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ORIGINAL ARTICLE

Gluten-free starch noodles from sweet potato with reduced starch digestibility and enhanced protein content

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Abstract Sweet potato starch (SPS) noodles despite being gluten-free, has low nutritional value as it lacks proteins, minerals, vitamins etc. The objective of this study was to develop gluten-free starch noodles from sweet potato with enhanced protein content through fortification with whey protein concentrate (WPC) and to study the effect of protein fortification and blending SPS with banana (BS), cassava (CS) and mung bean (MBS) starches and annealed cassava starch (ACS) in reducing the starch digestibility. The highest protein retention in cooked noodles was obtained for 20 % WPC fortification, while the lowest starch digestibility was observed for 40 % BS fortified noodles followed by 50 % ACS fortified noodles. The highest resistant starch (RS) retention was for BS and ACS fortified noodles, which also had medium glycemic index of 66.3 (BS) and 67.2 (ACS). High sensory scores were obtained for the BS and 20 % WPC fortified noodles. The study showed that protein and/or BS fortification with SPS could enhance the acceptability as well as functional value of SPS noodles.

Keywords Sweet potato · Starch noodles · Starch digestibility · Resistant starch

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Introduction

Starch noodles, presently known by different names such as glass noodles, cellophane noodles, vermicelli, *bihon* noodles etc. have been a favorite food in China since 1400 years (Tan et al. 2009). They are produced from purified starches of various plant sources and have become popular in several Asian countries as well (Mestres et al. 1988; Collado et al. 2001). Starch noodles differ in their quality and texture from Asian or Italian pasta/spaghetti, as the latter are made from wheat flour or semolina (Fu 2008), although many fortified pasta and noodle products have been attempted by subsequent researchers with a view to improving the quality (Gelencsér et al. 2008; Padalino et al. 2011). Although starch noodles have been classified according to the type of raw materials, size of the noodle strands, manufacturing method etc., their quality is decided mainly by the physicochemical properties of the starches (Chen et al. 2003a; Tan et al. 2009). Traditionally, starch noodle made from mung bean starch is considered as the best owing to the transparent appearance, fine threads, high tensile strength and low cooking loss (Lii and Chang 1981; Singh et al. 1989; Tan et al. 2009; Kaur et al. 2015). Starch based noodles have been attempted from legume starches such as broad bean or cow pea, corn starch or tuber starches such as potato, sweet potato and cassava (Kim et al. 1996; Collado and Corke 1997; Singh et al. 2002).

Sweet potato [*Ipomoea batatas* (L.), Lam] is one of the most important food crops of the world and China accounts for more than 85 % of the world production. The glycemic index (GI) is a ranking of carbohydrate foods based on their relative ability to release glucose into blood compared to pure glucose or white bread (Jenkins 2007) and its significance is combating lifestyle diseases such as type 2 diabetes has been extensively documented. Sweet potato is recognized as a low glycemic index (GI) food with a GI < 55 and hence has gained great significance in recent years as a health food (Björck et al. 2000). The possibility of using sweet potato flour for making pasta/spaghetti products has been explored by many researchers (Collado and Corke 1997; Limroongreungrat and Huang 2007; Jyothi et al. 2011, 2012; Renjusha et al. 2012). Sweet potato starch is reported to have free swelling and non-congealing properties and exhibit a type A-Brabender Amylograph pattern (Schoch and Maywald 1968). Sweet potato starch noodles are made on an industrial scale in China where more than 28 % of the processed sweet potato is made into starch noodles and the product is also extensively consumed in Vietnam, Korea and Taiwan (Tan et al. 2009). The physicochemical properties of native and modified sweet potato starches and their noodle making quality have been reported (Tian et al. 1991; Collado and Corke 1997; Chen et al. 2003a, b).

Celiac disease is a chronic autoimmune disorder affecting approximately 15 million consumers round the globe and occurs due to intolerance to dietary gluten, the protein found in wheat, rye, or barley (Green and Jabri 2003; Internet: www.penford.com). Consequently there is an increasing demand for gluten-free food products which has augmented the research efforts as well (Rai et al. 2014; Shevkani and Singh 2014). Ingestion of gluten containing foods by celiac patients causes atrophy of the small intestinal villi and ultimately leads to several symptoms such as cramping, bloating, nausea, diarrhoea, anaemia, fatigue, weight loss and vitamin and mineral deficiencies (Green and Cellier 2007). Although gluten is an essential component imparting the necessary consistency and texture to baked foods and pasta, exclusion of gluten from the diet is essential to lead a healthy life by the celiac patients. There are a number of reports on the development of gluten-free pasta using ingredients such as oat flour, egg albumin, buckwheat flour, maize flour etc. (Schoenlechner et al. 2010; Mastromatteo et al. 2012; Padalino et al. 2013; Susanna and Prabhasankar, 2013). Starch noodles developed from tuber starches such as cassava, sweet potato or *Canna edulis* are essentially gluten-free and hence an ideal choice for celiac patients. Nevertheless from the nutritional point of view, starch noodles are inferior due to the lack of nutrients such as protein, micronutrients, vitamins etc. Currently no information is available on protein-enhanced gluten-free starch noodles from sweet potato and hence the objective of the study was to raise the protein content through fortification with a gluten-mimicking protein such as whey protein concentrate and to compare how the various levels affected the cooking and starch digestibility characteristics of the noodles.

