Digestibility and antinutrient properties of acidified and extruded maize–finger millet blend in the production of uji

Calvin Onyango\textsuperscript{a,*}, Horst Noetzold\textsuperscript{b}, Annette Ziems\textsuperscript{a}, Thea Hofmann\textsuperscript{a}, Thomas Bley\textsuperscript{a}, Thomas Henle\textsuperscript{b}

\textsuperscript{a}Institute of Food Technology and Bioprocess Engineering, Technische Universität Dresden, 01062 Dresden, Germany
\textsuperscript{b}Institute of Food Chemistry, Technische Universität Dresden, 01062 Dresden, Germany

Received 13 July 2004; received in revised form 18 September 2004; accepted 22 September 2004

Abstract

Lactic and citric acids were used as alternatives to backslop fermentation in the manufacture of extruded uji (a thin porridge from eastern Africa). Acidity of the blends was reduced by fermentation or progressively lowered with 0.1, 0.5 and 1.0 mol/l lactic or citric acids before extrusion. The absence of ethanol soluble starch in the extrudates indicated that extrusion solubilizes starch without formation of maltodextrins. In vitro starch digestibility increased from 20mg maltose/g starch in the raw blend to about 200mg/g after extrusion. Extrusion reduced total dietary fibre by 39–68%, redistributed soluble to insoluble fibre ratios and had a negligible effect on the formation of resistant starch (less than 1 g/100 g). In vitro protein digestibility increased after fermentation or acid treatment followed by extrusion. Nitrogen solubility index decreased by 40–50% when the unfermented, lactic or citric acid treated blends were extruded, but increased by 20% when the blend was fermented before extrusion. Amino acid analysis showed that histidine, lysine and arginine contents were lowest in the fermented-extruded blends. Tannin content decreased from 1677 mg/100 g in the raw blend to between 551 and 1093 mg/100 g in the extrudates whereas phytate content remained unaffected by extrusion (248–286 mg/100 g).

Keywords: Maize; Finger millet; Organic acids; Extrusion; Digestibility; Antinutrients

1. Introduction

Uji is a thin lactic fermented porridge prepared from cassava flour or whole milled cereals of maize, sorghum and finger millet and is widely consumed in eastern Africa as a refreshing drink. A lot of flexibility exists in the formulation of the raw materials but the maize–finger millet blend is especially preferred because of the chocolate-brown colour of the end-product. This blend is first diluted with water to give a 30–40 g/100 ml slurry which is then spontaneously or backslop fermented for 24 h at 25–35 °C (Onyango, Henle, Hofmann, & Bley, 2004a). The fermented slurry is further diluted to 10 g/100 ml, cooked for 30 min, sweetened with sugar and served warm. Despite its low energy and nutrient content (Onyango, Noetzold, Bley, & Henle, 2004b), and high levels of polyphenols and phytates in the raw materials (Lorri & Svanberg, 1993; Mbithi-Mwikya, van Camp, Yiru, & Huyghebaert, 2000), uji remains the most important and affordable weaning food among the poor in eastern Africa. Lactic acid, resulting from the predominance and metabolic activities of lactic acid bacteria, is the main nonvolatile aroma compound in fermented uji although an extensive range of branched alcohols, carboxylic acids, esters and aldehydes are also produced and contribute to flavour (Masha, Ipsen, Petersen, & Jakobsen, 1998; Onyango, Bley, Raddatz, & Henle, 2004c). