI/WSI and D_0, D_∞, K and glycemia. While both WAI and WSI can be indicative of starch properties, the amount of water solubles, and hence WSI, can also be related to the total free sugars in the sweetpotato as shown in the similarity in the

correlation coefficients between total free sugars (and glucose or maltose) and digestibility parameters. With respect to the gelatinisation properties of the flours (Table 2), an inverse, though generally insignificant, relationship was obtained with the digestibility parameters. For example, a high gelatinisation enthalpy is indicative of a starch structure that requires more heat to disrupt during gelatinisation. Such a structure might be more difficult to digest because of hindrances to liquid and enzyme penetration to the granules. Once the destructurisation or gelatinisation had occurred, starch-containing systems are easier to digest, and this has been demonstrated in many food systems (e.g. Mahasukhonthachat et al., 2010b; Noda et al., 1992). In the present study, raw sweetpotato flours were used, and in follow-up studies from our laboratories, processed (extruded) samples of some of the 25 sweetpotato cultivars will be evaluated for their digestion behaviours.

An earlier study on the flours (Waramboi et al., 2011) grouped the cultivars into four distinct classes (highly, HSS; moderately, MSS; and slightly, SSS shear sensitive, and shear thickening, STK) based on their pasting properties. Although pasting and gelatinisation measure different properties of the starch, they are closely related, and the diversity in pasting behaviours of these cultivars reflect differences in the starch properties which may affect digestibility. As shown in Table 2, the initial, peak, trough, and final viscosities of the flours had an inverse but significant correlation with digestibility, especially with the D_∞, K and GI_{avg}. This is probably a reflection of variation in total starch, as correlation coefficients are very similar, and starch content is expected to affect all aspects of the RVA profile. To further explore possible relationships and mechanisms involved in starch digestion, we classified the sweetpotato cultivars according to their RVA pasting classes (Fig. 3). Fig. 3a shows that, the D_0 (~8 g/100 g dry starch) for the HSS cultivars in the GP approach was higher, while it was lower (<2 g/100 g dry starch) in the GPEB, and the average D_∞ values (~100 g/100 g dry starch) were similar for the HSS, MSS, SSS and STK classes. As expected, the K was higher in the GP approach because of salivary-gastric digestion compared to either P or GPEB values.

Fig. 3a–c show that, irrespective of the three approaches used to model the digestion behaviours, the STK cultivars consistently showed lower average D_∞ and K values, consistent with a higher proportion of slowly digested or resistant starch. The low digestibility behaviours of the STK sweetpotato cultivars could be related to their increasing RVA viscosities during the holding stage, 95 °C for 150 s (Waramboi et al., 2011), which is indicative of restricted, incomplete or delayed swelling of the starch granules. It is possible that a more condensed and/or molecularly entangled granular form could result in both delayed swelling on cooking and reduced digestibility in the raw state. Fig. 3d–f show the plots of GI and GL values of the cultivars by their RVA classes. The glycemic values were marginal and did not vary much among the RVA classes; with HSS (~80, GI_{avg}; 40, GL); MSS (~90, GI_{avg}; 35, GL); SSS (~80, GI_{avg}; 35, GL) and STK (~70, GI_{avg}; 40, GL). However, as a class, the GI values were generally lower in the STK cultivars and higher for the (HSS and) MSS cultivars.

While the large error bars in Fig. 3 warrant careful interpretation of the results, it can be seen that, grouping of cultivars by RVA classes has revealed some useful trends in understanding the digestibility properties of the sweetpotato cultivars. To further investigate major traits responsible for these differences, a Principle Component Analysis (PCA) was performed (Fig. 4a and b) using measured properties of the cultivars (Waramboi et al., 2011). The PCA revealed four principal components (PC1–PC4), and their eigenvalues (values that show the level of variability explained by each component axis), and the percentage variances are shown (Table 3). In classifying the cultivars, a trait with an absolute value of >0.60 was considered to load heavily on a given component axis according to Stevens (1992). The total starch, total