The need to develop low glycemic foods for celiac patients has been highlighted in the studies of Hager et al. (2011) who reported that the high intake of refined sugar by celiac patients could predispose them to type 2 diabetes mellitus. Additives such as resistant starches, hydrocolloids, fiber-rich sources etc. have been attempted to reduce the glycemic index of food products. Banana starch has reportedly high resistant starch (RS) content and its incorporation in many food products has been found to enhance the RS content and reduce starch digestibility (Faisant et al. 1995; Villalobos et al. 2008). Native cassava starch in the gelatinized form has the highest digestibility and annealing was reported as a means of enhancing its RS content (Asha et al. 2014). Hydrocolloids are extensively used in the food industry as gluten substitute and also to provide good dough properties (Gomez et al. 2007). The effect of addition of guar gum and xanthan gum on the noodle making properties of potato, corn and mung bean starches has been reported (Kaur et al. 2015). Starch digestibility characteristics of gum-fortified sweet potato flour noodles have also been studied (Renjusha et al. 2015). Oil addition has also been reported to reduce starch digestibility in pasta (Holm et al. 1983; Jyothi 2012).

Hence, the objective of the study was to compare the effects of additives such as resistant starches, guar gum or sun flower oil in reducing the starch digestibility of SPS noodles, without compromising on the quality.

Materials and methods

Raw materials

Sweet potato starch was used as the major ingredient in the formulation of starch noodles. Other starches used for blending included banana (nendran variety; *Musa paradisiaca*; AAB group) starch, green gram (mung bean; *Vigna radiata* L.) starch and cassava (*Manihot esculenta* Crantz) starch. Annealed cassava starch with an enhanced resistant starch content of 28.6 % was used for fortification of sweet potato starch in two treatments. Whey protein concentrate (WPC) with a crude protein content of 70 % and fat content of 4.32 % was purchased from M/s Mahaan Proteins Ltd., Uttar Pradesh, India. Edible grade guar gum was purchased from M/s Lucid Colloids Ltd., Mumbai, India.

Isolation of starch

Starch was extracted from freshly harvested sweet potato roots (Variety: Sree Arun) harvested at 105 days from the Institute farm as well as from mung bean and unripe banana (purchased from the local market) and cassava roots (Variety: Sree Jaya; 10 months maturity) by the methods described earlier (Renjusha et al. 2012).

Preparation of annealed cassava starch

Annealing of starch was done by suspending dry cassava starch in de-ionized water (1:3 w/v) and incubating at 50 °C in a thermostatic water bath (M/s Julabo Industries, Germany) for 72 h with gentle shaking (Asha et al. 2014). The starch was then filtered, dried at 55 °C for 18 h, ground to a fine powder and stored in airtight bottles till use.

Starch noodle formulations

Starch noodles were made from native sweet potato starch or its blends with other starches. Details of the various formulations used in the study (T1–T11) are given in Table 1. Protein enhanced noodles were made from sweet potato starch using three levels of whey protein concentrate (WPC) such as 10, 20 and 30 %, based on the earlier studies for sweet potato pasta (Jyothi et al. 2011). Starches such as banana starch (BS), cassava starch (CS) and mung bean starch (MBS) were selected based on previous studies on sweet potato flour based noodles (Renjusha et al. 2012). Annealing was reported as a good approach to enhance the resistant starch content of cassava starch (Asha et al. 2014) and hence with the aim of reducing the starch digestibility of starch noodles from sweet potato, annealed cassava starch (ACS) fortification was included and preliminary experiments showed that higher levels such as 40-50 % were essential to reduce the glycemic index. There are several reports showing the beneficial effect of oil in reducing the starch digestibility of pasta and previous studies on sweet potato pasta also showed that 5 % sun flower oil could reduce the starch digestibility (Jyothi, 2012) and hence this level was selected for the present study as well.

Table 1 Formulations for fortified sweet potato starch noodles

Treatments	Ingredients and their levels
Protein fortified starch noodles	
T1	90 % SPS + 10 % WPC
T2	80 % SPS + 20 % WPC
T3	70 % SPS + 30 % WPC
SPS noodles enriched with other starches	
T4	64 % SPS + 20 % banana starch (BS)
T5	44 % SPS + 40 % BS
T6	64 % SPS + 20 % cassava starch (CS)
T7	44 % SPS + 40 % CS
T8	64 % SPS + 20 % mung bean starch (MBS)
T9	44 % SPS + 40 % MBS
SPS noodles enriched with annealed cassava starch	
T10	40 % SPS + 45 % annealed cassava starch (ACS)
T11	35 % SPS + 50 % ACS

Formulae T4–T9 also contain 15 % WPC and 1 % guar gum; formulae T10 and T11 also contain 10 % WPC and 5 % sunflower oil

SPS sweet potato starch, *WPC* whey protein concentrate

Preparation of starch noodles

In the case of all experiments, 5 % sweet potato starch was gelatinized in a water bath using a double boiler (Tan et al. 2009) to avoid lump formation. Gelatinized starch was then added as a dough binder along with WPC, (which possesses gluten mimicking property), to the rest of the starch ingredients. Noodles mixes required 30 % moisture level as optimum and the mix was extruded using the noodle die (No. 9) in an Italian pasta machine (P3 model from M/S La Monferrina, Italy). The noodle strands were extruded directly into boiling water and allowed to stand for 3 min as described by Chen et al. (2002). The strands were then immediately transferred to ice cold water (8-10 °C) for 2 min and drained. The low temperature conditioned noodle strands were manually separated, uniformly arranged in a drying tray and dried in a hot air oven at 50 °C for 18 h. The dry noodles were sealed in poly ethylene bags until use.

Cooking properties

The dry noodles were oven dried at 105 °C for 2 h prior to cooking. Long noodle strands were cut to 5 cm length and 50 g were put to 500 ml boiling water containing 1 g sodium chloride. Optimum cooking time was determined when the center of the noodle strands was cooked using the Approved Method 66-50 (AACC 2000) and the noodles were then drained. The cooked noodles were surface dried and weighed to estimate the swelling index (SI). Swelling index (SI) was computed using the formula of Mestres et al. (1988) as:

$$SI = \frac{(\text{Weight of the cooked noodles} - \text{weight of dry noodles})}{\text{Weight of the dry noodles}} \quad (1)$$

The drained water after cooking was transferred to a pre-weighed petri dish for oven drying at 105 °C and the cooking loss (%) was determined as the weight of dry residue expressed as the percentage of original noodle sample (Debbous and Doetkott 1996).

Nutritional profile of cooked noodles

The major nutrients such as starch and crude protein were analysed in the cooked samples, in order to understand how cooking affected the loss of nutrients from the various treatment combinations. Starch was determined by method of Moorthy and Padmaja (2002). Crude protein was quantified on duplicate samples by Kjeldahl method (AOAC 1995) by multiplying the nitrogen value with 6.25.

Starch digestion kinetics

The in vitro starch digestibility of the cooked sweet potato starch noodles was monitored during 20–120 min, with sampling for glucose determination at every 20 min by the modified procedure reported by Renjusha et al. (2012). Starch fractions such as rapidly digested starch (RDS), slowly digested starch (SDS) and resistant starch (RS) were computed from the starch digestibility kinetics and as given below:

$$\text{RDS }(\%) = [\text{G20} \times 0.9] \text{ expressed as \% of total starch} \quad (2)$$

$$\text{SDS }(\%) = [\text{G120} \times 0.9 \text{ expressed as \% of total starch}] - \text{RDS} \quad (3)$$

G20 and G120 are glucose released respectively at 20 and 120 min.

$$\text{RS }(\%) = 100 - [\text{RDS} + \text{SDS}] \quad (4)$$

The hydrolysis index (HI) was calculated as:

$$\text{HI} = \frac{\text{Total glucose from 100 g cooked sample (on dry basis) at 120 min}}{\text{Total glucose from 100 g white bread (on dry basis) at 120 min}} \times 100 \quad (5)$$

Estimated glycemic index (EGI) was computed using the formula of Goñi et al. (1997).

$$\text{EGI} = 39.71 + 0.549 \times \text{HI} \quad (6)$$

Texture profile analysis

Textural properties of the dry as well as cooked noodle samples (two replicates) were measured using a Food Texture Analyser TAHDi (M/s Stable Microsystems, UK) as described by Renjusha et al. (2012).

Sensory evaluation

The cooked samples of noodles were evaluated by a semi-trained panel of seven judges on a hedonic scale of 1–5 with a scoring pattern of 5—excellent, 4—very good, 3—good, 2—fair and 1—poor. The parameters evaluated included appearance, flavor, mouth feel and overall acceptability. The products were coded and offered simultaneously to each of the panellist in a random order. They were instructed to clean and rinse their palette by drinking potable warm water before and in between while evaluating each of the products and the tests were conducted under uniform lighting conditions.

Statistical analysis

The data reported are the mean of triplicate analysis for most experiments except protein and textural parameters. Data were analyzed using the statistical package SAS 9.3 to perform ANOVA (SAS 2010). The treatments were considered statistically significant at 5 % level ($P < 0.05$). The mean comparisons were made by the Duncan's Multiple Range Test (DMRT).

