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Cooking quality, nutritional and antioxidant properties of gluten-free maize – Orange-fleshed sweet potato pasta produced by extrusion

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ABSTRACT

Maize and orange-fleshed sweet potato (OFSP) composite (100:0, 50:50, 70:30, 80:20) flours were extruded into pasta using a twin-screw extruder. The cooking quality, textural and nutritional properties of the pasta were assessed. An increase in the proportion of OFSP flour added increased the cooking loss but decreased cooking time and water absorption capacity of pasta. The dietary fibre in the OFSP flour caused a loosening of the compact structure of the pasta, disrupting the compact protein-starch matrix of maize, resulting in higher cooking loss and sticky pasta. Extruded pasta had low cooking time due to pre-gelatinized starch, which promotes greater water absorption and heat dissemination during cooking. Extruded pasta samples had lower beta-carotene, probably due to *cis*-trans isomerization, fragmentation, and oxidative decomposition, but the pasta showed higher antioxidant properties, likely due to Maillard reaction and caramelization products with reducing properties. These results indicate that OFSP can be composited with maize flour and extruded to produce good quality and nutritious gluten-free pasta.

1. Introduction

Micronutrient deficiency continues to be a significant nutritional concern in poor communities, especially in sub-Saharan Africa, with children and women being the most vulnerable (Bain et al., 2013). Vitamin A deficiency impairs numerous functions and, as a result, can lead to many health consequences such as impaired iron mobilization, growth retardation, blindness, reduced immune response, increased susceptibility to infectious disease, and increased childhood mortality in most developing countries (Liu et al., 2016: Xu et al., 2021) Bio-fortification of staple crops is an intervention that can be considered as a sustainable and innovative way to address micronutrient malnutrition, and it involves increasing the concentrations of nutrients in crops using agronomic approaches and plant breeding (Bouis et al., 2011). Examples of β-carotene bio-fortified food crops are yellow maize, yellow cassava, golden rice, and orange-fleshed sweet potato (OFSP).

According to Laurie et al. (2018), OFSP can be considered the most successful example of a bio-fortified staple crop and presents a possible option to address vitamin A deficiency. A study by Van Jaarsveld et al. (2006) reported that the vitamin A status of school-aged children increased from 78% to 87% when the white-fleshed potato was substituted with OFSP in their diet. Its high levels of β-carotene make OFSP an affordable food source with antioxidant properties that can potentially offer protection against oxidative stress-induced non-communicable diseases (Vimala et al., 2011). It is also gluten-free.

Consumers are currently shifting towards consuming gluten-free based foods due to personal choice to exclude gluten from their diet and for patients with gluten intolerance and celiac disease. This has led to the development of cereal-based gluten-free pasta made from rice and maize. However, the gluten-free diet may be deficient in nutrients such as fibre, B vitamins, iron, and trace minerals (Marti & Pagani, 2013; Theethira & Dennis, 2015). Pasta is mainly preferred due to its convenience, palatability, relatively long shelf stability, and nutritional properties. Considering this information, the diversification of diet through the inclusion of OFSP could help alleviate vitamin A deficiency.

Besides the nutritional aspect of gluten-free pasta production, the cooking and textural qualities also remain a major technological challenge. The difficulty in producing gluten-free products is associated with the lack of gluten in the food system (Marti & Pagani, 2013). Extrusion processing can be used to design a compact structure with gelatinized starch embedded in the protein matrix and aligned in the direction of flow through the extruder barrel. This may help create the matrix that can potentially show similar properties like wheat-based food (Wang et al., 1999).

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Extrusion processing is a technique that uses high-temperature short time regimes to produce foods, including breakfast cereals, snack products, and pasta products. Flours can be cold extruded (Arribas et al., 2020; Chanu & Jena, 2015; Da Silva et al., 2016) or hot extruded (Bouasla et al., 2016; Marti et al., 2013) to produce pasta. Cold extrusion involves using temperatures between 40 and 60 °C, and hot extrusion involves using temperatures of the order of about 100 °C in mixing and shaping the pasta product (Bordoloi & Ganguly, 2014).

Extrusion cooking is reported to improve the digestibility of proteins through the denaturation of proteins and the reduction of antinutrients (Nikmaram et al., 2017). Starch digestibility is also increased through the loss of structural integrity of the starch granules because of the high shear and temperatures used, increasing their susceptibility towards enzymatic attack (Singh et al., 2010) compared to conventional cooking. The key parameters in extrusion processing are temperature, pressure, shear rate, and residence time (Stojceska, 2013). Raw food materials during extrusion processing are subjected to thermal energy and shear forces causing structural, chemical, and nutritional transformations such as gelatinization and degradation of starch, denaturation of protein, oxidation of lipid, degradation of vitamins, antinutrients, and phytochemicals (Ilo & Berghofer, 2003; Singh, Sekhon, & Singh, 2007) formation of flavours, an increase of mineral bioavailability and solubility of dietary fibre which affects the physical, functional and nutritional properties of the end product (Riaz et al., 2009).

The most existing research reports on conventional methods used in the production of pasta. There has been limited work reported on using OFSP and extrusion processing technology to produce gluten-free pasta. The study's objective is to determine the effect of extrusion cooking on the functional and nutritional properties of gluten-free pasta made from maize: orange-fleshed sweet potato flour composites.

2. Materials and methodology

2.1. Materials and composites

White maize flour and OFSP flour were used in the study. A Superfine white maize meal was purchased from RCL foods (Pretoria, South Africa), and OFSP flour was purchased from Exilite 499 CC in Tzaneen (Limpopo Province, South Africa). Both flours were below 250-μm sieve size. Commercial pasta made from maize and rice was purchased from the supermarket. All other chemicals were of analytical grade.

The maize and OFSP flours were composited in the ratios 100:0, 80:20, 70:30, 50:50 (w/w) in an industrial bowl mixer (Talsa, Mix 90 ST, Zatamo, Spain) for 10 min. The bowl mixer has a dual blade paddle system that rotates clockwise and anticlockwise to have a homogenous mixture. The flour composites were then stored in airtight plastic buckets at – 4 °C until further use.

2.2. Methods

2.2.1. Extrusion processing

Extrusion processing was carried out with a TX 32 co-rotating twin-screw extruder (CFAM Technologies (Pty) Ltd, Potchefstroom, South Africa). The pre-prepared formulations (100% maize flour, 80:20% maize: OFSP, 70:30% maize: OFSP, 50:50% maize: OFSP) were subjected to extrusion processing. The barrel temperatures used were 60, 70, 80, 80, and 80 °C for zones 1, 2, 3, 4, and 5. The screw speed was set at 80 rpm with the raw material feed rate of 5 kg/h. Water flow into the extruder was at a dose rate of 2.5 L/h.