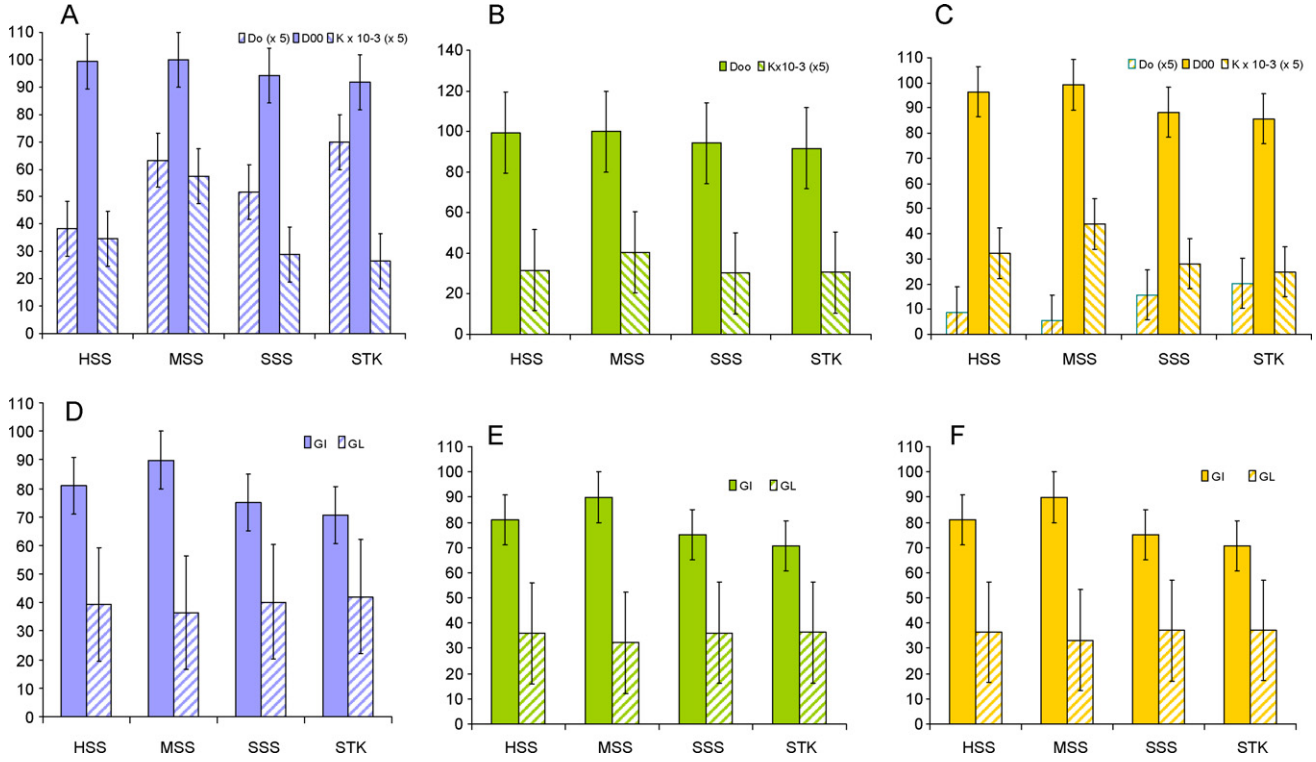

Fig. 3. Digestibility and glycemic parameters of the GP (A and D); P (B and E) and GPEB (C and F) approaches used to model the digestion behaviours of the sweetpotato cultivars according to RVA pasting classes (HSS = highly shear sensitive; MSS = moderately shear sensitive; SSS = slightly shear sensitive; STK = shear thickening (Waramboi et al., 2011)).

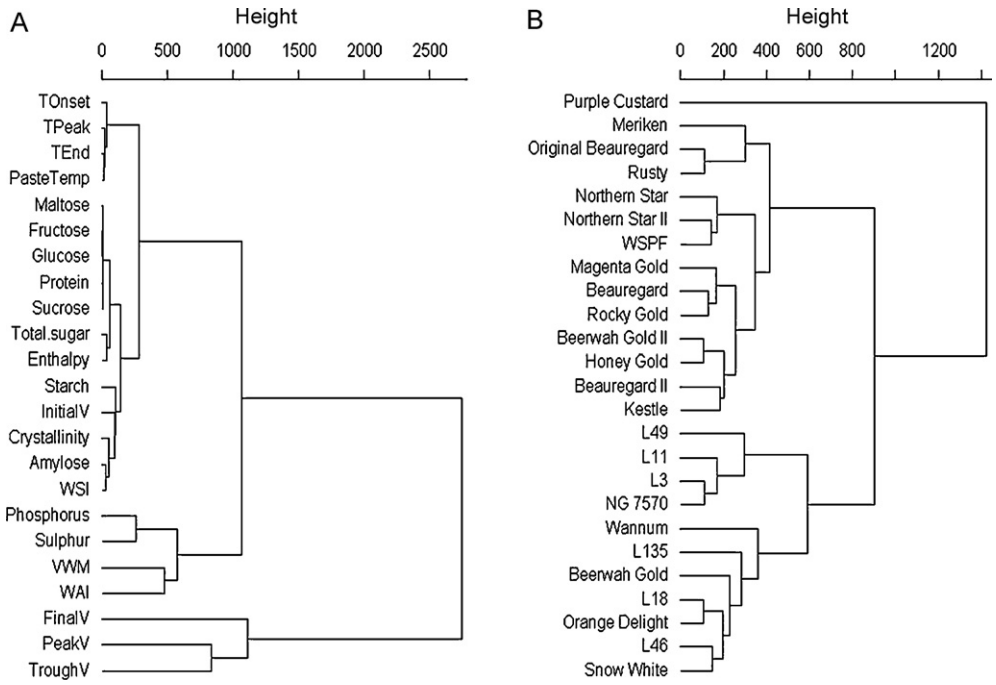

Fig. 4. Principal Component Analysis (PCA) showing clusters by the physicochemical and functional traits (A) and by sweetpotato cultivars (B) (TOnset, TPeak, TEnd, Enthalpy = onset, peak and end temperatures and enthalpy of gelatinisation in the Differential Scanning Calorimeter; PasteTemp, InitialV, PeakV, TroughV, FinalV = Pasting temperature, and initial, peak, trough and final viscosities in the Rapid Visco-Analyser; WSI, WAI = water solubility and absorption indices; VWM = volume weighted mean in the Malvern Mastersizer (Waramboi et al., 2011)).

