Accepted Manuscript

Influence of extrusion on expansion, functional and digestibility properties of whole sweetpotato flour

Joel G. Waramboi, Michael J. Gidley, Peter A. Sopade

PII: S0023-6438(14)00369-7

DOI: 10.1016/j.lwt.2014.06.016

Reference: YFSTL 3980

To appear in: *LWT - Food Science and Technology*

Received Date: 13 May 2013

Revised Date: 3 June 2014

Accepted Date: 4 June 2014

Please cite this article as: Waramboi, J.G., Gidley, M.J., Sopade, P.A., Influence of extrusion on expansion, functional and digestibility properties of whole sweetpotato flour, *LWT - Food Science and Technology* (2014), doi: 10.1016/j.lwt.2014.06.016.

Influence of extrusion on expansion, functional and digestibility properties of whole sweetpotato flour[1]

Joel G. Waramboi[a,b], Michael J. Gidley[b], Peter A. Sopade[a,b,*]

[a]*School of Agriculture & Food Sciences, University of Queensland, St Lucia 4072, Australia*

[b]*Centre for Nutrition & Food Sciences, Queensland Alliance for Agriculture and Food Innovations, University of Queensland, St Lucia 4072, Australia*

Abstract

Beerwah Gold, *Northern Star*, *Snow White*, and *L49* cultivars of sweetpotato from Australia and Papua New Guinea, were studied for their extrusion behaviours in a co-rotating twin-screw extruder at three moisture (30, 35, 40 g/100 g) and screw speed (150, 220, 300 rpm) levels with a slit die. Low moisture increased the die pressure (2 - 6 bar) and specific mechanical energy (280 - 600 kJ/kg) of the extruder. Expansion, functional and digestibility properties of the extrudates were extrusion-dependent and cultivar-specific. Extrusion moisture increased the longitudinal expansion (15 - 30 m/kg) of the extrudates, which were almost completely gelatinised (100 g/100 g degree of gelatinisation). *In-vitro* starch digestion revealed that salivary-gastric digestion in the extrudates ranged from 8 - 18 g/100 g dry starch, while the rate of

[1]Presented in part at the Australian Food Science Summer School, Australian Institute of Food Science & Technology, University of Melbourne, Melbourne, VIC 3010, Australia. 01-03 February, 2012.

*Corresponding author. Tel.: + 61 7 334 67653; Fax: + 61 7 336 51177.

E-mail address: p.sopade@uq.edu.au (P.A. Sopade).

starch digestion was 3.0 – 3.7 min^{-1}. Salivary-gastric digestion in the non-extrudates was from 2 – 11 g/100 g dry starch, with the rate of starch digestion being 0.1 – 0.8 min^{-1}. Estimated glycemic index of the extrudates ranged from 87 – 124 g/100 g, higher than in the non-extrudates and dependent on extrusion moisture and screw speed. This is the first study on extrusion-property relationships of the cultivars to guide global utilisation of sweetpotato.

Running title: Extrusion of whole sweetpotato flour …

Keywords:
Extrusion;
Expansion;
Pasting;
Water absorption;
In-vitro starch digestion;

1. Introduction

Sweetpotato (*Ipomoea batatas* Lam) is the fifteenth most produced agricultural commodity in the world, with an estimated global production of 103 million tonnes in 2012 (FAO, 2014). In Australia, about 42,000 tonnes were produced in 2012, with *Beauregard* and *Northern Star* as the main commercial cultivars (Maltby, Coleman, & Hughes, 2006; FAO, 2014). Sweetpotato is high in potassium that is important in acid-base balance, and its phytochemicals (e.g. carotenoids and anthocyanins), especially in coloured-flesh cultivars, project it as a nutraceutical commodity

(Woolfe, 1992; Ahmed, Akter, Lee, & Eun, 2010; Liu, Sabboh, Kirchoff, & Sopade, 2010; Peng, Lia, Guan, & Zhao, 2013). Specific studies have been conducted on the health benefits of white- and coloured-flesh sweetpotato, and, by virtue of its constituents (e.g. minerals and phytochemicals), sweetpotato is antihypertension, possesses antioxidant capacity, reduces insulin resistance (antidiabetic), enhances sight, and can lower total and LDL cholesterol (Kusano & Abe, 2000; Ludvik, Mahdjoobian, Waldhaeusl, Hofer, Prager, Kautzky-Willer, & Pacini, 2002; Bouvelle-Benjamin, 2007; Fan, Han, Gu, & Chen, 2008; Suda, Ishikawa, Hatakeyama, Miyawaki, Kudo, Hirano, Ito, Yamakawa, & Horiuchi, 2008; Park, Kim, Lee, Lee, & Cho, 2010; Zhu, Cai, Yang, Ke, & Corke, 2010). Sweetpotato is a main energy source in many countries in south Pacific, Asia, Africa, and South America (Woolfe, 1992; Bouvelle-Benjamin, 2007). However, sweetpotato is bulky, highly perishable and often fetch low value to weight in the market, and generally, postharvest losses can be up to 50 g/100 g (Spriggs, 2008) due to many issues that include poor packaging, storage, handling, and transportation leading to broken roots, spoilage and rotting. Sweetpotato consumption is reported to be declining in industrialised countries, but as with most perishables, processing increases their value, availability and storage stability, and extrusion is a well-known processing technique. (Grabowski, Truong, & Daubert, 2008; Menegassi, Pilosof, & Arêas, 2011; Potter, Stojceska, & Plunkett, 2013; Siddiq, Kelkar, Harte, Dolan, & Nyombaire, 2013).

Sweetpotato flour or starch has been extruded on its own or in combination with other materials to produce noodles, pasta, vermicelli and other products (Ahmed, Chang, Balaban, & Arreola, 1991; Khalil & Henry, 1997; Iwe, van Zuilichem, Ngoddy, & Ariahu, 2001; Dansby & Bouvelle-Benjamin, 2003). These studies mainly used one cultivar, did not study whole flour, and importantly, we are unaware of studies on Australian or south Pacific sweetpotato cultivars. Increase in global utilisation of sweetpotato demands knowledge of the processing characteristics of sweetpotato cultivars from various regions. Earlier studies in our laboratories reported on the physicochemical, functional and digestibility properties of non-processed sweetpotato flours to understand the food properties of the Papua New Guinean and Australian cultivars (Waramboi, Dennien, Gidley, & Sopade, 2011; Waramboi, Gidley, & Sopade, 2012). In the present study, some popular and lesser-known cultivars were selected for their different physicochemical characteristics, and their extrusion behaviours as whole flours were investigated.

2. Materials and Methods

2.1. Sweetpotato cultivar and flour

Beerwah Gold, *Northern Star*, *Snow White* and *L49* cultivars of sweetpotato were used, and had colour and dry matter properties as earlier reported (Waramboi et al., 2011). Flours from these cultivars were prepared as in Waramboi et al. (2011), and gave 65 – 84 g/100 g solids yields with an average particle size (volume weighted mean; Mastersizer, Model Hydro 2000MU, Malvern Instruments Ltd, Worcestershire, WR14 1XZ, UK) of 280 µm. The proximate composition of the flours (Table 1), was analysed using standard procedures (AOAC, 2007; Waramboi et al., 2011).

2.2. Extrusion

The sweetpotato flours were extruded in the Prism Eurolab KX 16 twin screw extruder (Thermo Prism, Emerald Way, ST15 0SR, UK), using a slit die (15 x 2 mm^2) at three levels each of moisture (30, 35, 40 g/100 g) and screw speed (150, 220, 300 rpm), maximum barrel temperature of 120°C, and feed rate of 1.5 kg/h. These conditions were obtained from preliminary studies in our laboratories on stable sweetpotato extrusion as evidenced by no die jetting, continuous run and minimum torque fluctuations (van Ruremonde, 2010). The extruder set-up is detailed in Yong, Chan, Garcia, & Sopade (2011). The extrudates were cooled overnight at room temperature before their expansion characteristics were assessed. They were then freeze-dried and cryo-milled as before (Yong et al., 2011) prior to further analysis. The non-extruded sweetpotato dried chips were also cryo-milled, and all the cryo-milled samples averaged 160 µm particle size. Due to a limited sample size, cultivars *Snow White* and *L49* were extruded at only one condition (35 g/100 g moisture, 300 rpm screw speed). The melt (die) temperature was measured using a thermocouple attached to the die, and the specific mechanical energy (SME) was calculated as in Eq (1) because the no-load torque was negligible.

$$\text{SME (kJ/kg)} = \frac{\text{SS x P x T}}{\text{SS}_{\text{max}} \text{ x Q x 100}} \quad (1)$$

where SS = screw speed (rpm); SS_{max} = maximum screw speed (500 rpm); T = average torque recorded over sampling time (%), P = power rating of extruder (1.8 kJ/s); Q = mass flow rate (kg/s). A block (cultivar) design was used for the extrusion experiment, which was randomised with two replicates.

2.3. Extrudate analysis

2.3.1. Expansion properties

The longitudinal (LE, length per unit weight, m/kg), transverse (TE, cross-sectional area of extrudate relative to the cross-sectional area of the slit die, m^2/m^2), width and thickness (width and thickness of extrudate relative to the width and thickness of the slit die respectively, m/m) expansion indices of the extrudates were determined, as well as their apparent specific volume (m^3/kg). From about 300 g of extrudate from each extrusion condition, three strands were cut, and measurements were taken at three random spots on each strand, to give nine data sets for TE and three data sets for LE. For each strand, the apparent specific volume, SpV, was calculated as in Eq (2) to yield three data sets:

$$\text{SpV} = \frac{\text{Length x Width}_{\text{AVG}} \text{ x Thickness}_{\text{AVG}}}{\text{Weight}} \quad (2)$$

where, Length = length of each strand, $\text{Width}_{\text{AVG}}$ = average width of each strand, $\text{Thickness}_{\text{AVG}}$ = average thickness of each strand, and Weight = weight of each strand.

2.3.2. Functional properties

The procedures in Waramboi et al. (2011) and Yong et al. (2011) were used to determine the water absorption (1 g sample + 30 mL water) and solubility (100°C, 24 h) indices, RVA pasting (25 g sample and water at 10 g/100 g solids, Standard Profile 1; Newport Scientific Pty Ltd, Warriewood, NSW 2102, Australia), and starch gelatinisation (5 mg sample and 20 mg water (ratio 1:4), 30°C isothermal, scan rate 10 °C/min to 120°C; Differential Scanning Calorimetry (DSC), Model Q2000, TA

Instruments, New Castle, DE 19720, USA) properties of the extruded and non-extruded flours. The degree of starch gelatinisation (DG) in the extrudates was calculated from the enthalpies of starch gelatinisation of the extruded and non-extruded flours following the method in Mahasukhonthachat, Sopade, & Gidley, (2010).