Results and discussion

Cooking behavior

Cooking loss (CL) is a measure of the loss of solids during cooking of sweet potato starch noodles and swelling index (SI) is indicative of the treatment effect on the absorption of water and subsequent swelling of starch during cooking. It was found that the cooking loss (%) was the least for control starch noodles (0.68 %) from 100 % sweet potato starch which was significantly not different from the MBS (20 %) fortified noodles (Table 2). However, Collado et al. (2001) reported a CL (%) of 3.0 for 100 % SPS (native) noodles, which might have resulted from the varietal characteristics. Protein fortification significantly enhanced the CL (%) of other noodles and proportionate increase with increase in protein level was observed. Unlike in the case of BS, CS or MBS, ACS resulted in significantly higher SI and CL. Except in the case of MBS fortification, SI was not significantly different from the control. Annealed cassava starch (ACS) fortified SPS noodles was found to have very high SI values of 4.43–4.88. The competitive hydration abilities of SPS and ACS in presence of WPC might have resulted in the high SI. Tan et al. (2009) reported the unsuitability of native cassava starch for noodles making due to the soft texture of the product and hence annealed cassava starch was evaluated in the present study. Besides, ACS was reported to have reduced solubility and similar swelling

Table 2 Cooking characteristics and nutritional profile of sweet potato starch noodles

Treatments	Swelling index (SI)	Cooking loss (%)	Starch (%)*	Protein** (%)
Control	3.41[def]	0.68[f]	82.82[a]	0.70
Protein fortified starch noodles				
T1 (10 % WPC)	4.07[bcd]	3.04[b]	78.27[b]	9.98
T2 (20 % WPC)	4.18[bc]	4.12[a]	73.17[e]	19.43
T3 (30 % WPC)	4.55[ab]	4.26[a]	70.69[g]	17.16
SPS noodles enriched with other starches				
T4 (20 % BS)	3.90[bcd]	1.53[e]	73.85[e]	12.26
T5 (40 % BS)	3.55[cde]	2.18[cd]	78.80[b]	12.78
T6 (20 % CS)	3.60[cde]	1.69[de]	72.01[f]	11.38
T7 (40 % CS)	3.73[cde]	1.49[e]	69.92[h]	11.21
T8 (20 % MBS)	2.87[f]	0.74[f]	75.40[d]	12.43
T9 (40 % MBS)	3.11[ef]	1.72[de]	78.84[b]	12.78
SPS noodles enriched with annealed cassava starch				
T10 (45 % ACS)	4.88[ab]	4.42[a]	76.87[c]	8.40
T11 (50 % ACS)	4.43[a]	2.46[bc]	78.02[b]	8.58

Statistical comparison was made between the treatments and the control

Means with the same superscript in each column are not statistically significant; * expressed as % in cooked noodles on dry weight basis; ** mean value from only two observations as % in cooked noodles on dry weight basis

volume as native cassava starch (Asha et al. 2014). A decreased hydration of amorphous regions leading to reduced granular swelling was reported for annealed corn and wheat starches (Tester and Morrison 1990; Zavareze and Dias 2011). Reduction in CL in wheat flour noodles fortified with gelatinized-retrograded starch with enhanced resistant starch (RS) content has been reported (Sharma et al. 2016). Lower swelling rate has been reported for MBS-SPS (20:80) blended noodles, which was approximately 1.84 after 1 h of cooking (Thao and Noomhorm 2011). Collado et al. (2001) observed SI of 2.62 for noodles made from heat moisture treated sweet potato starch, which was similar to the 20 % MBS fortified SPS noodles in the present study.

The ideal raw material for noodle manufacture was reported as mung bean starch due to its specific characteristics such as restricted swelling and C-type Brabender Viscoamylogram. Cooking loss occurs due to splitting of small strands of noodles from the main strand and these go into the water used for cooking. Lowest CL of 2.0 % was reported for MBS noodles while different sweet potato starch noodles exhibited cooking loss varying from 2.2 to 5.0 % (Chen et al. 2003a, b). It was found that SPS noodles made, exclusively from sweet potato starch, with 5 % starch in pregelatinized form (to serve as binder) had only 0.68 % CL, indicating that the heating of starch after extrusion followed by low temperature conditioning accelerated the retrogradation to set the structure of starch noodles as reported for MBS noodles (Mestres et al. 1988; Lii and Chang 1981; Singh et al. 1989). The noodle making properties of potato, corn and mung bean starches were compared by Kaur et al. (2015) who found that the latter had the lowest CL and further reduction in CL was brought about by guar gum fortification, which corroborated with the present findings. Tam et al. (2004) found that maize starch was a good substitute to MBS for noodle manufacture due to the low cooking loss of 1.6–1.8 %. Thao and Noomhorm (2011) attempted the quality improvement of SPS noodles through fortification with 20 % MBS. It was found from this study also that fortification with 20 % MBS fortification along with WPC and guar gum (GG) produced noodles with very low CL (%). Singh et al. (2002) associated the lowering of CL of noodles in presence of gums with the complex formation between amylose and hydrocolloid. Lowering of solubility of starch molecules within the swollen granules by gums has also been reported by Liu et al. (2003).