The extrudates (100% maize, 80:20% maize: OFSP, 70:30% maize: OFSP, 50:50% maize: OFSP gluten-free pasta samples) were shaped in spaghetti form with a diameter of 1.4,1.6, 1.5, 1.1 mm respectively and dried at an ambient temperature of 20 °C overnight. The pasta samples were stored in an airtight bucket at room temperature for further analysis. An analysis using milled samples, raw pasta samples were milled with a laboratory hammer mill (Perten Lab mill 3100, PerkinElmer, Waltham) and analyzed as described in section 2.3 below. Cooked samples were freeze-dried, milled, and analyzed.

2.3. Analyses

2.3.1. Proximate analysis of composite flours and uncooked gluten-free pasta

Composite flours and uncooked gluten-free pasta samples were analyzed for moisture (dry matter), ash, and crude fat according to the Association of Official Analytical Chemists (AOAC, 2019) methods 925.10, 923.03, and 920.39, respectively. Protein (N × 6.25) was determined according to the Dumas combustion method.

Solubles and insoluble dietary fibre was determined according to the Official Methods of Analysis 991.42 using the total dietary fibre Megazyme kit (K-TDFR). The flour sample (1 g) was dissolved in 40 mL of mes-tris buffer (0.05 M, pH 8.2) solution, and 50 μL of thermostable α-amylase (3000 U/mL of ceralpha reagent at pH 6.5 and 40 °C) was added to hydrolyze starch to dextrin. Protease (100 μL) with an activity of 350 tyrosine U/ml (E-BSPRT) was added to solubilize protein. Amyloglucosidase (AMG) (200 μL), with an activity of 3300 U/mL (E-BLAAM), was used to hydrolyze dextrin to glucose. The enzyme mixture and sample were filtered, and the residue was washed with acetone and ethanol to obtain the insoluble dietary fibre (IDF) portion. Four volumes of ethanol heated at 60 °C were added to the filtrate and left to stand for 60 min to form the soluble dietary fibre (SDF) precipitate, after which it was filtered. The soluble dietary fibre residues were washed with 78% and 95% (v/v) ethanol and acetone, respectively. The IDF and SDF residues were dried overnight at 103 °C. One part of the soluble dietary fibre and insoluble dietary fibre residues were used to determine protein. The other part was used to determine ash content for the final calculations of soluble dietary fibre and insoluble dietary fibre values. For uncooked pasta, samples were ground through a 0.5 mm screen using a laboratory mill. All analyses were carried out in triplicate on each pasta sample.

2.3.2. Optimal cooking time

The optimal cooking time was determined according to Giménez et al. (2013). Dried pasta (25 g) was boiled in 250 mL distilled water. At 30-s intervals, a small portion (3 to 4 strands) of the pasta was removed from the boiling water and squeezed between two glass slides. The pasta was considered cooked when the white centre core disappeared.

2.3.3. Cooking loss and water absorption capacity

Water absorption capacity and cooking loss were determined according to Giménez et al. (2013) with slight modifications. For cooking loss determination, a 25 g dried pasta sample was cooked in 250 mL boiling water. The cooking water was collected in a tared and pre-dried beaker; the content was dried to constant weight in an air oven at 100 °C. The residue was weighed, and the loss during cooking was calculated as a percentage of the starting material.

For water absorption capacity, 25 g dried pasta samples were weighed and boiled in 250 mL water. During the cooking time previously determined, pasta was then removed and weighed; the weight difference before and after cooking was used to calculate the water absorption using the following equation:

$$\text{WA} \ (\%) \ = \frac{cpw - DPW}{DPW} \times 100$$

Where CPW = cooked (wet) pasta weight (g) and DPW = dried pasta weight (g)

2.3.4. Texture analysis

Texture Profile Analysis (TPA) was done according to Curiel et al. (2014) with slight modification. The firmness and stickiness of the cooked pasta samples were determined using an EZ Test (Model: EZ-L, Shimadzu, Tokyo, Japan) texture analyzer equipped with a mini-Kramer shear cell with a square probe (3 mm × 3 mm). Pasta samples were cooked till the optimal cooking time. The texture analyzer was calibrated for a load cell at 200 N. Cooked pasta (20 g) was compressed once at a rate of 30 mm/min at a ratio of 50% with the compression probe. Firmness was measured at the maximum force (N) during compression, and stickiness (N) was measured as the minimum force of the curve obtained. The test was conducted at least in triplicate.

2.3.5. In vitro starch digestibility

In vitro starch digestibility of the cooked pasta samples were done using the Englyst method described by Englyst et al., 1992, Goñi et al., 1997 with slight modification as described by Mapengo and Emmambux (2020).

2.3.6. Thermal properties

The thermal properties of raw and cooked milled pasta samples were determined according to the method described by Wokadala et al. (2012) using a DSC system (HP DSC827^e, Mettler Toledo, Greifensee, Switzerland). Indium (T_p = 156.6, ΔH = 28.45 Jg^{-1}) was used as a standard. The samples were tested under a nitrogen flow of (60 mL/min) and a pressure of 40 bars. Sample flour (10 mg) was mixed with 30 μL of distilled water in a stainless-steel pan and hermetically sealed and equilibrated for a day at 25 °C. Each sample was heated from 25 °C to 120 °C at a heating rate of 10 °C/min. An empty hermetically sealed aluminium tin was used as a reference. The results were analyzed using STARe software (Mettler Toledo) to get onset temperature (T_o), endset temperature (T_c) and peak temperature (T_p).

2.3.7. Determination of β-carotene content

β-Carotene was extracted from about 2 g of raw flours and cooked milled extruded pasta samples with 10 mL tetrahydrofuran (THF) in a small beaker by magnetic stirring for 30 min. The mixture was centrifuged using (NUVE NF 400 centrifuge, Henderson Biomedical Lower Sydenham, United Kingdom) at 1149×*g* for 10 min, and the supernatant was set aside. The extraction was repeated three times with a fresh 10 mL THF aliquot and separated the supernatant after centrifugation until the pasta flour residue was colourless. The THF was evaporated to dryness using a rotary evaporator (IKA rotary evaporator, GmbH & Co. KG, Deutschland, Germany) at 27 °C. The crude carotene extract was dissolved in 10 ml toluene. In preparation for chromatography, the carotene extract in toluene was filtered using 0.45 μm PTFE membrane filters directly into amber vials.

Chromatographic analysis of β-carotene content was done using a Prominence Ultra-Fast Liquid Chromatography (UFLC) (Shimadzu, Tokyo, Japan) equipped with a SIL-20A Prominence auto-sampler, a DGU-20A3 Prominence degasser, a CTO-10AS VP Shimadzu column oven, and an SPD-M20A Prominence diode array detector. UV/Vis spectra of carotenoids were recorded between 200 and 600 nm with detection of β-carotene at 450 nm. The separation of carotenoids was performed at 30 °C on a C18 Waters Nova-Pak carotenoid column (300 × 3.9 mm, 4 μm particle size) by isocratic elution with acetonitrile (58%), HPLC grade methanol (35%), and THF (7%) as mobile phase, at a flow rate of 1.0 mL/min for 30 min. The quantification of β-carotene was done using a calibration curve of β-carotene standard, and the vitamin A content was approximated as retinol activity equivalents (RAE) using a conversion factor of 12 μg β-carotene to 1 μg retinol (Van Jaarsveld et al., 2006).

2.3.8. Determination of ABTS•+ radical scavenging capacity

A modification of the 2, 2′-azinobis-3-ethylbenzothiazoline-6-sulphonic acid (ABTS) radical scavenging assay described by Awika et al. (2003) was used. The mother solution was prepared by mixing equal volumes of 8 mM ABTS and 3 mM potassium persulphate to 2 ml in an Eppendorf tube. The mother solution was incubated for a maximum of 12 h in the dark. A working solution was prepared in an aluminium foil-wrapped bottle. Serial dilutions of Trolox standard were prepared by diluting Trolox with PBS. The sample extract, Trolox standard and working solution were mixed in a 96-well microplate. The absorbance was read at 570 nm (using Multiskan™ FC Microplate Photometer, Thermo Scientific, Rastastie, Finland) after incubation for 30 min, and the radical scavenging capacity was expressed as μmol Trolox equivalents per gram of samples on a dry basis.

2.3.9. Bright field light microscopy

Milled extruded pasta and cooked pasta samples suspended in 30% glycerol were visualized with a VS3 Series Biological Trinocular Light Microscope from Micromet Scientific with a Biowizard Image Analysis Software (Delhi, India) equipped with a Polarising filter lens. To stain starch, an iodine solution was added. Images were taken with 20 × magnification and evaluated with the ImageJ®software package.

2.3.10. Scanning electron microscopy (SEM)

Scanning electron microscopy of raw and cooked pasta (wet) was done by first freezing the pasta using liquid nitrogen, and a freeze-fracture of a small fraction was taken. The small fractions were mounted on aluminium stubs with the aid of double-sided carbon tape, followed by coating with a carbon of about 20 nm in thickness. The coated pasta was viewed and photographed using the Zeiss Crossbeam 540 FE 6 Scanning Electron Microscope (Carl Zeiss Microscopy, 6mbH, Germany) at an accelerating voltage of 5.0 kV.

2.4. Statistical analysis

Multivariate analysis was used to analyze the interaction between extrusion cooking and compositing maize flour with orange-fleshed sweet potato flour of the physical, functional, and nutritional characteristics. Two-way analysis of variance (ANOVA) was used to analyze the data using SPSS version 22. Means were compared at $p \leq 0.05$ using Fisher's Least Significant Difference (LSD) test. Experiments were conducted at least in triplicate.

3. Results and discussion

3.1. Proximate composition

The proximate composition of raw flour samples and extruded pasta samples is shown in Table 1. The moisture content of pasta samples ranged from 6.29 to 9.21%. The protein content in 100% maize flour was significantly ($P < 0.05$) higher than that in 100% OFSP flour. The different composite flours and pasta samples showed similar protein content. Commercial pasta showed the highest protein content of 9.64%.

A progressive increase in ash content was observed with the increasing proportion of OFSP in maize: OFSP composite flours and pasta samples, most likely because the ash content of OFSP was 10 times higher than that of maize. The higher ash content in OFSP suggests higher mineral content as the proportions of OFSP flour in the maize: OFSP flour and pasta samples increased. This agrees with other researchers (Haile et al., 2015; Rodrigues et al., 2016), who reported a higher ash content in OFSP flour.

The insoluble and soluble dietary fibre content of the composited flours increased with increasing proportions of OFSP flours. Insoluble dietary fibre decreased as soluble dietary fibre increased after extrusion cooking for all pasta samples. This suggests thermal and mechanical decomposition of insoluble dietary fibre to soluble fibre. The mechanical shear and high temperature during extrusion lead to the breakage of polysaccharide glycosidic linkages. This leads to redistributing insoluble to soluble dietary fibre content (Oladiran & Emmambux, 2018).

Extrusion cooking decreased the crude fat content in the pasta samples. The low-fat content of OFSP agrees with a previous report by Alam et al., 2016, who showed low-fat content of different varieties of OFSP ranging from 0.17 to 0.63%. Singh, Gamlath, and Wakeling (2007)

Table 1
Effect of compositing maize flour with orange-fleshed sweet potato (OFSP) flour on the proximate composition (g/100g) of flour and extruded gluten-free pasta.

Sample	Composite	Moisture[a]	Protein[b]	Ash[b]	Fat[b]	IDF[b]	SDF[b]
Flour	100% Maize	12.0 ± 0.04[h]	8.37 ± 0.08[c]	0.44 ± 0.02[b]	1.51 ± 0.07[f]	1.27 ± 0.03[c]	0.45 ± 0.05[b]
	80% Maize: 20% OFSP	11.0 ± 0.06[g]	8.04 ± 0.10[b]	1.24 ± 0.00[c]	1.45 ± 0.13[f]	2.95 ± 0.13[e]	2.48 ± 0.03[d]
	70% Maize: 30% OFSP	9.19 ± 0.16[f]	8.22 ± 0.02[bc]	1.74 ± 0.07[e]	1.15 ± 0.08[e]	2.83 ± 0.08[e]	2.46 ± 0.02[d]
	50% Maize: 50% OFSP	7.64 ± 0.15[e]	8.11 ± 0.02[b]	2.54 ± 0.10[g]	1.24 ± 0.01[e]	6.03 ± 0.04[g]	4.10 ± 0.19[f]
Pasta	100% Maize	6.64 ± 0.12[c]	8.15 ± 0.10[b]	0.53 ± 0.01[b]	0.91 ± 0.03[d]	0.34 ± 0.06[a]	0.77 ± 0.03[c]
	80% Maize: 20% OFSP	6.29 ± 0.05[b]	7.66 ± 0.01[a]	1.42 ± 0.09[d]	0.69 ± 0.02[cb]	1.92 ± 0.04[d]	2.86 ± 0.10[e]
	70% Maize: 30% OFSP	6.63 ± 0.05[c]	7.67 ± 0.05[a]	1.97 ± 0.00[f]	0.80 ± 0.02[cd]	1.97 ± 0.07[d]	2.74 ± 0.02[e]
	50% Maize: 50% OFSP	7.15 ± 0.05[d]	8.03 ± 0.17[b]	2.92 ± 0.05[h]	0.59 ± 0.04[b]	3.32 ± 0.08[f]	4.23 ± 0.13[f]
Commercial pasta		9.21 ± 0.20[f]	9.64 ± 0.06[d]	0.27 ± 0.03[a]	0.42 ± 0.01[a]	0.74 ± 0.07[b]	0.22 ± 0.02[a]
100% OFSP flour		4.05 ± 0.06[a]	7.77 ± 0.09[a]	4.36 ± 0.05[I]	1.15 ± 0.07[e]	10.5 ± 0.22[h]	5.04 ± 0.19[g]