2.3.3. Structural properties

The crystallinity properties of the samples were obtained by scanning in a diffractometer (D8 Advance X-ray Diffractometer, Bruker Biosciences Pty Ltd, Preston, VIC 3073, Australia) using 40 kV target voltage, 30 mA current, 2-40° 2θ scanning range, 0.02^{o} step interval, 1.00^{o}/min scan speed, and monochromatic Cu-Kα radiation anode at 1.5406 Å wavelength. The diffractograms were analyzed (Traces®; Diffraction Technology Pty Ltd, Mitchell, ACT 2911, Australia), and the degree of crystallinity and d-spacing were calculated as below:

$$\text{Crystallinity (\%)} = 100 \times \left(\sum_{i=1}^{n} A_{Pi}\right) / A_T \quad (3)$$

$$\text{d-spacing (Å)} = \lambda / (2\, Sin\, \theta) \quad (4)$$

where, A_{Pi} = area of the ith peaks, A_T = total area, λ (lambda) = wavelength in angstroms (1.5406 Å) for copper, θ (theta) = diffraction angle in degrees, and d-spacing = interatomic spacing in angstroms (Waramboi et al., 2011).

The procedures in Waramboi et al. (2011) were also used in scanning electron microscopy (SEM), and they involved mounting the samples on 12-mm aluminium stubs with double-sided carbon tape, coated for 10 min. (Platinum Sputter Ion Coater, Model IB-5, Eiko Engineering Company, Japan), and observed at 5 kV at 10 μm field depth (Scanning Electron Microscope, Model 6400F, JEOL Ltd., Akishima, Tokyo 196-8558, Japan). Images were recorded using the ImageSlave software (Science Solutions Pty Ltd, Redlynch, QLD 4870, Australia).

2.3.4. In-vitro starch digestion

In-vitro starch digestion was done following the glucometry procedure in Chen & Sopade (2013). About 500 mg sample was digested with artifical saliva (250 U per mL; α-amylase from *Aspergillus oryzae;* Sigma-P4676; Sigma-Aldrich, Castle Hill, NSW 2154, Australia), before pepsin (1 mg per mL; gastric porcine mucosa, Sigma P-6887, in 0.02M HCl, pH 2) was added, and incubated in a reciprocating water bath (85 rpm, 37°C, 30 min). The digesta was neutralized, adjusted to pH 6 with a 0.2M sodium acetate buffer, before a mixture of pancreatin (2 mg per mL; porcine pancreas; Sigma P1750) and amyloglucosidase (28 U per mL; *Aspergillus niger*; Sigma A-7420) in the acetate buffer was added. The glucose concentration in the digesta was measured by a glucometer (Accu-Check® Performa®, Roche Diagnostics Australia Pty Ltd, Caste Hill, NSW 2154, Australia), and digested starch per 100 g dry starch was calculated as in Sopade & Gidley (2009).

2.3.5. Modelling of starch digestogram

The digestograms were modelled using a modified first-order kinetic (MFOK) model (Eq. (5)) following the procedures in Waramboi et al. (2012). The area under the digestograms between times t_1 = 0 min, and t_2 = 240 min was calculated, and relative to that of freshly baked white bread as described before (Yong et al., 2011;

Waramboi et al., 2012), was used to calculate the glycemic parameters (glycemic index and load) of the extrudates and non-extrudates.

$$D_t = D_o + D_{\infty\text{-}o} (1 - \exp(-k\,t)) \quad (5)$$

$$D_\infty = D_o + D_{\infty\text{-}o}$$

where, D_t = digested starch at time t, D_o = digested starch at time t = 0, D_∞ = digested starch at time t = ∞, and K = rate of digestion.

In modelling the digestograms, three approaches were used (Waramboi et al., 2012):

a. Gastric–pancreatic (GP). Digested starch that covers the complete gastric and pancreatic digestion process.

b. Pancreatic (P). This subtracted salivary-gastric digested starch (D_0) from the digested starch values from (a). This procedure removes the actual starch digested during the salivary-gastric stage, and 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^{o}C for 1 h. 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 the analyses were done with at least two duplicates, and the extrudates and non-extrudates were randomised before analysis. The General Linear Model in Minitab® ver16 software (Minitab Inc., State College, PA 16801-3008, USA) was used for analysis of variance (ANOVA) and tests of significance at 95% confidence level. The software was also used for the Pearson's correlations test.

3. Results and Discussion

3.1. Physicochemical properties of the flours

The starch content of the sweetpotato cultivars ranged from 46 - 73 g/100 g solids, the sugar content was from 13 – 25 g/100 g solids, and the amylose content was between 26 and 32 g/100 g solids (Table 1). These values are within the range reported for sweetpotato (Liu et al., 2010; Waramboi et al., 2011), and, compared to an earlier study that used the same cultivars from an earlier planting season, they suggest minimal seasonal variations. With reference to extrusion, amylose content and other physicochemical properties affect extruder response and extrudate properties. (Camire, Camire, & Krumbar, 1990; Chaudhary, Miler, Torley, Sopade, & Halley, 2008; Li, Liu, Zou, Yu, Xie, Pu, Liu, & Chen, 2011; Vargas-Solórzano, Carvalho, Takeiti, Ascheri, & Queiroz, 2014).

3.2. Extruder response

There were cultivar differences in the extruder response with the *Beerwah Gold* cultivar showing the least SME and die pressure (Table 2). Vargas-Solórzano et al. (2014) measured differences in extruder response when six Brazilian sorghum genotypes were extruded, and associated this to the inherent physicochemical differences of the genotypes. In the present study, although the *Snow White* cultivar had the least starch content (46 g/100 g solids), the starch content of the *Beerwah Gold* was also low (57 g/100 g solids) with a slightly lower amylose content (26 g/100 g solids) than the *Snow White* (28 g/100 g solids). There were no significant cultivar effects on the die temperature, but the *L49* appeared to have the lowest temperature and significantly, the highest SME. Even though the specific heat capacity of the starches was not measured, high-amylose starches can have higher heat capacity than regular or waxy starches (Tan, Wee, Sopade, & Halley, 2004). This implies that high-amylose starch melts require more heat to increase in temperature. Moreover, possibly because of its linear structure, amylose increases SME during extrusion (Chaudhary et al., 2008; Li et al., 2011). The *L49* could be said to have the highest amylose content amongst the cultivars (Table 1), and its extrusion behaviours agree with these published studies. Although non-significant ($p>0.05$), the amylose content of the cultivar appeared to be directly related to the SME, and inversely related to the melt temperature.

For the *Beerwah Gold* and *Northern Star* cultivars, the extrusion moisture significantly reduced the SME and pressure, while the screw speed increased the melt temperature and SME (Table 2). These effects are consistent with published studies as it relates to how these extrusion conditions influence melt heat capacity, viscosity and frictional heat generation (Ding, Ainsworth, Plunkett, Tucker, & Marson, 2006; Mahasukhonthachat et al., 2010; Yong et al., 2011; Ma, Pan, Li, Atungulu, Olson, Wall, & McHugh, 2012). The extrusion moisture and screw speed significantly interacted to define the extruder response. Generally for all the cultivars, a high SME would result from low moisture and high screw speed (Fig. 1A), a combined condition that could yield a high melt temperature (Fig. 1B) and barrel pressure (Fig. 1C) that are favourable for directly-expanded extrudates. This is because high melt temperatures can superheat water in the melt to increase internal pressure, which on dropping to atmospheric pressure, aids moisture escape and extrudate expansion on cooling (Mason & Hoseney, 1986; Pansawat, Jangchud, Jangchud, Wuttijumnong, Saalia, Eitenmiller, Phillips, 2008; Yong et al., 2011; Ma et al., 2012).

3.3. Expansion properties

The expansion properties were cultivar dependent (Table 2) with the *Beerwah Gold* having the highest longitudinal (28 m/kg) and the lowest transverse (TE) or cross-sectional (CSE) expansion properties. An increase in the moisture content significantly increased the LE, while the effects of the screw speed were non-significant on the expansion properties (Table 2). Even though extruding either the *Beerwah Gold* or *Northern Star* cultivar at high screw speed and low moisture could yield a low LE (Fig. 1D), a less dense extrudate (Fig. 1F) would be produced with a high CSE (Fig. 1E). This is consistent with published studies that low moisture favours CSE or TE because of high melt viscosity, but melt elasticity reduces with low moisture to adversely affect LE (Singh, Sekhon, & Singh, 2007; Stojceska, Ainsworth, Plunkett, & Ibanoglu, 2009; Ma et al., 2012). In a composite wheat flourcorn starch-brewers spent grain-red cabbage extrusion study, for example, Stojceska et al. (2009) reported a reduction in expansion with moisture. From Eq (1), high screw speeds will directly increase SME, and the attendant frictional heat could lead to superheated water that generally increases expansion. In general, the SpV and expansion properties were affected by the moisture and screw speed levels in the present study. Other studies have shown that factors like the residence time, barrel temperature and feed rate also affect extrudate expansion and other food properties (Iwe et al., 2001; Stojceska et al., 2009; Ma et al., 2012).

3.4. Pasting, gelatinisation and structural properties

Irrespective of the cultivar, the non-extrudates pasted at a temperature from 72 - 75°C and exhibited diverse pasting behaviours (shear thickening, and slightly- and moderately-shear thinning). These pasting and gelatinisation behaviours are similar to those sweetpotato cultivars earlier studied (Waramboi et al., 2011). As expected, the heat-moisture-shear effects of extrusion gelatinised the starch in the sweetpotato, and as typified in Fig. 2, the pasting behaviours of the extrudates were different from those of the non-extrudates. The extrudates generally exhibited lower RVA viscosities than the non-extrudates, but their initial viscosity (>70 cP) was higher than that of the non-extrudates (<50 cP) because the gelatinised starch in the extrudates absorbed more water than the raw starch in the non-extrudates (Ma et al., 2012). However, the extrusion conditions exercised different effects on the RVA parameters. Increasing the screw speed (or shear rate) generally lowered the RVA viscosity (Table 3), and this is expected because of a possible increase in starch destructurisation and/or depolymerisation (Menegassi et al., 2011; Ma et al., 2012; Siddiq et al., 2013). An increase in the moisture, however, significantly ($p<0.05$) increased the RVA peak and final viscosities (Table 3). While the trend between the extrusion moisture and RVA properties could indicate varied changes to the degree of starch gelatinisation (DG), the DSC revealed that, irrespective of the extrusion conditions and cultivars, starch was completely gelatinised in the extrudates.