Nutritional profile

Significant leaching of starch occurred during cooking from the protein fortified noodles. Protein was significantly elevated in the three protein fortified noodles and maximum retention was observed in the 20 % protein fortified cooked noodles (Table 2). Increasing the addition of BS and MBS to 40 % enhanced the retention of starch in the cooked noodles. While native cassava starch fortification enhanced the starch loss from noodles, annealing resulted in higher starch retention in the noodles. Proteins were retained to the same extent in BS and MBS fortified noodles, irrespective of the level of addition. Nevertheless, lowest protein retention was observed in CS fortified noodles, among the WPC fortified samples.

The Chinese Agriculture Trade Standard for Starch Noodles (NY 5188-2002) has set a standard of >75 % starch and it was found that the control, T1 (10 % WPC), T5 (40 % BS), T8 (20 % MBS) and T9 (40 % MBS) as well as the ACS fortified SPS noodles conformed to this standard. Chansri et al. (2005) reported very high values of 90 % starch and low protein content (0.2–0.3 %) in dry noodles made from 100 % canna starch, although the starch in cooked product has not been reported. Control SPS noodles were found to retain 0.7 % protein, while maximum retention of 19.4 % protein was observed for 20 % WPC fortified SPS noodles. In the case of SPS noodles fortified with other starches (T4-T9), protein was retained to the extent of 11–13 % out of 15 % WPC used for fortification, while 8.4–8.5 % protein was retained after cooking from 10 % WPC in the ACS-fortified dry SPS-noodles. This indicated that in all the noodles there was an excellent starch-protein network formation and such network formation was reported earlier in sweet potato pasta as well (Jyothi et al. 2011). High extent of protein fortification and its retention is a significant feature of the present study, since it led to enhancement in the nutritional quality of the noodles.

In vitro starch digestion kinetics and starch fractions

It was found that more than 50 g glucose was released from 100 g starch in the cooked noodles (DM basis) at 20 min digestion itself from most samples (Table 3). The digestion proceeded fast from 60 min onwards and after 2 h, as high as 94 g glucose were released from the control SPS noodles, while 89 g glucose were released from 10 % WPC fortified noodles. Starch digestion rate decreased with increase in the level of addition of WPC. Fortification with starches such as BS and MBS reduced the rate of release of glucose from cooked noodles under in vitro conditions. Nevertheless, CS-fortification could not appreciably reduce the starch digestion kinetics compared to the control. Unlike in the WPC alone fortified noodles, BS-fortification resulted in drastic reduction in glucose release at 20 min digestion itself. Fortification with ACS resulted in noodles having higher IVSD than the BS-fortified starch noodles at all periods from 20 to 120 min.

Starch is divided nutritionally into three fractions such as rapidly digested starch (RDS), slowly digested starch (SDS) and resistant starch. The comparative proportions of these fractions in the raw and cooked food decide the digestibility of the food. Slowly digested starch (SDS) is considered as the most desirable form of starch that is digested slowly in 2 h in the small intestine. Resistant starch (RS) is the fraction that escapes digestion in the small intestine and has properties similar to dietary fibre (Englyst et al. 1992). The rapidly digested starch (RDS) fraction was the highest in 30 % WPC fortified starches noodles, while the lowest was observed in 20 % WPC fortified noodles. Nevertheless, the slowly digested starch (SDS) fraction was the highest in the control (100 % SPS) noodles and lowest in 30 % WPC fortified noodles. Fortification of sweet potato starch with other starches such as

Table 3 In vitro starch digestibility of SPS noodles fortified with protein, other starches and annealed cassava starch

Sample	Glucose released (g glucose per 100 g starch in cooked noodles on dry basis)					
	20 min	40 min	60 min	80 min	100 min	120 min
Control	50.71^{b}	51.90^{bcd}	74.16^{a}	80.68^{a}	85.12^{a}	93.73^{a}
Protein fortified starch noodles						
T1	55.25^{a}	66.71^{a}	70.23^{b}	73.01^{c}	85.61^{a}	88.68^{b}
T2	43.91^{cd}	50.58^{cd}	63.65^{c}	72.83^{c}	80.00^{b}	84.65^{c}
T3	57.21^{a}	69.80^{a}	73.42^{a}	76.27^{b}	79.66^{b}	82.30^{c}
SPS noodles enriched with other starches						
T4	29.28^{f}	38.02^{e}	55.60^{ef}	64.75^{d}	69.73^{cd}	73.58^{f}
T5	30.02^{f}	39.16^{e}	51.75^{g}	57.53^{g}	61.94^{f}	67.00^{h}
T6	36.55^{e}	54.89^{b}	67.59^{b}	76.39^{b}	81.90^{b}	87.76^{b}
T7	37.64^{e}	39.78^{e}	47.71^{h}	53.33^{h}	69.67^{d}	82.49^{c}
T8	41.91^{d}	54.08^{bc}	56.52^{def}	59.81^{fg}	70.78^{cd}	79.18^{d}
T9	50.48^{d}	52.94^{bcd}	58.60^{de}	63.29^{de}	66.23^{e}	75.78^{ef}
SPS noodles enriched with annealed cassava starch						
T10	51.44^{b}	55.21^{b}	59.26^{d}	66.02^{d}	72.58^{c}	76.98^{de}
T11	45.37^{c}	49.73^{d}	53.58^{fg}	60.71^{ef}	67.63^{de}	69.95^{g}