Data are expressed as means ± standard deviation, means within a column with different letters are significantly different ($p < 0.05$).
IDF- Insoluble Dietary Fibre.
SDF- Soluble Dietary Fibre.
Commercial gluten-free pasta made from maize and rice.
[a] In as-is basis.
[b] In a dry matter basis.

reported that extrusion cooking decreases the extractable fat, possibly due to thermal degradation and complexation. Free fatty acids can form complexes with amylose, therefore, resulting in difficulty in extracting with organic solvent (Mercier et al., 1980). The formation of amylose-lipid complexes in pasta samples will be discussed in detail in a later part of this paper.

3.2. Cooking time

Pasta made with 100% maize, 70% maize: 30% OFSP and 80% maize: 20% OFSP pasta showed no significant difference ($p > 0.05$) in cooking time (Table 2). Extruded pasta samples statistically ($p > 0.05$) showed a lower cooking time as compared to the commercial pasta. This could have been due to the lower diameter of the extruded pasta strands (1.1 to 1.5 mm) compared to the commercial pasta (1.8 mm), resulting in faster water penetration to the core during cooking. The dietary fibre component in OFSP flour tends to disrupt the physical structure of the pasta and limit its ability to expand (Wang et al., 2019) compared to the 100% maize and commercial pasta.

The light microscopy (Fig. 1) showed indistinct starch granules and a lack of birefringence in the extruded pasta samples compared to the commercial pasta that shows ungelatinized starch. This could be due to the pre-gelatinization process that occurs during the extrusion process leading to rapid hydration of starch during cooking, resulting in lower cooking time. The minimal preparation time for the pasta samples in this study was similar to other researchers who reported a minimal preparation time for extruded gluten-free pasta from yellow pea ranging from 5.5 to 7.0 min (Wójtowicz & Mościcki, 2014), rice pasta composited with lentil ranging from 8 to 9 min (Bouasla et al., 2017), rice pasta composited with yellow pea ranging from 7 to 8 min (Bouasla et al., 2016).

Table 2
Effect of compositing maize flour with orange-fleshed sweet potato (OFSP) flour on the cooking properties of their extruded pasta.

Pasta samples	Cooking time (min)	Cooking loss (%)	WAC (%)	Firmness (N)	Stickiness (N)
100% Maize	4.53 ± 0.40[b]	4.36 ± 0.43[a]	111 ± 0.93[b]	21.1 ± 0.43[bc]	−0.43 ± 0.09[bc]
80% Maize: 20% OFSP	4.20 ± 0.17[b]	5.43 ± 0.08[b]	93.2 ± 0.15[a]	22.1 ± 1.95[c]	−0.54 ± 0.04[bc]
70% Maize: 30% OFSP	4.00 ± 0.00[b]	8.13 ± 0.51[c]	97.9 ± 0.61[a]	11.6 ± 0.41[a]	−0.46 ± 0.07[bc]
50% Maize: 50% OFSP	2.17 ± 0.29[a]	12.5 ± 0.59[d]	96.0 ± 0.73[a]	8.69 ± 1.99[a]	−0.37 ± 0.03[c]
Commercial pasta	10.0 ± 0.00[c]	7.70 ± 0.20[c]	121 ± 0.23[c]	17.9 ± 0.73[b]	−0.58 ± 0.08[a]

Data are expressed as means ± standard deviation, means within a column with different letters are significantly different ($p < 0.05$).
Commercial gluten-free pasta made from maize and rice.
WAC – Water absorption capacity.

3.3. Firmness and stickiness

The starch, protein, and fibre content present in the composite flours influenced the firmness and the stickiness of the pasta (Table 2). The stickiness of pasta is caused by the surface structure of the strand and the leach out of starch onto the surface of the strand during cooking (Susanna & Prabhasankar, 2013). It was observed that the firmer the pasta, the less sticky it was. The decrease in proportions of maize flour in maize: OFSP composites decreased the pasta firmness and increased its stickiness. The increase in stickiness may be due to higher cooking loss. This will further be discussed under the cooking loss section.

3.4. Cooking loss

There was a progressive increase in cooking loss with an increase in the proportion of OFSP in maize: OFSP composite pasta samples (Table 2). Cooking loss is due to the loosening of the compact structure of the pasta and the leach out of soluble materials (Petitot, Boyer, et al., 2010). The cooking loss of the extruded pasta samples ranged from 4.36 to 12.5%. A high cooking loss is undesirable as it represents the high solubility of starch, resulting in turbid cooking water and pasta having a sticky mouthfeel. According to Khan et al. (2013), the acceptable cooking loss of pasta considered desirable for good quality pasta should be less than or equal to 8%, thereby making pasta samples in this current study acceptable except for 50% maize: 50% OFSP pasta.

This increase in cooking loss with pasta samples composited with OFSP flour could result from the fibre content in OFSP. The extrusion process and dietary fibre may disrupt the compact protein-starch matrix causing weakness in its structure, leading to loss of solids during cooking (Muneer et al., 2018). During high-temperature processing, the glycosidic linkages in dietary fibre polysaccharides may be broken. A decreased association between fibre molecules and depolymerization of the fibre results in solubilization (Chindapan et al., 2015). The scanning electron microscopy (SEM) (Fig. 2) for the composited pasta with OFSP showed what could be a discontinuity of protein matrix and damage of starch granules, further exposing it to leaching during cooking in water.