Being a heat-moisture phenomenon, degree of starch gelatinisation is dependent on extrusion moisture and temperature. However, because of differences in feed materials, extruder or range of extrusion conditions, different trends have been measured on how extrusion conditions affect starch gelatinisation. For example, Govindasamy, Campanella, & Oates (1996) reported that increasing the barrel temperature and feed moisture (~40 g/100 g) enhanced the DG in extruded sago starch, while Ding et al. (2006) found the DG in extruded rice snacks decreased with increasing moisture and temperature. In the present study, neither the main nor interaction effects of the moisture, temperature and screw speed significantly ($p>0.05$) affected the degree of starch gelatinisation. However, the changes in the RVA properties would suggest certain characteristics of the sweetpotato starch in the cultivars were dependent on extrusion.

3.5. Water absorption and solubility properties

The WAI and WSI of the extrudates significantly increased (more than 200%) when compared to the non-extrudates (Table 3) as the starch was gelatinised during the heat-moisture treatments in the extruder. For the extrudates, there were increases, then decreases in WAI and WSI when the moisture or screw speed was changed.

Although significant effects were measured, the moisture or screw speed levels did not materially change the WAI and WSI.

Generally, low feed moisture or high screw speeds decrease WAI while high temperatures or low feed moisture increase WSI in many extruded food systems (Mason & Hoseney, 1986; Govindasamy et al., 1996; Ding et al., 2006; Stojceska et al., 2009). The WSI gives an indication of the degree of starch conversion and molecular degradation possibly due to melting and degradation of amylopectin crystals into dextrins and soluble polysaccharides (Menegassi et al., 2011; Siddiq et al., 2013).

3.6. Granular structure

Prior to extrusion, the sweetpotato flours (non-extrudates) showed (Fig. 3) heterogeneous granule shapes (oval-, round-, angular-, polygonal-) with no surface pores, as reported before (Huang, 2009; Waramboi et al., 2011). Upon extrusion, and irrespective of the cultivars studied, the starch granules were destructurised, as expected (Fig. 3). The destructurisation effects of extrusion are well documented (Govindasamy et al., 1996; Ding et al., 2006; Mahasukhonthachat et al., 2010), and have consequences for starch solubles or low-molecular weight products being leached out (Gautam & Choudhury, 1999; Dansby & Bouvelle-Benjamin, 2003; Ding et al., 2006; Stojceska et al., 2009). However, as discussed above, there were no clear effects of extrusion on WSI in the present study.

3.7. Crystallinity properties

X-ray diffraction provides an in-sight into starch or extrudate structures. The non-extrudates, with 34 - 40% level of starch crystallinity (Table 3), showed type-A crystalline pattern with four distinct peaks (5.9Å, 5.2Å, 4.9Å, 3.9Å) at 2-theta angles (Fig. 4) as reported before for sweetpotato (Waramboi et al., 2011). Crystallinity is affected by the ratio of amylose and amylopectin components of the starch, and reflects molecular and structural organisation of the material. Irrespective of the cultivars, the extrusion significantly reduced crystalline peak intensities in the extrudates (Table 3). There were no significant effects of the screw speed, but the high moisture extrusion (e.g. 40 g/100 g) yielded 35% starch crystallinity in the extrudates.

Moisture-driven starch gelatinisation is thought to proceed more at high moisture extrusion (Govindasamy et al., 1996; Mahasukhonthachat et al., 2010), with the high specific heat capacity, low viscosity and low melt temperature at high moisture favouring this. Consequently, starch retrogradation, a re-crystallisation phenomenon, is reported to be enhanced at high moisture extrusion where the glass transition temperature is low as not to impede molecular reorganisation at ambient temperature (Knudsen, Lærke, Steenfeldt, Hedemann, & Jørgensen, 2006; Potter et al., 2013). The increase in extrudate crystallinity obtained at the 40 g/100 g moisture level (Table 3) could have resulted from this. Possibly retrograded resistant starch (type-3 resistant starch) was more at this moisture level to reduce digestible starch.

3.8. Digestibility properties

Both the extruded and non-extruded sweetpotato exhibited monophasic starch digestograms (Fig. 5) as reported before for non-processed sweetpotato (Waramboi et al., 2012; Chen & Sopade, 2013). Monophasic digestograms are commonly described by food systems, and Delgado, Castro & Vázquez (2009) reported an identical pattern when potato was hydrolysed by amylases. These authors suitably described the digestograms with a first-order kinetic model. The digestograms of the sweetpotato were also suitably ($r^2 > 0.97$) described by the MFOK model (Eq (5)), and Table 4 show the digestibility and glycemic properties of the samples for the GP-, P- and GPEB- digestion modelling approaches (2.3.5). The D_o, which represents very rapidly digestible starches (VRDS), in the GP-approach (Table 4) differed significantly ($p<0.05$) among the non-extrudates (2.3 - 11.1 g/100 g dry starch) and extrudates (7.9 - 18.4 g/100 g dry starch). Generally, there were no significant effects of the moisture and screw speed on the D_o for the GP-approach. In the GPEB-approach, the D_o of the non-extrudates was almost negligible, suggesting the presence of variable amounts of soluble glucose in the cultivars (Waramboi et al., 2012), which possibly contributed to the high D_o in the GP-approach. On the other hand, the extrudates had higher D_o (4.6 - 6.3 g/100 g dry starch) than the non-extrudates because the heat-moisture-shear effects of extrusion almost completely disrupted or gelatinised the starch granules as discussed earlier (3.4).

Moreover, there were significant differences in the maximum digested starch (D_∞) of the cultivars, and across the three modelling approaches. In the GP- approach, the non-extruded flours of cultivars *Beerwah Gold* and *Snow White* would be completely digested (D_∞ = 100 g/100 g dry starch), while cultivars *Northern Star* and

L49 could have ~20 g/100 g dry solids resistant starch (RS). For the extrudates, cultivar *Northern Star* had the highest RS of ~36 g/100 g dry solids, while the *Snow White* had < 1 g/100 g dry solids RS, or would be completely digested in both the extruded and non-extruded forms. Irrespective of the modelling approach, there were no substantial effects of the extrusion moisture and screw speed on D_{∞}, and this parameter being less than 100 g/100 g dry starch in the extrudates, suggests the presence of resistant starch, possibly type-3 (retrograded starch). We came to this conclusion because the extrudates were almost completely gelatinised, and resistant starch (Englyst, Kingman, & Cummings, 1992) type-1 (encapsulated starch), type-2 (uncooked starch), or their mixtures could not have been present. Although this was not independently evaluated, RS type-3 could have formed during cooling and storage of the extrudates as expected in starch-containing processed foods. However, contrary to expectations, there were no moisture effects on D_{∞}, and the increase in starch crystallinity at the 40 g/100 g moisture was possibly not due to measurable retrogradation effects.

The rate of digestion (K) was marginal across the three modelling approaches, and the extrudates had higher K values than the non-extrudates (Table 4). The K values decreased at the high moisture but increased with increasing the screw speed irrespective of the modelling approaches. High shear rate is expected to degrade starch structure, and possibly multi-cellular and inhibitory materials (e.g. cell walls) that maybe present, and this could explain the slightly higher rate of starch digestion as observed at the 300 rpm screw speed ($\geq 3.1 \times 10^{-2}$ min^{-1}) in Table 4. Across the modelling approaches, significant differences were observed in the GI_{AVG} of the non-extrudates (> 65 g/100 g dry starch) and extrudates (> 87 g/100 g dry starch). Similarly, the extrudates showed high GL (~60 g/100 g solids) compared to the non-extrudates (~40 g/100 g solids). There were only marginal effects of the extrusion moisture and screw speed levels on the GL.

Using white bread as a reference, foods with GI >100 and <80 g/100 g dry starch are considered as high and low GI foods respectively, while those with a GL >36 g/100 g solids are high GL foods (Foster-Powell, Holt, & Brand-Miller 2002; Atkinson, Foster-Powell, & Brand-Miller 2008). As such, all the samples, irrespective of the state (extruded or non-extruded) can be classified as medium to high GI or GL foods. Low GI foods are advisable for health and nutritional benefits, and understanding the factors that influence the glycemic properties of processed sweetpotato is advantageous to produce sweetpotato-based products.

This is probably the first study to report on extrusion behaviours of sweetpotato cultivars that are commonly grown in Australia, Papua New Guinea and south Pacific, as well as among the few studies on non-supplemented sweetpotato flours. The properties of the extrudates are diverse, and to maximize value addition and utilisation of the root crop, it is important to establish and understand possible relationships that may define the behaviours of these cultivars. Table 5 shows the Pearson's correlations between the different properties of the sweetpotato cultivars, and although certain trends are inconsistent with theory, some are worth emphasising.

As discussed earlier, the sweetpotato cultivars differed in their starch contents, and starch affects functional and processing properties, for example, extruder response (e.g. SME) and extrudate expansion. In preliminary studies in our laboratories (not reported), we could not extrude flours of cultivar Northern Star at ≤ 25 g/100 g moisture levels because of high torque or SME that possibly resulted from its high starch content (Table 1), and thick paste viscosity (Table 3). The SME, which reflects the shear effects during extrusion, appeared to positively correlate with the rate of starch digestion, K (r = 0.85) as the sweetpotato starch was possibly destructurised by the high shear effects to enhance digestion. This agrees with the conclusions of Mahasukhonthachat et al. (2010). Also, the destructurisation effects could have enhanced water binding to possibly explain the positive correlation, though non-significant, between the SME and WAI. Being a measure of the water binding ability, the WAI significantly correlated (r = 0.98) with the initial pasting viscosity, and swelling of starch granules could have increased leaching out of solubles to explain the positive correlation with the WSI (r = 0.45) as shown in Table 5. The WSI also directly correlated with the gastric (D_o, r = 0.992) and maximum (D_∞, r = 0.699) digested starch. Interestingly, both the IV and FV pasting properties were negatively correlated. This is not expected, but it probably reflects the negative correlation between the WAI and FV. The two main measures of expansion, the LE and TE exhibited a negative correlation as previously reported by Yong et al. (2011). The starch content significantly affected the GL (r = 0.997), as expected in high-starch foods such as sweetpotato.