Statistical comparison was made between the treatments and the control

Means with the same superscript in each column are not statistically significant; treatment details as in Table 1 banana, cassava and mung bean reduced the RDS fraction significantly for the former two starches at both 20 and 40 % level and MBS at 20 % level. The digestible starch fraction (RDS + SDS) was the lowest for BS-fortified SPS-noodles (Table 4). As a result, these samples had the highest RS content (Table 4). The annealed cassava starch used in the study had RS content of 28.6 % (Asha et al. 2014). Use of RS enhanced cassava starch (ACS) at 45 and 50 % level for blending with 40 and 35 % SPS respectively had only 69 and 63 % total digestible starch (RDS + SDS), with very high RS retention of 30.7 and 37 %. The low RS content in 100 % SPS noodles suggests that a major part of starch (84 %) was available for alpha-amylase action.

Starch noodles generally have very high digestibility, although it was reported by Panlasigui et al. (1990) that *bihon* noodles from rice could lower the glycemic index of diabetic patients. Mestres et al. (1988) also reported that starch noodles are essentially retrograded starch, which should show a slow digestibility pattern. However, in the present study, the 100 % SPS noodles were found to be highly digestible and as high as 93 g glucose was released from 100 g starch in 2 h. Among the other starches, cassava starch blending resulted in SPS noodles having higher digestibility (84–87 g glucose/100 g starch). Noodles fortified with ACS had high RDS and RS values coupled with low SDS values. This indicated that although the initial starch digestibility was high, progressive glucose release was slow for ACS incorporated noodles. Least digestibility was observed for the 40 % BS fortified SPS noodles, followed by the 50 % ACS-fortified SPS noodles. Chung et al. (2009) reported that enhanced interactions between starch chains (AMAM) and/or (AMAMP) during annealing could enhance the RS content. Holm et al. (1983) found that the swollen amylose that leaches out of cooked pasta has a tendency to react with oil to form complexes and these have been reported to reduce starch digestibility in rats. Such complex formation in ACS fortified noodles which also had 5 % sun flower oil might have resulted in the low starch digestibility under in vitro conditions as well.

Protein fortification obviously helped to bring a firm network of starch and protein in the cooked noodles. Whey protein concentrate (WPC) is reported to have gluten mimicking properties, which also might have helped for a strong network. Zhang and Hamaker (2012) found that cooked banana starch retained its slow digestion property and contained 19 % SDS and 27 % RS. Besides, banana starch behaved like chemically cross linked starch and hence the slowly digestible behavior of BS-fortified SPS noodles could be attributed to this property. Substitution of banana flour in wheat flour noodles was reported to elevate the RS content (Choo and Noor Aziah 2010; Ritthiruangdej et al. 2011). Further, SPS noodles made with blends of other starches (T4–T9) also contained 1 % guar gum as well as an additive. Fortification of wheat flour noodles with gelatinized-retrograded starch or extruded starch was found to enhance the RS content to 2.2–2.7 % (Kaur et al. 2015), which was much less compared to 20-37 %

Table 4 Starch fractions in SPS noodles fortified with protein, other starches and annealed cassava starch

Treatments	Starch fractions(g per 100 g starch in cooked noodles on dry basis)		
	RDS	SDS	RS
Control	45.64^{b}	38.72^{cd}	15.64^{h}
Protein fortified starch noodles			
T1	49.73^{a}	30.09^{f}	20.18^{g}
T2	39.52^{cd}	36.67^{d}	23.82^{f}
T3	51.49^{a}	22.58^{g}	25.93^{f}
SPS noodles enriched with other starches			
T4	26.35^{f}	39.87^{c}	33.77^{c}
T5	27.02^{f}	33.28^{e}	39.70^{a}
T6	32.89^{e}	46.09^{a}	21.02^{g}
T7	33.87^{e}	40.37^{b}	25.76^{f}
T8	37.72^{d}	33.55^{e}	28.74^{e}
T9	45.43^{b}	22.70^{g}	31.80^{cd}
SPS noodles enriched with annealed cassava starch			
T10	46.29^{b}	22.99^{g}	30.72^{de}
T11	41.19^{c}	22.13^{g}	37.05^{b}