In a study on the inclusion of high fibre legume flour to rice in a gluten-free pasta using a high-temperature single screw extrusion process, Bouasla et al. (2017) showed similar results to those in our study. They attributed the higher cooking loss to the fact that cooking loss was

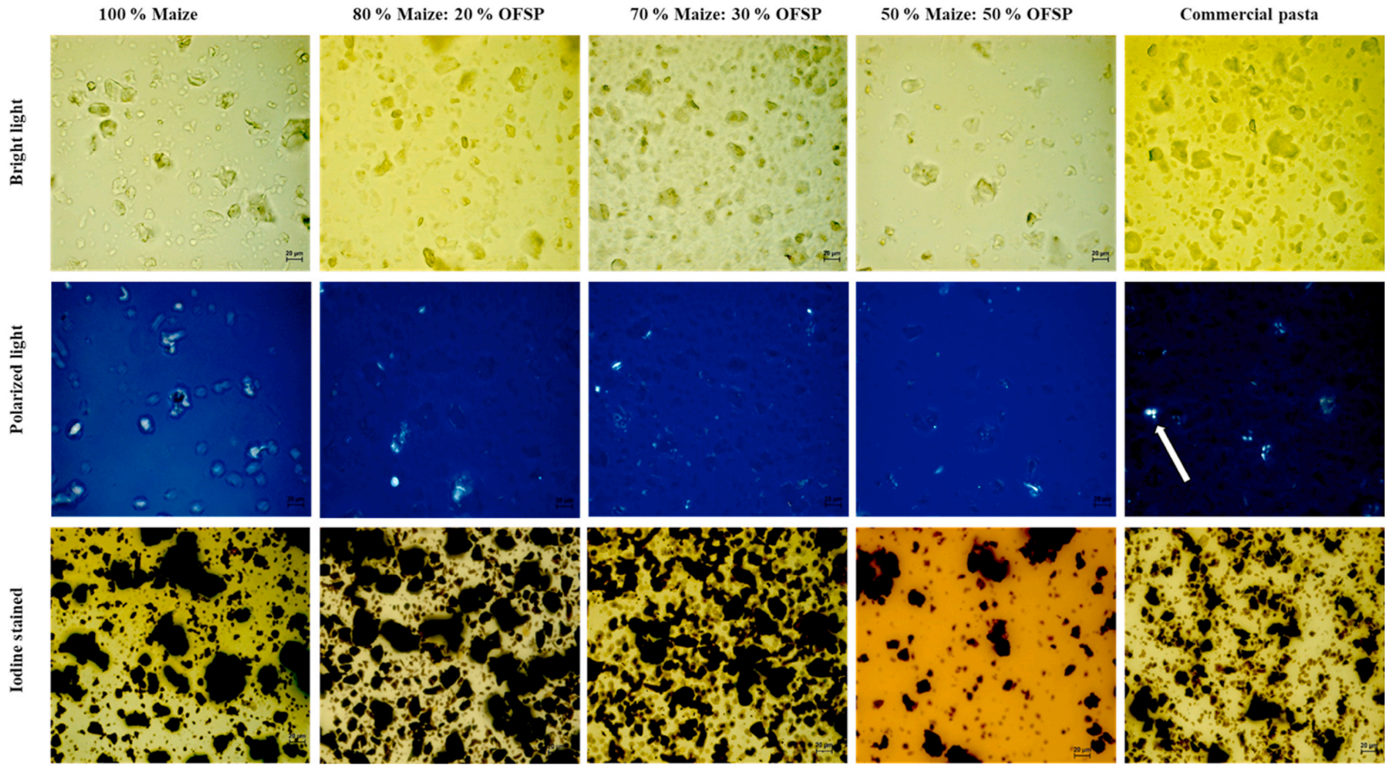

Fig. 1. Light micrographs of milled extruded pasta: viewed under a light microscope, polarized lens, and stained with iodine.
Starch was stained blue\violet. Bar 20 μm. Arrow indicates birefringence of un-gelatinized starch. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

due to the weakening of the starch network by fibre. Foschia et al. (2015) also reported a similar study on the effect of dietary fibre on the physicochemical characteristics of conventionally made pasta. They proposed that the increased cooking loss may be related to the presence of water-soluble components and the disruption of the protein-starch matrix, and the uneven distribution of water within the pasta matrix due to the competitive hydration tendencies of fibre.

3.5. Water absorption capacity (WAC)

The water absorption capacity (WAC) ranged from 96 to 121%. Commercial pasta exhibited higher water absorption capacity than the composited pasta samples with OFSP flour. OFSP has a lower content of biopolymers such as starch and protein compared to maize flour. The higher cooking time (Table 2) and WAC for the commercial pasta could probably be due to its compact starch-protein network due to the low temperature used in conventional pasta production. The SEM microscopy (Fig. 2) for commercial pasta showed visible starch granules embedded in the protein matrix, which indicated less gelatinization of starch and protein damage resulting in more extended hydration, increasing the cooking time and resulting in higher uptake of water during cooking.

3.6. β-Carotene content

There was a significant decrease in β–carotene content of the pasta samples after extrusion cooking, as shown in Table 3. Similar observations have been reported by Shih et al. (2009), who recorded a decrease in the β-carotene content in OFSP after extrusion cooking with barrel temperatures ranging from 100 to 115 °C. During extrusion cooking, the pasta samples are exposed to light, oxygen, and high-temperature conditions. Under these conditions, β–carotene is labile and could be lost through mechanisms such as *cis*-trans isomerization, fragmentation, and oxidation (Syamila et al., 2019).

During *cis*-trans isomerization, the trans forms of β–carotene are converted to cis forms. The cis isomers have significantly reduced vitamin A activity (Gul et al., 2015), and they are susceptible to further degradation. The temperatures used during extrusion cooking to produce the pasta samples could lead to the fragmentation of trans β–carotene, resulting in aromatic compounds such as toluene, *m*-xylene, and 2,6-dimethylnaphthalene (Rios et al., 2008). A significant amount of trans β–carotene could be lost through this mechanism.

3.7. Antioxidant activity

The observed progressive increase in antioxidant activity of the raw flours with increasing levels of incorporation of OFSP flour suggests that β-carotene was a significant contributor to the antioxidant properties of the flours. However, that was not the case with the extruded pasta sample. There was a significant increase in the antioxidant activity of composite pasta samples relative to their flours, and the different pasta samples had similar antioxidant activity. This suggests that for the pasta samples, in addition to β-carotene, other compounds could have contributed to the antioxidant activity. These compounds are likely to be products of the Maillard reaction and caramelization of sugars. The high-temperature conditions of the extrusion process can promote the Maillard reaction (between amino groups of proteins and reducing sugars) and the caramelization of sugars. The products of these reactions are well-known to have reducing properties and, therefore, could contribute to the observed antioxidant activity of the pasta samples (Benjakul et al., 2005; Chawla et al., 2009).