4. Conclusions

The specific mechanical energy (SME) varied with the sweetpotato cultivars, and at low moisture, the SME generally increased, while high screw speed directly increased the SME and expansion. The extrudates showed higher pasting, gelatinisation, solubilisation and digestibility properties than the non-extrudates, which had higher starch crystallinity. Generally, extruder response was affected by both the moisture and screw speed levels, and the type of cultivars. The results from this study will enable sweetpotato extrudates of defined properties (e.g. expansion and digestibility) to be produced from the stated cultivars. This is important for value addition, diversification of products and maximising the use of sweetpotato globally.

Acknowledgements

The authors are grateful to Sandra Dennien and Tom Okpul, respectively of the Queensland Department of Agriculture, Fisheries and Forestry, and the University of Queensland, Australia for material support.

Conflict of interest

Authors declare no conflict of interest.

References

The five starred references are key references because they deal with extrusion, and its significance to modern food processing, and the importance of sweetpotato to human nutrition.

Ahmed, E.M., Chang, F.C., Balaban, M.O., & Arreola, A.G. (1991). Extrusion cooking of sweet potato roots. *Journal of Food Quality, 14*, 229-239.

Ahmed, M., Akter, M.S., Lee, J.-C., & Eun, J.-B. (2010). Encapsulation by spray drying of bioactive components, physicochemical and morphological properties from purple sweet potato. *LWT - Food Science and Technology, 43*, 1307-1312

AOAC. (2007). *Official Method of Analysis.* (18th ed.). Association of Official Analytical Chemists, Arlington, USA.

Atkinson, F.S., Foster-Powell, K., & Brand-Miller, J.C. (2008). International tables of glycemic index and glycemic load values: 2008. *Diabetes Care, 31*, 2281-2283.

Bouvelle-Benjamin, A.C. (2007). Sweetpotato: A review of its past, present and future role in human nutrition. *Advances in Food and Nutrition Research, 52*, 1-59.

Camire, M.E., Camire, A., & Krumbar, K. (1990). Chemical and nutritional changes in foods during extrusion. *Critical Reviews in Food Science and Nutrition, 29*, 35-57.

Chaudhary, A.L., Miler, M., Torley, P.J., Sopade, P.A., & Halley, P.J. (2008). Amylose content and chemical modification effects on the extrusion of thermoplastic starch from maize. *Carbohydrate Polymers, 74*, 907.

Chen, G., & Sopade, P.A. (2013). *In-vitro* starch digestion in sweetpotato (*Ipomoea batatas* L.) flour and its dependence on particle size. *International Journal of Food Science and Technology, 48*, 150-156.

Dansby, M.Y., & Bouvelle-Benjamin, A.C. (2003). Physical properties and sixth graders acceptance of an extruded ready-to-eat sweetpotato breakfast cereal. *Journal of Food Science, 68*, 2607-2612.

Delgado, R., Castro, A.J. & Vázquez, M. (2009). A kinetic assessment of the enzymatic hydrolysis of potato (*Solanum tuberosum*). *LWT – Food Science and Technology, 42,* 797-804.

*Ding, Q., Ainsworth, P., Plunkett, A., Tucker, G., & Marson, H. (2006). The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. *Journal of Food Engineering, 73,* 142-148.

Englyst, H.N., Kingman, S.M., & Cummings, J.H. (1992). Classification and measurement of nutritionally important starch fractions. *European Journal of Clinical Nutrition, 46,* 33-50.

Fan, G., Han, Y., Gu, Z., & Chen, D. (2008). Optimizing conditions for anthocyanins extraction from purple sweet potato using response surface methodology (RSM). *LWT-Food Science and Technology, 41,* 155–160.

FAO. (2014). FAOSTAT Database. FAO, Rome, Italy. http://faostat3.fao.org/faostat-gateway/go/to/browse/Q/QC/E. Accessed on 14 February 2014.

Foster-Powell, K., Holt, S.H.A., & Brand-Miller, J.C. (2002). International table of glycemic index and glycemic load values: 2002. *American Journal of Clinical Nutrition, 76,* 5–56.

Gautam, A., & Choudhury, G.S. (1999). Screw configuration effects on starch breakdown during twin-screw extrusion of rice flour. *Journal of Food Processing and Preservation*, *23*, 355-375.

Grabowski, J.A., Truong, V.-D. & Daubert, C.R. (2008). Nutritional and rheological characterization of spray dried sweetpotato powder. *LWT - Food Science and Technology, 41,* 206–216.

Govindasamy, S., Campanella, O.H., & Oates, C.G. (1996). High moisture twin-screw extrusion of sago starch: effect on granule morphology and structure. *Carbohydrate Polymers, 30*, 275-286.

Huang, C. (2009). Physico-chemical, pasting and thermal properties of tuber starches as modified by guar gum and locust bean gum. *International Journal of Food Science and Technology, 44*, 50-57.

Iwe, M.O., van Zuilichem, D.J., Ngoddy, P.O., Ariahu, C.C. (2001). Residence time distribution in a single-screw extruder processing soy-sweet potato mixtures. *Lebensm.-Wiss. u.-Technologie, 34*, 478-483.

*Khalil, H.M. & Henry, B.R. (1997). Feasibility of utilizing sweet potato solids in extrusion cooking. *Food Science and Technology International, 3,* 171-174.

Knudsen, K.E.B., Lærke, H.N., Steenfeldt, S., Hedemann, M.S., & Jørgensen, H. (2006). In vivo methods to study the digestion of starch in pigs and poultry. *Animal Feed Science and Technology*, 130, 114-135.

Kusano, S. & Abe, H. (2000). Antidiabetic activity of white skinned sweet potato (*Ipomoea batatas* L.) in obese Zucker fatty rats. *Biological and Pharmaceutical Bulletin, 23,* 23-26.

Li, M., Liu, P., Zou, W., Yu, L., Xie, F., Pu, H., Liu, H., & Chen, L. (2011). Extrusion processing and characterization of edible starch films with different amylose contents. *Journal of Food Engineering, 106,* 95–101.

Lin, Y., Hsieh, F., Heymann, H., & Huff, H.E. (2000). Effect of process conditions on the physical and sensory properties of extruded oat-corn puff. *Journal of Food Science, 65,* 1253-1259.

Liu, Y., Sabboh, H., Kirchoff, G., & Sopade, P.A. (2010). In vitro starch digestion and potassium release in sweet potato from Papua New Guinea. *International Journal of Food Science and Technology, 45,* 1925-1931.

Ludvik, B.H., Mahdjoobian, K., Waldhaeusl, W., Hofer, A., Prager, R., Kautzky-Willer, A., & Pacini, G. (2002). The effect of Ipomoea batatas (Caiapo) on glucose metabolism and serum cholesterol in patients with type 2 diabetes: A randomised study. *Diabetes Care, 25,* 239-240.

*Ma, H., Pan, Z., Li, B., Atungulu, G.G., Olson, D.A., Wall, M.M. & McHugh, T.H. (2012). Properties of extruded expandable breadfruit products. *LWT - Food Science and Technology, 46*, 326-334

Mahasukhonthachat, K., Sopade, P.A., & Gidley, M.J. (2010). Kinetics of starch digestion and functional properties of twin-screw extruded sorghum. *Journal of Cereal Science, 51*, 392-401.

Maltby, J., Coleman, E., & Hughes, M. (2006). *Sweetpotato in Australia: An overview of production and research*. Paper presented at the sweetpotato workshop, Madang, Papua New Guinea.

Mason, W.R., & Hoseney, R.C. (1986). Factors affecting the viscosity of extrusion cooked wheat starch. *Cereal Chemistry, 63*, 436-441.

Menegassi, B., Pilosof, A.M.R. & Arêas, J.A.G. (2011). Comparison of properties of native and extruded amaranth (*Amaranthus cruentus* L. - BRS Alegria) flour. *LWT - Food Science and Technology, 44*, 1915-1921.

Pansawat, N., Jangchud, K, Jangchud, A., Wuttijumnong, P., Saalia, F.K., Eitenmiller, R.R. & Phillips, R.D. (2008). Effects of extrusion conditions on secondary extrusion variables and physical properties of fish, rice-based snacks. *LWT - Food Science and Technology, 41*, 632–641.

Park, K.-H., Kim, J.-R., Lee, J.-S., Lee, H., & Cho, K.-H. (2010). Ethanol and water extract of purple sweet potato exhibits anti-atherosclerotic activity and inhibits protein glycation. *Journal of Medicinal Food, 13*, 91-98.

Peng, Z., Li, J., Guan, Y. & Zhao, G. (2013). Effect of carriers on physicochemical properties, antioxidant activities and biological components of spray-dried purple sweet potato flours. *LWT - Food Science and Technology, 51*, 348–355.

Potter, R., Stojceska, V., Plunkett, A. (2013). The use of fruit powders in extruded snacks for children. *LWT- Food Science and Technology, 51*, 537-544.

Siddiq, M., Kelkar, S. Harte, J.B., Dolan, K.D., & Nyombaire, G. (2013). Functional properties of flour from low-temperature extruded navy and pinto beans (*Phaseolus vulgaris* L.). *LWT- Food Science and Technology, 50*, 215-219.

Singh, B., Sekhon, K.S., & Singh, N. (2007). Effect of moisture, temperature and level of pea grits on extrusion behaviour and product characteristics of rice. *Food Chemistry, 100*, 198-202.

Sopade, P.A., & Gidley, M.J. (2009). A rapid *in-vitro* digestibility assay based on glucometry for investigating kinetics of starch digestion. *Starch/Starke, 61*, 245-255.

Spriggs, J. (2008). Towards a research agenda for improving consumer demand and marketing of sweetpotato in Papua New Guinea. *A report submitted to the Australian Centre for International Agricultural Research*. University of Canberra, Australia.

*Stojceska, V., Ainsworth, P., Plunkett, A., & Ibanoglu, Ş. (2009). The effect of extrusion cooking using different water feed rates on the quality of ready-to-eat snacks made from food products. *Food Chemistry, 114*, 226-232.