Statistical comparison was made between the treatments and the control; means with the same superscript in each column are not statistically significant; treatment details as in Table 1

RDS rapidly digested starch, *SDS* slowly digested starch, *RS* resistant starch obtained in the protein-fortified SPS noodles in this study. Guar gum also might have contributed to the low starch digestibility of BS fortified SPS noodles. Annealed cassava starch also behaves like cross linked starch and this was responsible for the high retention of RS in the ACS-fortified noodles. Gums have been reported to reduce the starch digestibility of pasta and noodles and the differential behaviour of various gums such as xanthan gum (glucomannan) and guar/locust bean gums (galactomannans) depends on their structural features and interaction with starches (Briani et al. 2006; Mandala et al. 2007).

Estimated glycemic index (EGI)

Highest glycemic index of 78.89 was observed for the SPS-noodles, while fortification with WPC at 10, 20 and 30 % level, proportionately reduced the EGI to 74.55, 70.83 and 68.73 respectively (Fig. 1). Fortification of SPS with other starches along with 15 % WPC and 1 % guar gum also reduced the EGI significantly, with the maximum reduction in BS-fortification (Fig. 1). Fortification with ACS at 45 and 50 % level produced noodles with EGI of 69.2 and 67.2 respectively and the former was similar to 40 % CS and 20 % MBS fortification, while the latter was similar to 20 % BS fortification (Fig. 1).The study showed that fortification with BS or ACS could significantly bring down the EGI to medium level. Earlier studies also indicated that low glycemic spaghetti could be produced from sweet potato flour through fortification with banana starch or legume starches (Renjusha et al. 2012).

Glycemic index of food is closely related to the occurrence/prevention of type 2 diabetes. Although sweet potato is already documented as a low glycemic (GI $<$ 55) food, its consumption is limited (Björck et al. 2000). Pasta or spaghetti/noodles is getting wide acceptance in many countries as a health food which could slow down the glycemic response and hence of use in the management of Type 2 diabetes and obesity (Gelencsér et al. 2008; Nugent 2005). EGI was positively correlated to RDS and negatively correlated to the RS values in the spaghetti (Madhusudhan and Tharanathan 1995; Sandhu and Lim 2008).

Texture profile analysis

While cooking significantly reduced the firmness (N) of all the noodles, protein fortification enhanced the firmness of both raw and cooked starch noodles and the highest firmness was observed for the dry samples of 10 % WPC noodles, while the highest value was obtained for cooked noodles in the case of 20 % fortification (Table 5). One striking difference was that fortified noodles from other starches had less firmness in dry state than the WPC alone fortified noodles. Nevertheless, these cooked noodles invariably had higher firmness than WPC alone fortification. Fortification with ACS also resulted in very high firmness of the cooked noodles, which might be due to the preponderance of crystalline regions in ACS (Tester and Morrison 1990). Chen et al. (2003b) also reported reduced firmness of SPS noodles, both in dry and cooked form, compared to the MBS noodles. The firmness of the dry and cooked noodles from 100 % SPS was 122.9 N and 0.45 N respectively, compared to the respective values of 19.69 N and 1.58 N for the Chinese sweet potato variety, Su Shu 8 (Chen et al. 2003b). This indicated that the cooked noodles from the present study were much softer than the Chinese noodles. The polymeric structure of gums enables their use as gluten substitutes, leading to a nice texture for the fortified foods (Gomez et al. 2007).

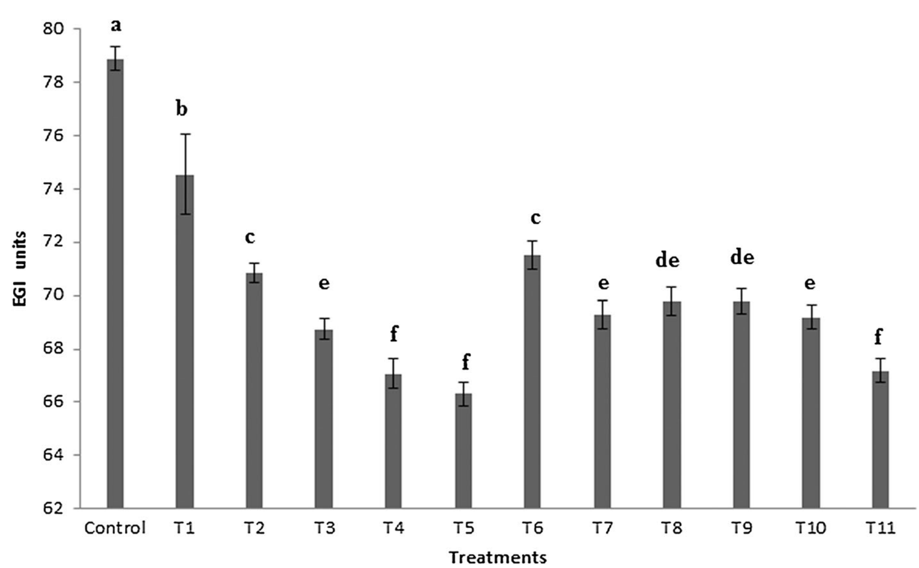

Fig. 1 Estimated glycemic index of protein fortified sweet potato starch noodles (Mean ± SD from three replicates; statistical comparison was made between the treatments and the control; *line with different superscripts* are statistically significant at $P < 0.05$)