sugar, maltose, sulphur, crystallinity, WAI, WSI and the RVA viscosity parameters all loaded on PC1, contributing 43% to the overall variability among the cultivars. On PC2, the protein content, DSC peak gelatinisation and the RVA pasting temperatures respectively contributed 20% to the variation, while the glucose and DSC gelatinisation enthalpy accounted for 13% variability on PC3. Collectively, the four components accounted for 81% of the total variation across the sweetpotato cultivars.

Table 3
Eigenvalues, percentage variances and variable loadings for the four principal components.

Parameter[a]	PC1	PC2	PC3	PC4
Eigenvalues	9.971	4.703	2.97	1.131
Variance (%)	43.35	20.45	12.92	4.92
Cumulative variance (%)	43.35	63.80	76.71	81.63
Loadings				
Total starch	0.86	−0.15	0.35	−0.19
Amylose	0.31	0.57	0.14	0.32
Protein	−0.63	0.60	−0.11	−0.20
Total sugar	−0.79	0.16	0.55	0.03
Glucose	−0.53	0.23	0.80	0.04
Maltose	−0.82	−0.27	0.05	−0.27
Phosphorus	−0.58	0.31	−0.44	−0.03
Sulphur	−0.77	0.39	−0.07	0.33
Crystallinity	0.75	−0.39	0.09	0.24
Water absorption index	−0.73	0.20	0.12	0.29
Water solubility index	−0.85	0.34	0.22	−0.02
Enthalpy	0.09	0.35	−0.68	−0.13
Peak temperature	0.39	0.85	−0.12	−0.12
Initial viscosity	−0.71	0.05	−0.16	0.51
Peak viscosity	0.92	0.11	0.04	0.27
Trough viscosity	0.84	0.37	0.14	0.22
Final viscosity	0.80	0.41	0.14	0.27
Pasting temperature	0.58	0.70	0.07	−0.09

[a] Enthalpy and peak temperature = enthalpy and peak temperature of gelatinisation in the Differential Scanning Calorimeter; Initial, Peak, Trough and Final viscosities, and Pasting temperature in the Rapid Visco-Analyser (Waramboi et al., 2011).

Cluster analysis of the cultivars and their properties (Fig. 4a and b) revealed that the properties of cultivar Purple Custard lay outside those of the other cultivars. Although sub-clusters exist, the 25 sweetpotato cultivars can be clustered into two main groups. One cluster represents the 'gold' cultivars (e.g. Beauregard, Magenta Gold, Honey Gold and Rocky Gold), which are characterised by their low dry matter and starch, and high sugar contents, while the other is made up of the 'cream' cultivars (e.g. L49, L3, Wanmun, Orange Delight, and Snow White) that have inverse properties (high dry matter and starch, low sugar) to that of the gold cultivars. Hence, the PCA appears to demonstrate useful trends in understanding the associations and interactions between starch and non-starch components, and their effects on digestibility in the sweetpotato cultivars. Other studies, for example, sweetpotato curd (Mohapatra, Panda, Sahoo, Sivakumar, & Ray, 2007), beef meat (Destefanis, Barget, Brugiapaglia, & Tassone, 2000), apple (Soria, Recasens, Gatius, & Puy, 1999), and liquor (Pokorny, Kalinova, & Velisek, 1995) have reported the usefulness of the PCA in identifying variations among samples. In particular, properties (e.g. starch, sugar, protein, and mineral contents) similar to those measured in the present study were found to be responsible for variations or differences in sensory, organoleptic and overall acceptability qualities of sweetpotato curd (Mohapatra et al., 2007).

4. Conclusions

The sweetpotato cultivars displayed monophasic digestion behaviours, and the first-order kinetic model was suitable for predicting the time-course of starch digestion. Interactions and associations between starch and non-starch components affected starch digestibility. Some cultivars had predicted 100% starch hydrolysis, while others had RS fractions. Flours from all of the cultivars were predicted to be high GI and high GL foods, with possible differences between 'gold' and 'cream' cultivars with the former generally having more antioxidant properties. The digestibility properties found here, reported for the first time, are diverse, and

suggest that choice of cultivar can affect the nutritional value of sweetpotato-based foods. There is also the strong possibility of G x E effects on the choice of and nutrient availability from sweetpotato. Studies are on-going in our laboratories that will contribute to the understanding of the behaviours reported, and the differences measured.

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