Suda, I., Ishikawa, F., Hatakeyama, M., Miyawaki, M., Kudo, T., Hirano, K., Ito, A., Yamakawa, O., & Horiuchi, S. (2008). Intake of purple sweet potato beverage affects on serum hepatic biomarker levels of healthy adult men with borderline hepatitis. *European Journal of Clinical Nutrition, 62*, 60–67.

Tan, I., Wee, C.C., Sopade, P.A., & Halley, P.J. (2004). Estimating the specific heat capacity of starch-water-glycerol systems as a function of temperature and compositions. *Starch/Stärke, 56*, 6-12.

van Ruremonde, T. (2010). Influence of extrusion on the physical, chemical, functional and digestibility properties of sweetpotato. *Unpublished Internship Report* (Food Physics and Physical Chemistry, Wageningen University, Wageningen, The Netherlands). Centre for Nutrition & Food Sciences, University of Queensland, St Lucia QLD 4072, Australia.

Vargas-Solórzano, J.W., Carvalho, C.W.P., Takeiti, C.Y., Ascheri, J.L.R., & Queiroz, V.A.V. (2014). Physicochemical properties of expanded extrudates from colored sorghum genotypes. *Food Research International, 55*, 37–44.

*Waramboi, J.G., Dennien, S., Gidley, M.J., & Sopade, P.A. (2011). Characterization of sweetpotato from Papua New Guinea and Australia: Physicochemical, pasting and gelatinization properties. *Food Chemistry*, *126*, 1759-1770.

Waramboi, J.G., Gidley, M.J., & Sopade, P.A. (2012). Kinetics of starch digestion in sweetpotato flours from Papua New Guinean and Australian cultivars. *Carbohydrate Polymers, 87*, 461-470.

Woolfe, J.A. (1992). *Sweet potato: An untapped food resource.* Cambridge, United Kingdom: Cambridge University Press.

Yong, L.Z., Chan, C.H., Garcia, C., & Sopade, P.A. (2011). 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.

Zhu, F., Cai, Y.-Z., Yang, X., Ke, J., & Corke, H. (2010). Anthocyanins, hydroxycinnamic acid derivatives, and antioxidant activity in roots of different Chinese purple-fleshed sweetpotato genotypes. *Journal of Agricultural Food Chemistry*, *58*, 7588–7596.

Table 1
Physicochemical properties (g/100g dry solids) of the sweetpotato cultivars*

Cultivar	Starch	Amylose	Protein	Sugar
Beerwah Gold	56.9 ± 0.02c	26.5 ± 2.30a	2.9 ± 0.03a	24.9 ± 0.02a
Northern Star	72.7 ± 0.04a	30.5 ± 0.13a	1.2 ± 0.03d	12.6 ± 0.02d
Snow White	45.9 ± 0.01d	28.2 ± 0.63a	2.0 ± 0.01b	20.6 ± 0.02b
L49	61.9 ± 0.02b	31.5 ± 1.39a	1.9 ± 0.04c	14.1 ± 0.02c

*For each column, means with the same letters are not significantly different (p>0.05). There were two duplicates (n = 2) per analysis.

Table 2
Extruder response and expansion properties of the sweetpotato cultivars – Main effects*

Parameter	Melt temperature (°C)	Pressure (bar)	Specific		Expansion properties			
			mechanical energy (kJ kg^{-1})	volume x 10^{-6} (m^3 kg^{-1})	longitudinal (m kg^{-1})	transverse (m^2/m^2)	width (m m^{-1})	thickness (m m^{-1})
Cultivars†								
Beerwah Gold	82.8 ± 1.15a	3.6 ± 0.04c	482.6 ± 27.92b	402.1 ± 50.54c	27.5 ± 1.39a	0.5 ± 0.11b	0.7 ± 0.00a	0.7 ± 0.14b
Northern Star	84.8 ± 0.40a	6.4 ± 2.05b	689.9 ± 78.55ab	612.3 ± 81.97b	18.3 ± 2.45b	2.3 ± 0.31a	0.8 ± 0.00a	1.5 ± 0.42ab
Snow White	86.5 ± 2.16a	8.2 ± 0.51a	873.3 ± 25.31a	842.9 ± 149.6a	15.4 ± 0.50b	2.0 ± 0.44a	0.9 ± 0.00a	1.5 ± 0.21ab
L49	79.4 ± 2.12a	8.9 ± 0.04a	904.7 ± 125.87a	655.8 ± 241.84b	14.8 ± 2.69b	1.3 ± 0.31ab	0.9 ± 0.14a	2.4 ± 0.35a
Moisture content (g kg^{-1})‡								
300	81.9 ± 2.68a	5.5 ± 1.72a	594.6 ± 152.09a	590.2 ± 237.79a	20.7 ± 5.25b	1.1 ± 0.65a	0.8 ± 0.10a	1.3 ± 0.69a
350	82.6 ± 2.60a	5.2 ± 1.86a	535.8 ± 122.13b	596.8 ± 255.08a	21.7 ± 5.05b	1.0 ± 0.67a	0.8 ± 0.10a	1.3 ± 0.74a
400	80.8 ± 2.24a	2.4 ± 0.89b	288.3 ± 47.27c	447.0 ± 108.84a	32.2 ± 10.56a	0.5 ± 0.24b	0.7 ± 0.09b	0.8 ± 0.29b
Screw speed (rpm) ‡								
150	80.6 ± 2.44a	4.9 ± 2.43a	392.6 ± 134.89b	508.8 ± 173.35a	22.8 ± 6.80a	0.8 ± 0.49a	0.8 ± 0.12a	1.1 ± 0.47a
220	81.8 ± 2.90ab	4.3 ± 1.84a	511.3 ± 181.65a	533.7 ± 210.45a	25.6 ± 9.99a	0.8 ± 0.62a	0.8 ± 0.13a	1.1 ± 0.58a
300	82.9 ± 1.85a	3.9 ± 1.95a	514.8 ± 190.22a	591.5 ± 266.13a	26.2 ± 9.95a	0.9 ± 0.72a	0.7 ± 0.11a	1.2 ± 0.85a

*For each parameter and column, means that do not share a letter are significantly different ($p<0.05$).
†Cultivars data are for the four sweetpotato cultivars at 35 g/100g moisture and 300 rpm screw speed extrusion conditions (n = 4).
‡Data for the *Beerwah Gold* and *Northern Star* sweetpotato cultivars (n = 4).
These apply to all the tables (Tables 3 and 4) where they appear.

Table 3
Functional and structural properties of the extrudates and non-extruded sweetpotato – Main effects*

Parameter	RVA viscosity properties (cP)				Water index (g 100g^{-1} solids)		Crystallinity (%)
	Initial	Peak	Trough	Final	WAI	WSI	
Cultivar (non-extrudate)							
Beerwah Gold	27 ± 5.0a	927 ± 28.3b	893 ± 24.8b	1243 ± 58.0b	59 ± 3.4b	27 ± 0.1a	40 ± 0.4a
Northern Star	18 ± 1.4a	2161 ± 48.1a	1920 ± 23.3a	2771 ± 60.1a	42 ± 1.9b	18 ± 0.1c	39 ± 0.7ab
Snow White	35 ± 2.1a	310 ± 7.1c	181 ± 7.1c	263 ± 1.4c	93 ± 1.5a	24 ± 0.6b	34 ± 1.9b
L49	40 ± 7.8a	409 ± 9.9c	216 ± 5.7c	294 ± 18.4c	95 ± 9.3a	23 ± 0.3b	39 ± 1.7ab
Cultivar (extrudate)							
Beerwah Gold	79 ± 5.7b	213 ± 9.7a	171 ± 5.6a	226 ± 9.8a	270 ± 16.3a	44 ± 1.1ab	33 ± 2.3a
Northern Star	97 ± 3.7a	146 ± 18.9b	62 ± 17.7b	113 ± 41.4b	255 ± 50.1a	51 ± 8.8a	27 ± 2.0b
Snow White	82 ± 5.7ab	129 ± 20.8b	81 ± 6.4b	143 ± 10.8b	209 ± 14.7b	32 ± 0.8b	20 ± 1.9c
L49	77 ± 9.5b	117 ± 53.4b	76 ± 15.3b	114 ± 53.9b	190 ± 17.3b	36 ± 11.4b	23 ± 1.6bc
Moisture content (g kg^{-1})							
300	88 ± 47.9a	256 ± 131.5b	189 ± 131.3ab	273 ± 154.4b	239 ± 75.0b	35 ± 8.7a	31 ± 3.7b
350	103 ± 36.8a	233 ± 90.2b	168 ± 103.9b	251 ± 114.5b	278 ± 38.3a	36 ± 8.0a	31 ± 4.1b
400	104 ± 69.0a	463 ± 203.7a	214 ± 68.1a	337 ± 103.7a	191 ± 50.8c	27 ± 4.7b	35 ± 2.8a
Screw speed (rpm)							
150	89 ± 40.5b	386 ± 232.2a	243 ± 137.1a	363 ± 165.8a	233 ± 73.4a	29 ± 5.1c	33 ± 3.5a
220	118 ± 73.2a	335 ± 170.2b	184 ± 81.8b	291 ± 90.9b	244 ± 70.9a	32 ± 6.5b	33 ± 4.2a
300	89 ± 31.7b	230 ± 66.2c	143 ± 55.1c	208 ± 59.1c	231 ± 55.7a	37 ± 11.0a	31 ± 3.8a

Table 4
Digestibility and glycemic parameters of the extruded and non-extruded sweetpotato – Main effects*