Table 5 Textural and sensory evaluation of SPS noodles fortified with protein, other starches and annealed cassava starch

Treatments	Firmness (N)*		Sensorial attributes**			
	Raw	Cooked	Appearance	Flavour	Mouth feel	Overall acceptability
Control	122.90	0.45	2.87^{d}	1.75^{c}	0.92^{e}	2.42^{c}
Protein fortified starch noodles						
T1	206.40	0.93	4.30^{ab}	3.40^{b}	2.80^{c}	4.00^{a}
T2	192.13	1.97	4.40^{a}	3.05^{b}	4.12^{a}	4.00^{a}
T3	190.41	1.12	4.13^{ab}	2.20^{c}	4.07^{a}	3.12^{b}
SPS noodles enriched with other starches						
T4	135.24	2.96	2.87^{d}	2.98^{b}	3.88^{a}	3.90^{a}
T5	124.02	4.57	3.17^{cd}	1.95^{c}	3.97^{a}	4.03^{a}
T6	69.63	2.33	3.40^{c}	2.23^{c}	1.98^{d}	3.07^{b}
T7	185.71	2.19	3.23^{c}	2.17^{c}	3.03^{bc}	2.08^{c}
T8	99.20	1.94	3.30^{c}	2.08^{c}	3.23^{b}	3.20^{b}
T9	122.70	2.34	3.37^{c}	2.20^{b}	3.00^{bc}	3.27^{b}
SPS noodles enriched with annealed cassava starch						
T10	162.34	3.94	3.40^{c}	4.12^{a}	3.33^{b}	3.03^{b}
T11	134.75	2.43	4.03^{b}	3.03^{b}	3.07^{bc}	3.06^{b}

Means with the same superscript in each column are not statistically significant; treatment details as in Table 1

* Mean from two observations; ** statistical comparison was made between the treatments and the control

Sensory evaluation

Highest scores of above four were obtained for appearance for all the three WPC fortified noodles, while flavour scores were the highest for the ACS fortified noodles (Table 5). Mouth feel and overall acceptability were the highest for the 20 % WPC and BS-fortified noodles, while both the scores were very low for the 100 % SPS noodles. Native cassava starch fortification also resulted in noodles having low scores for mouth feel and overall acceptability. Thao and Noomhorm (2011) also reported the lowest scores for appearance for 100 % SPS noodles (2.92 on a hedonic scale of 1–9) compared to 5.0 for MBS noodles. Overall acceptability score was the highest for 20 % WPC fortified noodles, indicating that protein fortification enhanced the acceptance scores of the noodles, which was not significantly different from either 10 % WPC fortified noodles or the BS (20 %) fortified noodles. ACS fortification further reduced the sensory scores, with 'very good' rating for appearance in the case of 50 % fortification. Collado et al. (2001) reported that the acceptability scores of plain cooked noodles from 100 % heat moisture treated SPS or its blend with MBS in 50:50 ratio were not significantly different from commercial *bihon* noodles. Thao and Noomhorm (2011) found that blending of 80 % MBS with 20 % SPS did not significantly affect the sensory scores such as appearance, texture and overall acceptability compared to pure MBS noodles. Fortification of SPS with 40 % MBS gave an overall acceptability score of 3.0 compared to 2.0 for 100 % SPS noodles. It should also be noted that a comparison of the sensory evaluation data from various studies may not be truly relevant for a global comparison, as the sensory scores greatly depend on regional food preferences, consumption pattern etc. Non-availability of 100 % starch-based noodles in the local market made it impossible to evaluate the protein-enhanced noodles *vis-à-vis* market samples.

Conclusion

Sweet potato starch noodles with enhanced protein content (8.4–19.43 %) could be obtained through fortification with whey protein concentrate, while the pure starch based noodles had only 0.70 % protein. Starch digestibility of cooked noodles could be significantly reduced by fortification with banana or mung bean starches or annealed cassava starch (ACS) with a consequent retention of resistant starch in them. Besides being gluten-free, the SPS-noodles from blends of sweet potato and banana starch or ACS had also medium glycemic index of 66.3 and 67.2 respectively. High acceptability scores of the protein-fortified noodles indicated that the nutritive value enhancement could also help overcome the bland taste of 100 % starch-based noodles. High RS content coupled with medium GI are positive attributes that could promote the product as ideal food choice not only for celiac patients but also for those suffering from obesity-linked complications.

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