3.8. In-vitro starch digestibility

In-vitro starch digestibility allowed for the determination of starch fractions in the cooked pasta samples (Fig. 3, Table 4), that is, slowly

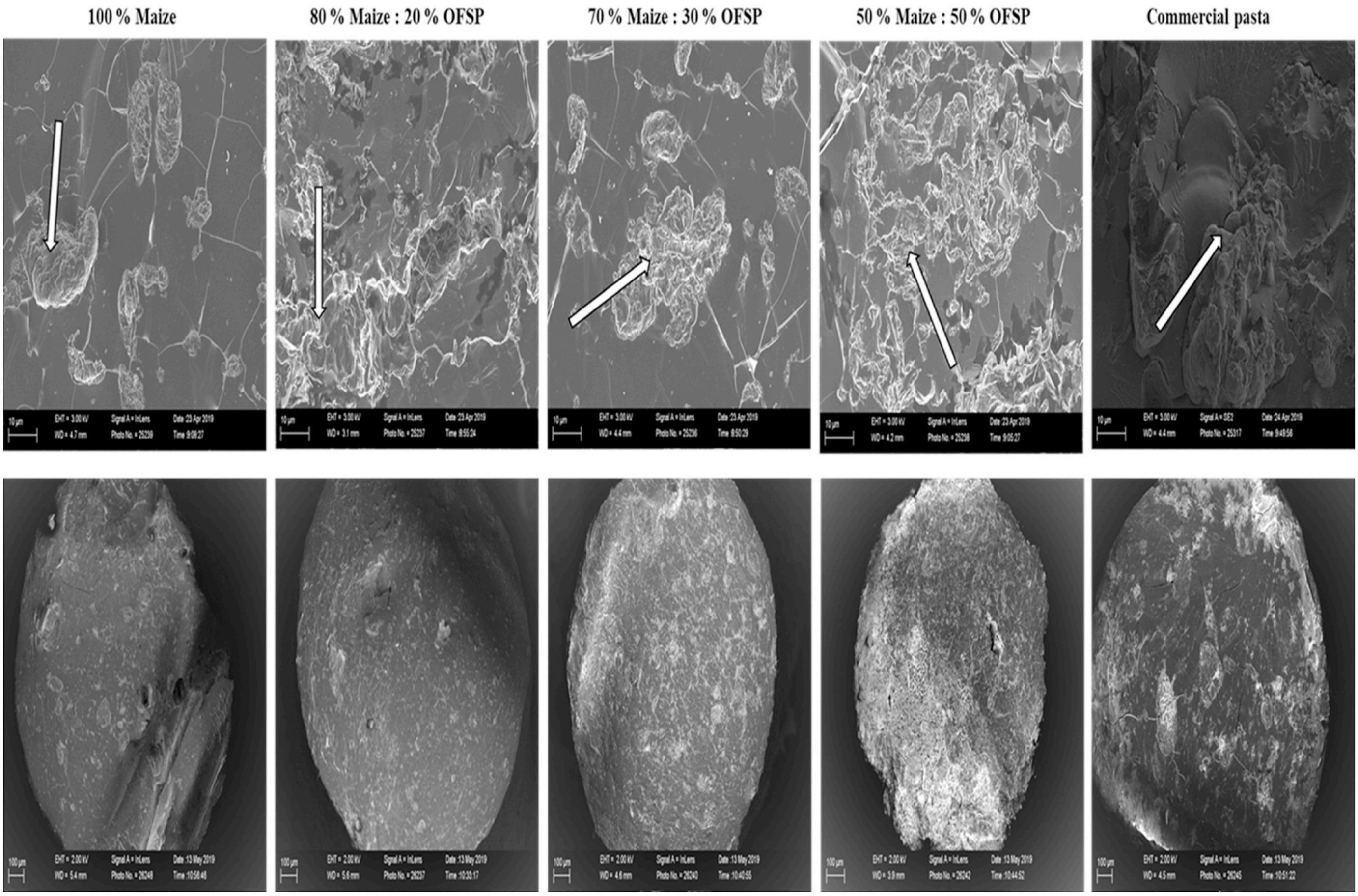

Fig. 2. Scanning electron microscopy images of raw pasta. Surface images showing a cross-section of pasta.
Bar: 10 μm, 100 μm. Arrows pointing on starch protein network.

Table 3
Effect of extrusion cooking and compositing with orange-fleshed sweet potato (OFSP) flour on the β-carotene and antioxidant activity (ABTS radical scavenging) of maize flour pasta.

Treatment	Composites	β-carotene (μg/g)	Antioxidant activity (μmol TE/g)
Raw flour	100% Maize	ND	3.38 ± 0.18[a]
	100% OFSP	611 ± 37.0[g]	23.5 ± 1.98[e]
	80% Maize: 20% OFSP	126 ± 13.9[d]	9.91 ± 0.52[b]
	70% Maize: 30% OFSP	167 ± 10.0[e]	13.3 ± 0.92[c]
	50% Maize: 50% OFSP	339 ± 38.5[f]	16.7 ± 0.05[d]
Extrusion cooked pasta	100% Maize	ND	1.42 ± 1.22[a]
	80% Maize: 20% OFSP	7.88 ± 1.79[a]	51.4 ± 0.82[f]
	70% Maize: 30% OFSP	27.7 ± 4.72[b]	52.2 ± 0.78[f]
	50% Maize: 50% OFSP	43.4 ± 7.26[c]	52.0 ± 0.94[f]

Data are expressed as means ± standard deviation, means within a column with different letters are significantly different ($p < 0.05$).
ABTS- 2, 2′-Azinobis-3-Ethylbenzothiazoline-6-Sulphonic acid.
TE- Trolox Equivalent.
ND- Not detected.

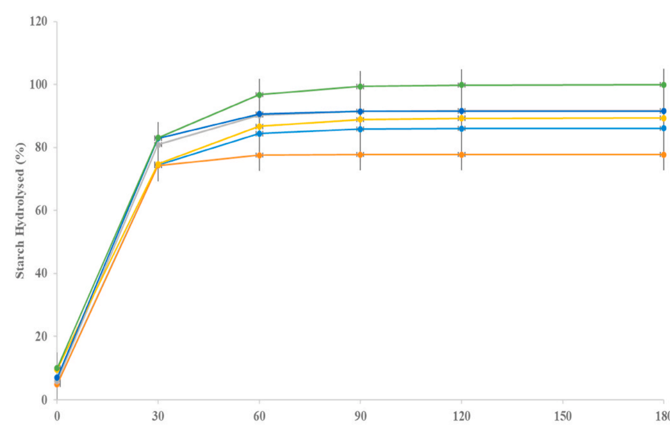

Fig. 3. Effects of compositing maize flour with orange-fleshed sweet potato (OFSP) flour and extrusion cooking on *in-vitro* starch hydrolysis of extruded cooked pasta. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

digestible starch (SDS), rapidly digestible starch (RDS) and resistant starch (RS). The kinetics of *in-vitro* starch digestibility was monitored from 0 to 180 min for the various pasta samples. The total starch digested for the commercial pasta was significantly higher than the extruded pasta samples. The lower total digestible starch in the extruded pasta could have been due to the formation of amylose-lipid complexes. The DSC results indicated that commercial pasta showed lower peak temperature (Table 5) than the extruded pasta samples, which could partly explain the formation of lower amounts of amylose-lipid complexes.

Table 4
Effect of compositing maize flour with orange-fleshed sweet potato flour (OFSP) and extrusion cooking on the percent starch hydrolysed after 180 min, hydrolysis constant, RDS, SDS, and estimated glycaemic index of cooked pasta.