Parameter	Gastric-pancreatic (GP)±					Pancreatic (P)				Gastric-pancreatic-enzyme blank (GPEB)				
	D_o	D_∞	K x 10^{-2}	GI_{AVG}	GL	D_∞	K x 10^{-2}	GI_{AVG}	GL	D_o	D_∞	K x 10^{-2}	GI_{AVG}	GL
Cultivar (non-extrudate)														
Beerwah Gold	11.1 ± 0.56a	100.0 ± 0.00a	0.5 ± 0.25c	81.6 ± 0.90b	46.5 ± 0.51c	90.3 ± 6.01b	0.5 ± 0.43b	71.5 ± 0.87b	40.7 ± 0.50c	0.0 ± 0.00a	70.2 ± 4.22b	0.1 ± 0.01a	68.8 ± 0.01b	39.2 ± 0.00bc
Northern Star	2.3 ± 0.32d	83.0 ± 7.57b	0.5 ± 0.45c	70.6 ± 0.99d	51.5 ± 0.72a	91.3 ± 4.58b	0.4 ± 0.29c	67.1 ± 1.28c	49.0 ± 0.93a	0.0 ± 0.00a	92.0 ± 11.30a	0.1 ± 0.01a	65.3 ± 0.04b	47.7 ± 0.03a
Snow White	7.2 ± 0.42b	100.0 ± 0.00a	0.8 ± 0.30a	91.5 ± 0.98a	42.1 ± 0.45d	99.1 ± 1.83a	0.7 ± 0.25a	83.4 ± 0.81a	38.4 ± 0.37d	0.0 ± 0.00a	72.4 ± 7.67b	0.1 ± 0.12a	78.4 ± 1.46a	36.1 ± 0.67c
L49	6.1 ± 0.41c	80.7 ± 0.94b	0.7 ± 0.16b	77.5 ± 0.39c	48.1 ± 0.24b	74.3 ± 1.33c	0.7 ± 0.13a	72.1 ± 0.33b	44.7 ± 0.21b	0.3 ± 0.40a	74.3 ± 36.34b	0.1 ± 0.44a	70.9 ± 4.16ab	43.9 ± 2.58ab
Cultivar (extrudate)														
Beerwah Gold	17.2 ± 0.75a	81.3 ± 3.97b	3.1 ± 0.41a	107.6 ± 2.05b	61.3 ± 1.17b	63.7 ± 2.82bc	3.6 ± 0.31a	93.0 ± 1.91bc	53.0 ± 1.09c	5.4 ± 0.58a	69.4 ± 4.10b	3.1 ± 0.36a	96.9 ± 2.42b	55.2 ± 1.38c
Northern Star	7.9 ± 1.31b	63.6 ± 1.75c	3.2 ± 0.19a	92.7 ± 1.09d	67.6 ± 0.78a	56.9 ± 2.31c	3.5 ± 0.14a	87.2 ± 1.83c	63.6 ± 1.33a	4.6 ± 1.18a	60.4 ± 1.84c	3.2 ± 0.19a	89.7 ± 1.19c	65.5 ± 0.87a
Snow White	18.4 ± 1.84a	99.1 ± 1.89a	3.4 ± 0.12a	123.6 ± 1.72a	56.9 ± 0.79c	83.0 ± 3.87a	3.7 ± 0.20a	109.5 ± 2.96a	50.4 ± 1.36c	6.3 ± 1.24a	87.6 ± 3.28a	3.3 ± 0.14a	112.8 ± 2.51a	51.9 ± 1.15d
L49	8.8 ± 0.45b	74.6 ± 4.10b	3.3 ± 0.34a	102.1 ± 2.68c	63.3 ± 1.66b	67.1 ± 4.02b	3.6 ± 0.29a	95.8 ± 2.91b	59.4 ± 1.80b	5.6 ± 0.45a	71.5 ± 4.11b	3.3 ± 0.34a	99.2 ± 2.70b	61.5 ± 1.67b
Moisture content (g kg^{-1})														
30	11.8 ± 4.19b	72.2 ± 10.27a	3.0 ± 0.50a	99.7 ± 8.64a	64.1 ± 2.84a	61.3 ± 6.02a	3.5 ± 0.39a	90.7 ± 4.59a	58.6 ± 4.65a	4.1 ± 1.30ab	64.5 ± 6.01a	3.1 ± 0.42a	92.8 ± 4.39a	60.0 ± 4.96a
35	12.7 ± 4.99a	72.7 ± 10.30a	3.1 ± 0.38a	100.1 ± 8.53a	64.4 ± 2.91a	60.8 ± 5.12a	3.4 ± 0.38a	90.1 ± 3.91a	58.3 ± 5.13a	4.9 ± 1.22a	64.6 ± 5.68a	3.1 ± 0.38a	92.9 ± 3.91a	60.1 ± 5.24a
40	11.5 ± 4.28b	72.1 ± 11.16a	3.0 ± 0.36a	99.2 ± 8.93a	63.8 ± 3.16a	61.5 ± 7.35a	3.3 ± 0.59a	90.1 ± 4.79a	58.3 ± 4.96a	3.8 ± 1.02b	64.4 ± 7.18a	3.0 ± 0.55a	91.9 ± 4.39a	59.4 ± 5.18a
Screw speed (rpm)														
150	12.0 ± 4.18a	73.3 ± 10.28a	3.0 ± 0.36a	100.3 ± 8.33a	64.6 ± 3.00a	62.5 ±5.94a	3.3 ± 0.38b	91.1 ± 4.13a	58.9 ± 4.92a	4.2 ± 1.30a	65.3 ± 5.63a	3.0 ± 0.36a	92.9 ± 3.71a	60.1 ± 5.30a
220	11.9 ± 5.01a	71.9 ± 11.14a	3.1 ± 0.43a	99.4 ± 9.11a	63.9 ± 2.80a	60.8 ± 6.62ab	3.4 ± 0.51ab	90.0 ± 4.39a	58.2 ± 4.98ab	4.2 ± 1.34a	64.0 ± 6.92a	3.1 ± 0.54a	92.1 ± 4.36a	59.6 ± 4.95a
300	12.2 ± 4.34a	71.8 ± 10.25a	3.1 ± 0.45a	99.4 ± 8.64a	64.0 ± 3.10a	60.3 ± 6.17b	3.5 ± 0.47a	89.8 ± 4.70a	58.0 ± 4.79b	4.5 ± 1.12a	64.2 ± 6.29a	3.1 ± 0.45a	92.5 ± 4.61a	59.8 ± 5.14a

*The units of D_o and D_∞ are g/100 g dry starch; K, min^{-1}; GI_{avg}, g/100 g; and GL, g/g solids.

Table 5
Pearson's correlation coefficients between the physicochemical, functional, digestibility and extrusion processing properties of the sweetpotato cultivars[†]

	STA	MT	PRS	SME	SpV	LE	TE	WAI	WSI	IV	PV	TV	FV	PT	D_o	D_∞	K	GI_{avg}
STA	1																	
MT	-0.322	1																
PRS	-0.139	-0.147	1															
SME	-0.216	-0.112	0.997**	1														
SpV	-0.408	0.386	0.848	0.872	1													
LE	0.046	-0.029	-0.972*	-0.963*	-0.894	1												
TE	0.224	0.530	0.556	0.536	0.724	-0.737	1											
WAI	-0.675	-0.268	0.712	0.753	0.601	-0.554	-0.086	1										
WSI	-0.677	-0.189	-0.397	-0.342	-0.360	0.572	-0.866	0.361	1									
IV	-0.601	-0.448	0.632	0.666	0.433	-0.442	-0.252	0.978*	0.445	1								
PV	0.829	0.232	-0.405	-0.462	-0.361	0.219	0.381	-0.930	-0.675	-0.935	1							
TV	0.796	0.251	-0.492	-0.544	-0.426	0.310	0.312	-0.961*	-0.602	-0.961*	0.995**	1						
FV	0.795	0.260	-0.478	-0.531	-0.409	0.293	0.329	-0.957*	-0.615	-0.960*	0.996**	1.000***	1					
PT	-0.417	-0.724	0.312	0.334	-0.010	-0.078	-0.616	0.784	0.629	0.895	-0.836	-0.838	-0.844	1				
D_o	-0.646	-0.117	-0.502	-0.447	-0.424	0.656	-0.867	0.250	0.992**	0.331	-0.587	-0.507	-0.520	0.53	1			
D_∞	-0.785	0.569	-0.464	-0.394	-0.045	0.480	-0.349	0.082	0.699	0.024	-0.376	-0.299	-0.304	-0.01	0.75	1		
K	-0.704	0.098	0.801	0.846	0.859	-0.727	0.270	0.915	0.119	0.811	-0.787	-0.829	-0.819	0.47	0.03	0.143	1	
GI_{avg}	-0.995**	0.409	0.154	0.231	0.462	-0.083	-0.138	0.642	0.613	0.549	-0.782	-0.752	-0.750	0.33	0.59	0.794	0.712	1
GL	0.997**	-0.378	-0.171	-0.249	-0.463	0.093	0.152	-0.667	-0.622	-0.578	0.804	0.775	0.773	-0.37	-0.59	-0.78	-0.73	-0.999***

[†]Significance level: *, ** and *** = p ≤0.05, 0.01 and 0.001 respectively. STA = starch content; MT = melt temperature at the die; PRS = pressure in the extruder; SME = specific mechanical energy; SpV = specific volume; LE = longitudinal expansion; TE = transverse expansion; WAI = water absorption index; WSI = water solubility index; IV, PV, TV, and FV = initial, peak, trough, and final viscosities respectively, and PT = pasting temperature in the RVA; and D_o = salivary-gastric digested starch (very rapidly digested starch), D_∞ = maximum digested starch ($t \rightarrow \infty$), K = rate of starch digestion, GI_{avg} = average glycemic index and GL = glycemic load from the GP approach.

Legends to Figures

1. Contour plots showing two-way interaction effects of moisture and screw speed on different properties of the sweetpotato during extrusion processing.

   (A) Specific mechanical energy
   (B) Melt temperature
   (C) Die pressure
   (D) Longitudinal expansion
   (E) Cross-sectional expansion
   (F) Specific volume

Note that the interactions represent the average of the four sweetpotato cultivars.

2. Pasting properties of the non-extruded sweetpotato flours (TOP), and their extrudates at 35 g/100g moisture and 300 rpm screw speed (BOTTOM).

3. Scanning electron micrographs of the non-extruded sweetpotato flours (LEFT), and their extrudates at 35 g/100g moisture and 300 rpm screw speed (RIGHT).

4. X-ray diffractograms of the non-extruded sweetpotato flours (TOP), and their extrudates at 35 g/100g moisture and 300 rpm screw speed (BOTTOM).

5. Starch digestograms of the non-extruded sweetpotato flours, and their extrudates at 35 g/100g moisture and 300 rpm screw speed (extrudate - GP ◆; P ▲; GPEB ●; non-extrudate – GP ■; predicted ——). Error bars are standard deviations of four (n = 4) measurements.

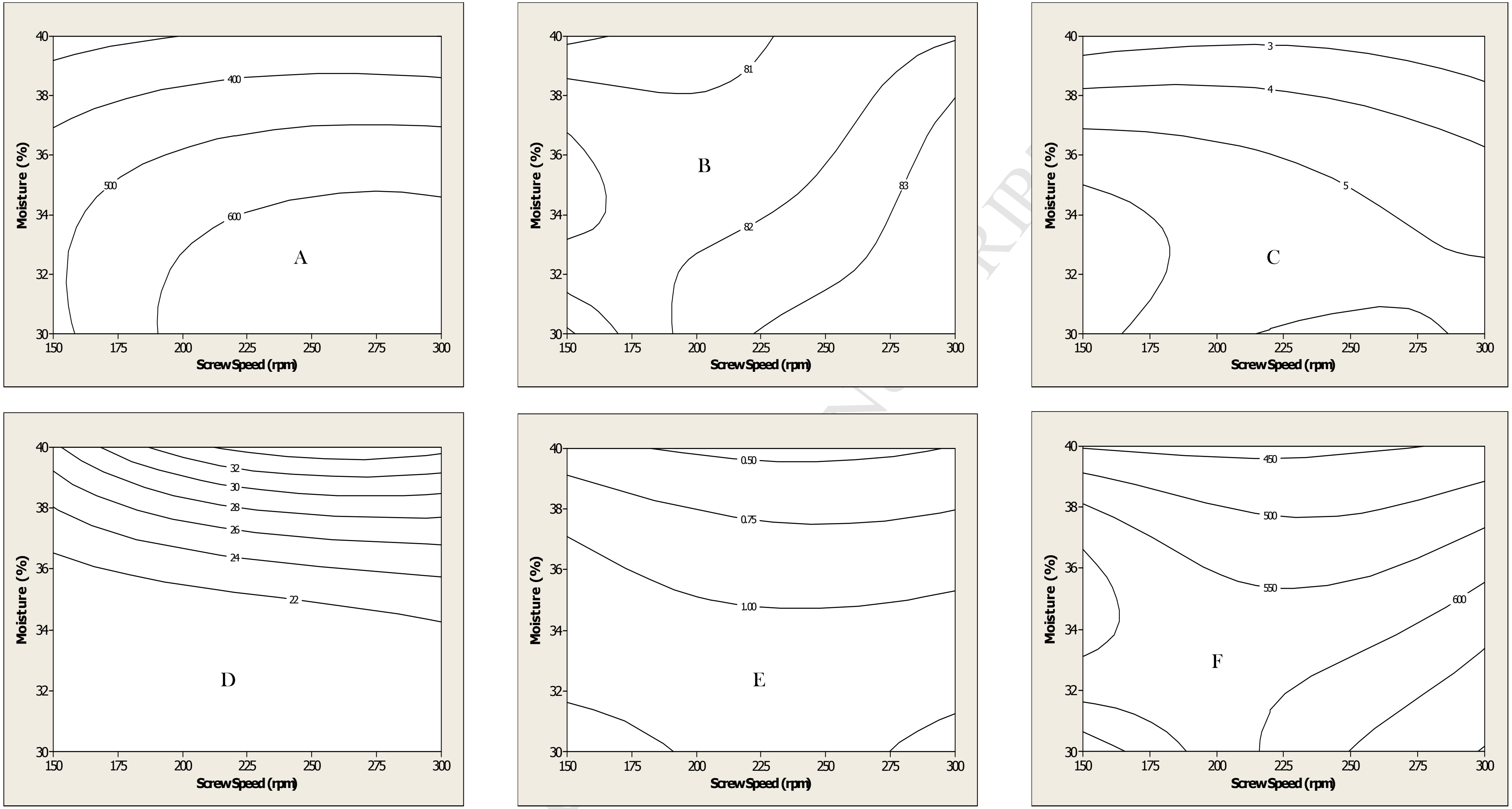
A
B
C
D
E
F
Moisture (%)
Screw Speed (rpm)
150
175
200
225
250
275
300
30
32
34
36
38
40
400
500
600
81
82
83
3
4
5
22
24
26
28
30
32
0.50
0.75
1.00
450
500
550
600

Figure 1

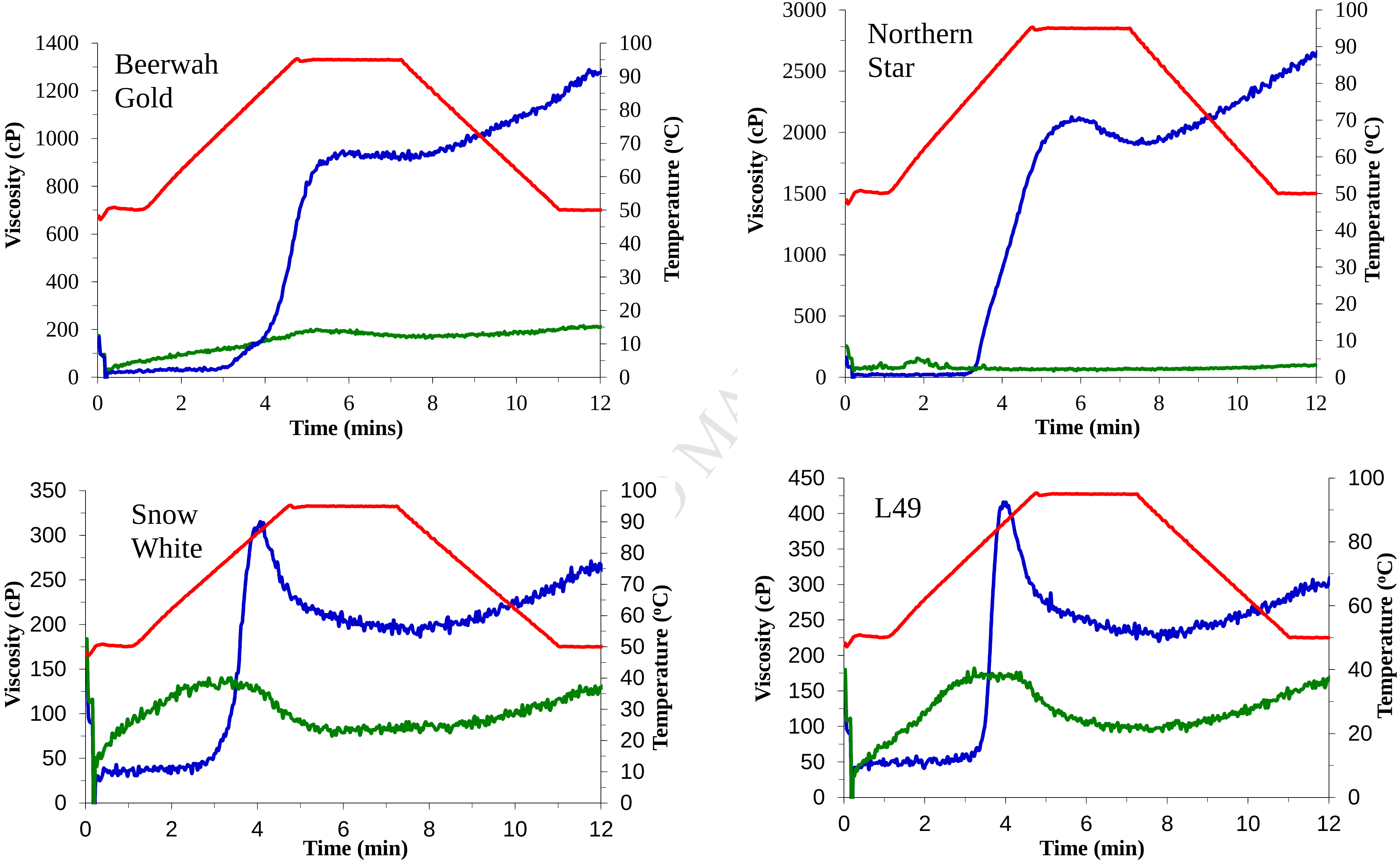
Beerwah Gold
Viscosity (cP)
Temperature (ºC)
Time (mins)
Northern Star
Viscosity (cP)
Temperature (ºC)
Time (min)
Snow White
Viscosity (cP)
Temperature (ºC)
Time (min)
L49
Viscosity (cP)
Temperature (ºC)
Time (min)

Figure 2

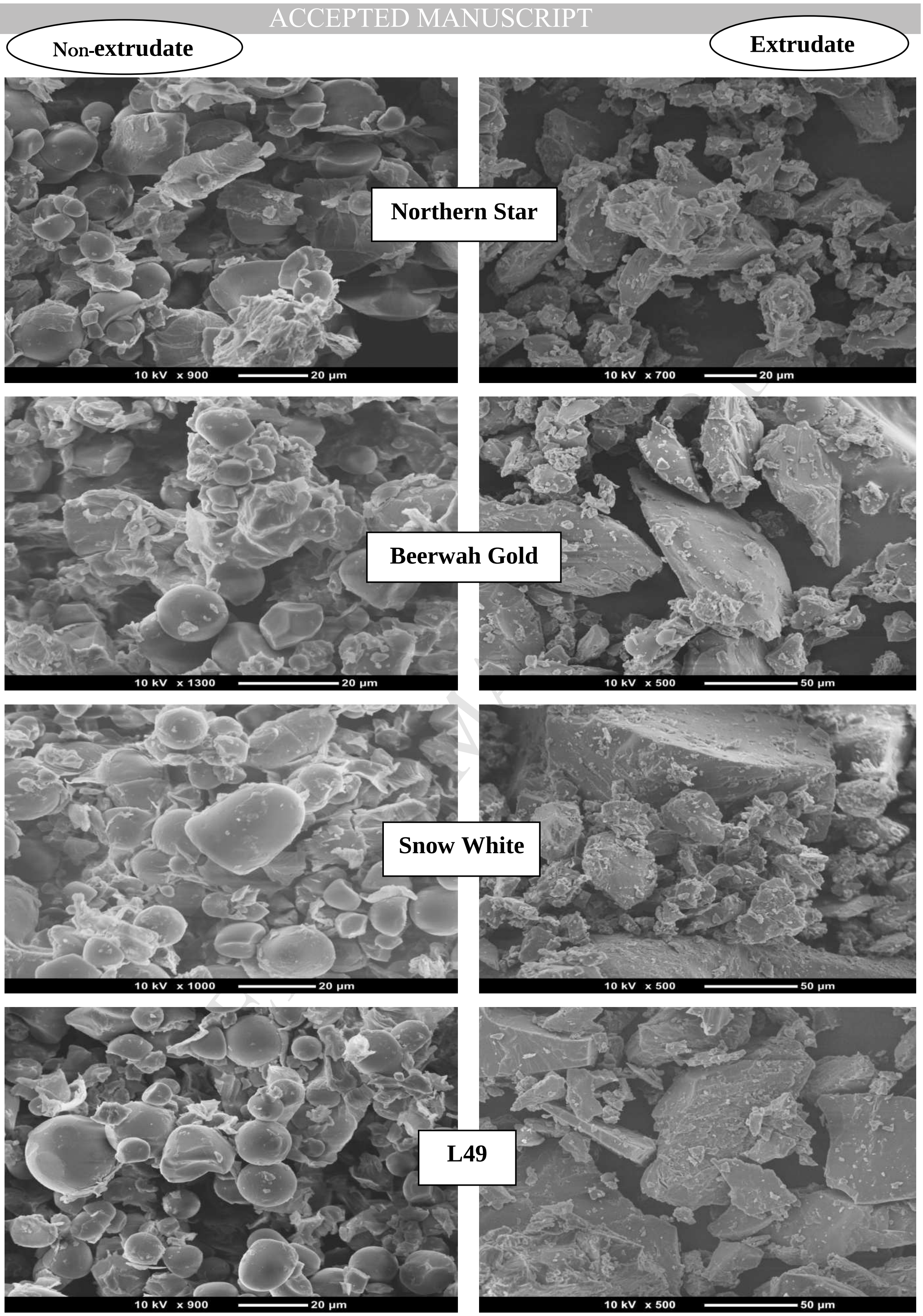
Non-extrudate
Extrudate
Northern Star
Beerwah Gold
Snow White
L49
10 kV x 900 20 µm
10 kV x 700 20 µm
10 kV x 1300 20 µm
10 kV x 500 50 µm
10 kV x 1000 20 µm
10 kV x 500 50 µm
10 kV x 900 20 µm
10 kV x 500 50 µm