Pasta sample	$^{1}C\infty$ (%)	^{1}K (min)^{ab}	$^{1}EGI^{a}$	HI	RDS (%)	SDS (%)	RS (%)
100% Maize	83.2 ± 0.97^{b}	0.25 ± 0.03^{a}	87.5 ± 0.49^{b}	87.1 ± 0.88^{b}	75.1 ± 2.54^{a}	4.17 ± 0.78^{a}	23.4 ± 1.29^{d}
80% Maize:20% OFSP	76.6 ± 1.87^{a}	0.89 ± 0.12^{b}	85.3 ± 0.37^{a}	83.1 ± 0.67^{a}	72.0 ± 1.06^{a}	4.65 ± 0.17^{a}	22.3 ± 1.92^{d}
70% Maize:30% OFSP	87.8 ± 3.56^{b}	0.28 ± 0.03^{a}	90.9 ± 1.89^{c}	93.2 ± 3.45^{c}	82.3 ± 1.12^{b}	8.86 ± 0.69^{b}	8.98 ± 0.56^{b}
50% Maize:50% OFSP	88.5 ± 1.17^{b}	1.26 ± 0.06^{c}	92.8 ± 1.32^{c}	96.7 ± 2.41^{ef}	82.4 ± 1.90^{b}	15.6 ± 1.85^{c}	9.32 ± 0.20^{b}
Commercial pasta	88.4 ± 5.43^{b}	12.1 ± 0.17^{d}	91.7 ± 0.88^{c}	94.7 ± 1.59^{d}	83.6 ± 1.50^{b}	4.03 ± 0.29^{a}	13.1 ± 0.96^{c}
Bread	96.8 ± 0.29^{c}	0.12 ± 0.00^{a}	94.9 ± 0.44^{d}	99.7 ± 0.58^{f}	84.4 ± 2.96^{b}	16.3 ± 1.08^{c}	0.38 ± 0.09^{a}

Data are expressed as means ± standard deviation, means within a column with different letters are significantly different ($p < 0.05$).
[a]EGI (estimated glycaemic) was calculated using equation (39.71 + 0.549HI) according to Goni et al., 1997.
[ab]C∞ (percentage of starch hydrolysed after 180 min) and K (Kinetic hydrolysis) were calculated using equation $C = C\infty\ (1\text{-}e^{-kt})$.
White wheat bread was used as the reference to calculate the EGI. Commercial gluten-free pasta was made from maize and rice.
RSD-rapidly digested starch.
SDS- slowly digested starch.
RS- resistant starch.

Table 5
Effect of compositing maize flour with orange-fleshed sweet potato (OFSP) flour on the thermal properties of raw and cooked pasta sample.

Sample	Composite	To (°C)	Tp (°C)	Tc (°C)	ΔH (J/g)
Raw	100% Maize	90.2 ± 0.48^{b}	96.0 ± 0.15^{ab}	102 ± 0.23^{abc}	1.28 ± 0.22^{e}
	80% Maize: 20% OFSP	90.0 ± 0.62^{ab}	96.0 ± 0.21^{ab}	101 ± 0.37^{a}	0.97 ± 0.09^{cd}
	70% Maize: 30% OFSP	91.9 ± 0.06^{c}	97.4 ± 0.75^{cd}	104 ± 1.16^{cde}	1.12 ± 0.03^{de}
	50% Maize: 50% OFSP	91.9 ± 0.26^{c}	97.6 ± 0.95^{cd}	103 ± 1.19^{bcd}	1.13 ± 0.17^{de}
	Commercial pasta	88.7 ± 0.36^{a}	95.4 ± 0.29^{a}	102 ± 0.05^{ab}	1.40 ± 0.17^{e}
Cooked	100% Maize	93.0 ± 0.51^{c}	97.6 ± 0.80^{cd}	103 ± 0.74^{abcd}	0.79 ± 0.06^{bc}
	80% Maize: 20% OFSP	92.3 ± 0.17^{c}	98.2 ± 0.28^{cd}	104 ± 1.05^{de}	0.48 ± 0.03^{a}
	70% Maize: 30% OFSP	94.7 ± 0.58^{d}	99.0 ± 0.72^{de}	104 ± 0.36^{de}	0.42 ± 0.16^{a}
	50% Maize: 50% OFSP	95.2 ± 1.33^{d}	100 ± 1.51^{e}	105 ± 0.86^{e}	0.63 ± 0.03^{ab}
	Commercial pasta	91.8 ± 0.30^{c}	96.9 ± 0.78^{abc}	101 ± 0.14^{a}	0.64 ± 0.00^{ab}

Data are expressed as means ± standard deviation, means within a column with different letters are significantly different ($p < 0.05$).
Commercial gluten-free pasta made from maize and rice.
To is onset temperature, Tc is conclusion temperature and Tp is peak temperature.
ΔH is heat flow.

According to De Pilli et al. (2008), lower starch digestibility in extruded starchy foods could be attributed to the formation of amylose-lipid complexation, which prolongs starch digestibility during enzymatic hydrolysis. During extrusion processing of starchy foods, there is gelatinization of starch and the formation of complexes between starch and lipids (De Pilli et al., 2008). The formation of complexes between starches and lipids is due to the ability of the amylose to bind lipids such as fatty acids (Panyoo & Emmambux, 2017). The strong, stable complex limits cross-linking and double-helical structure formation between amylose molecules. Amylose lipid complex can then inhibit starch hydrolysis due to reduced accessibility of the glycosidic bonds by α-amylase enzyme (Fig. 4) (Ye et al., 2018b).

3.9. Thermal properties

The thermal properties of the raw extruded pasta samples did not exhibit any first endotherm except for raw commercial pasta, which showed the first endotherm with a temperature range of 69.1 to 80.2 °C, indicating starch gelatinization temperature. This confirms the non-occurrence of birefringence under polarized light for the extruded pasta samples (Fig. 1). Generally, the absence of the first endotherm indicates the mechanical disruption of the molecular bond and a complete gelatinization of starch by extrusion process (Warren et al., 2016). Comparing the extruded pasta samples with the commercial pasta, which was made using the conventional method, extrusion cooking brings about starch damage and gelatinization of starch granules which required less energy to melt (Petitot, Barron, et al., 2010), which could explain the results. The incomplete gelatinization of the commercial pasta could have also resulted in the longer cooking time of the pasta.

The raw extruded pasta samples (Fig. 4) showed a single endotherm with a temperature ranging from 90.0 to 103 °C, higher than the commercial raw pasta, which showed a second endotherm with temperatures ranging from 88.7 to 102 °C, indicating the formation of type I amylose lipid-complex. During extrusion, the high temperature could have resulted in more amylose-lipid complexes formed, which slowly inhibit the starch digestibility. Many researchers have confirmed the formation of amylose-lipid complexes with a twin-screw extruder. The formation of complexes could probably be due to the amylose content present in the flours used. According to Panyoo and Emmambux (2017), the degree of lipid-binding depends on amylose content. Merayo et al. (2011) stated that, during extrusion cooking, the native structure of amylose is partially destroyed, and new crystalline ones, corresponding to the amylose-lipid complex are formed. De Pilli et al. (2008) further explained that the higher temperature and high moisture content used during extrusion processing promotes the gelatinization of starch to increase the amylose availability for complexation. After cooking, all pasta samples stilled the second endotherm, as shown in Fig. 5.

4. Conclusions

The progressive increase in the proportion of OFSP flour affects the cooking quality and the nutritional properties of the pasta. The pregelatinized starch of the extruded pasta resulted in faster water absorption and heat dissemination during cooking resulting in lower cooking time. Extrusion promotes the conversion of insoluble fibre to soluble fibre in the OFSP flour. The fibre in the OFSP could disrupt the compact starch-protein networks in the pasta samples and increase the leach out of materials resulting in stickiness. Although there was a decrease in the β-carotene content after extrusion, pasta samples had some radical scavenging properties, indicating some potential health benefits. This study demonstrates that pasta can be produced from OFSP using extrusion, which might appeal to consumers as it has appreciable antioxidant properties and has quick cooking time.

CRediT authorship contribution statement

R.O. Baah: Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft. **K.G. Duodu:** Conceptualization, Supervision, Visualization, Writing – review & editing. **M.N. Emmambux:** Conceptualization, Resources, Validation, Funding acquisition,

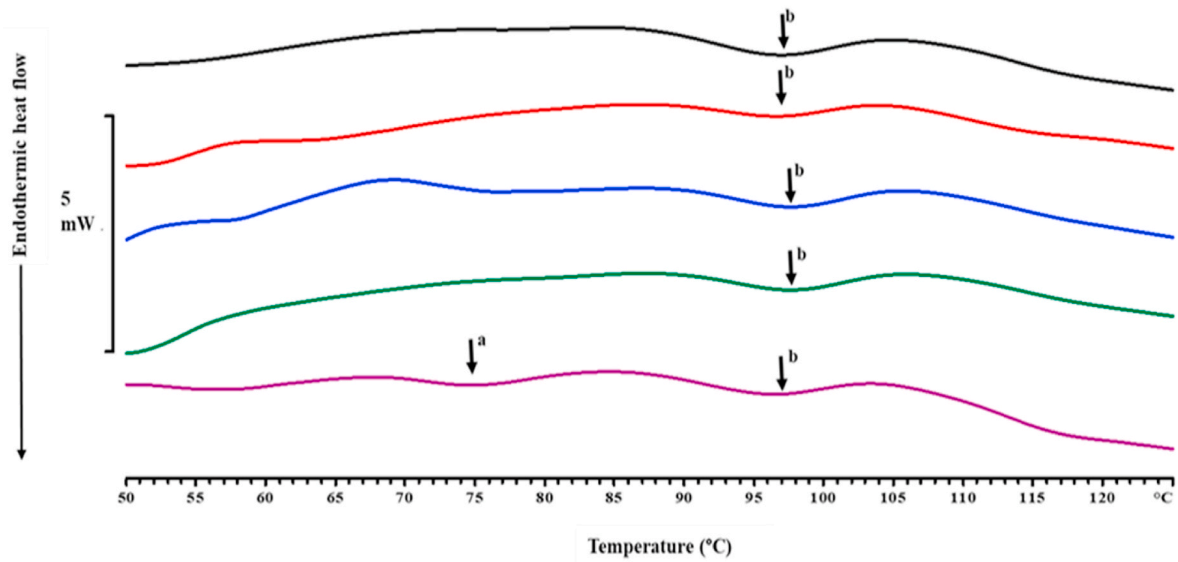

Fig. 4. Effect of compositing maize flour with orange-fleshed sweet potato (OFSP) flour on the thermal properties of raw pasta samples ——100% maize —— 80% Maize: 20% OFSP —— 70% Maize: 30% OFSP —— 50% maize: 50% OFSP ——commercial pasta Commercial gluten-free pasta made from maize and rice [a] Endotherm for type 1 amylose-lipid complex [b] Endotherm for type 1 amylose-lipid complex. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

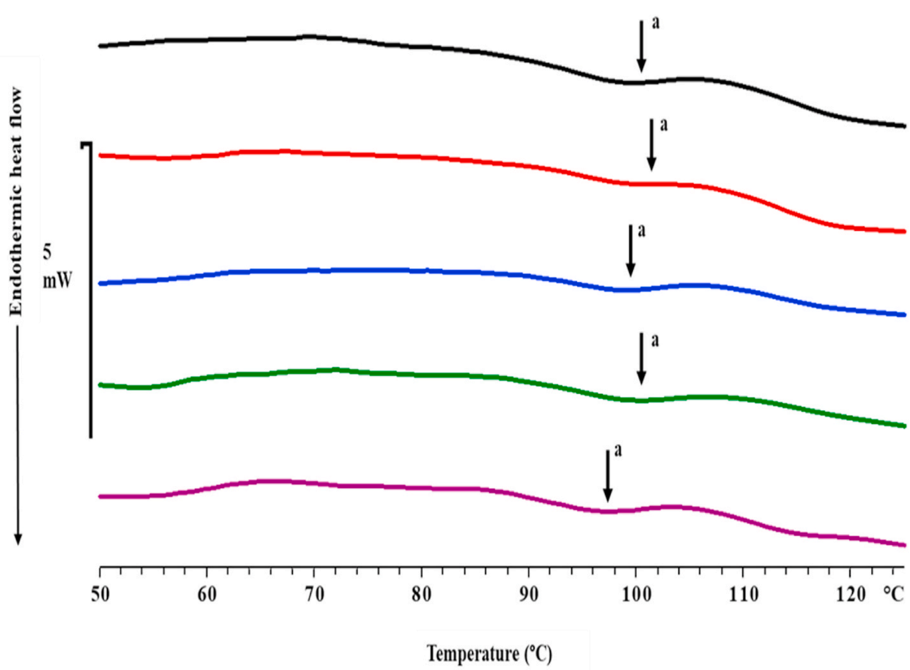

Fig. 5. Effect of compositing maize flour with orange-fleshed sweet potato (OFSP) flour on the thermal properties of cooked pasta samples ——100% maize —— 80% Maize: 20% OFSP —— 70% Maize: 30% OFSP —— 50% maize: 50% OFSP ——commercial pasta Commercial gluten-free pasta made from maize and rice [a] Endotherm for gelatinization temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Supervision, Visualization, Writing – review & editing, Project administration.

Declaration of competing interest

All authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2022.113415.

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