Figure 3

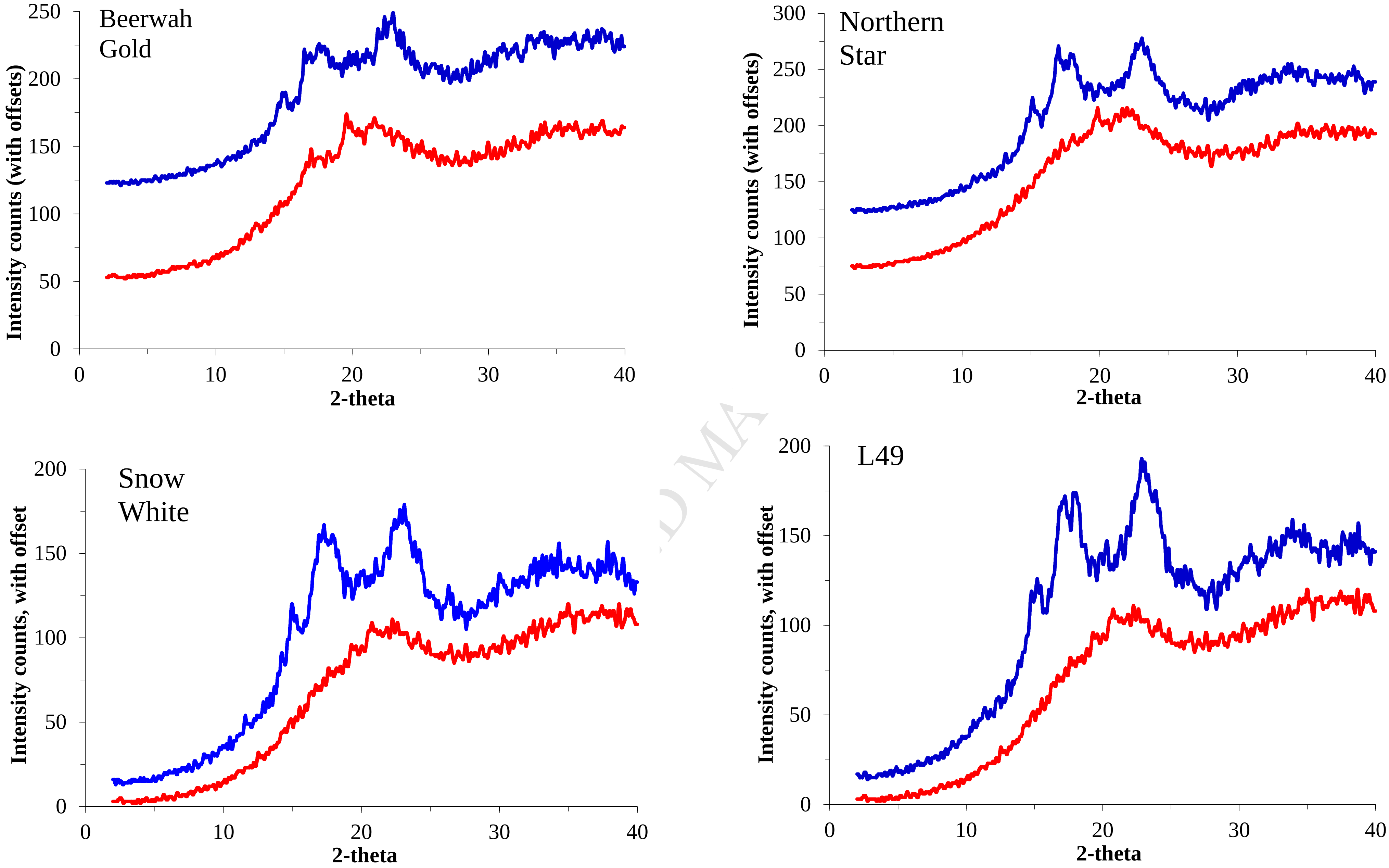
Beerwah Gold
Intensity counts (with offsets)
2-theta
Northern Star
Intensity counts (with offsets)
2-theta
Snow White
Intensity counts, with offset
2-theta
L49
Intensity counts, with offset
2-theta

Figure 4

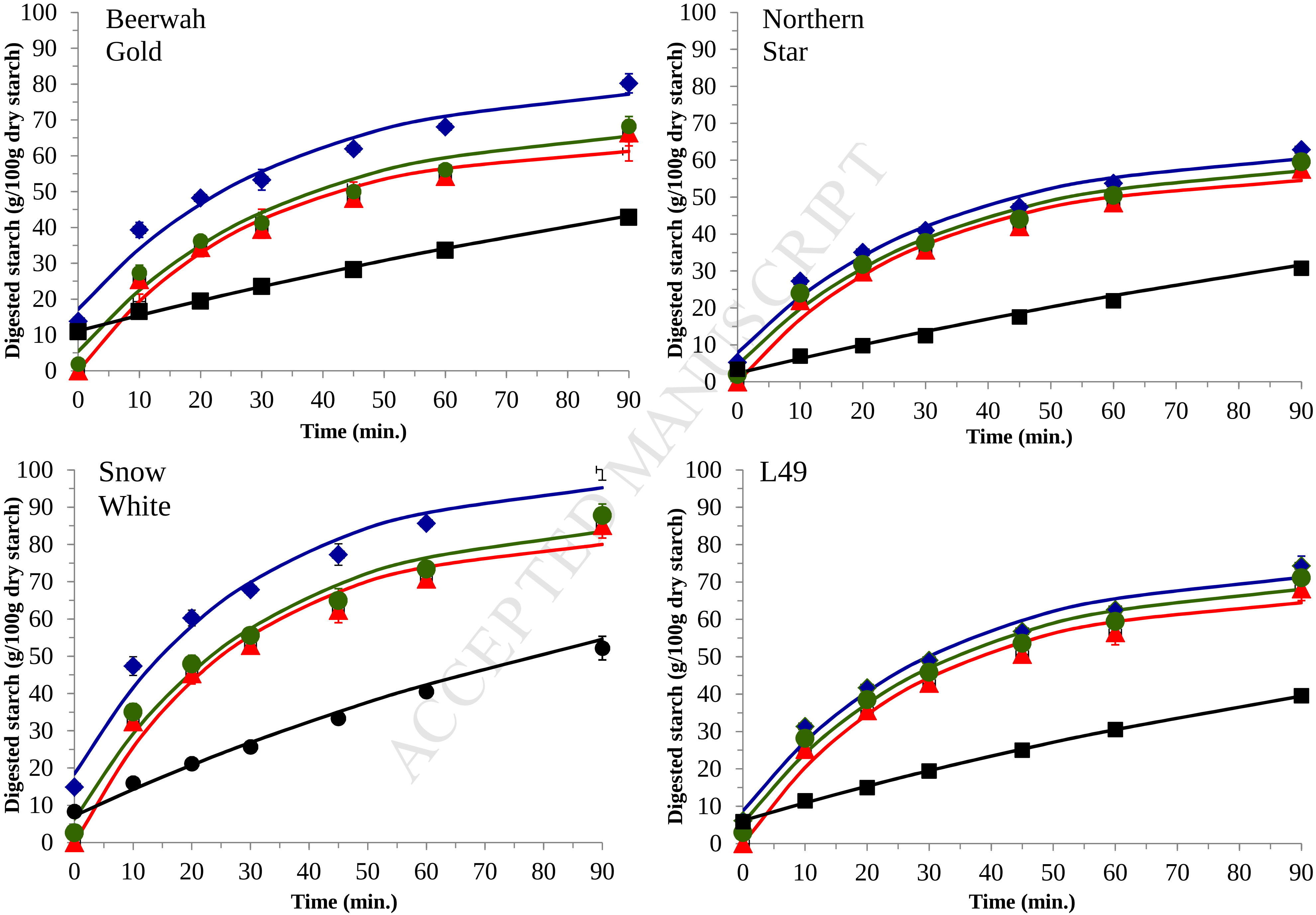
Beerwah Gold
Northern Star
Snow White
L49
Digested starch (g/100g dry starch)
Time (min.)
0
10
20
30
40
50
60
70
80
90
100

Figure 5

Research Highlights

- Four cultivars of sweetpotato were extruded at different moisture and screw speed.
- The extruder responded different to sweetpotato cultivars and process conditions.
- Extrusion moisture exercised more significant effects on extrudate properties.
- Pearson's correlation test showed relationships between extrudate properties.
- Results will guide extrusion and utilisation of the sweetpotato cultivars.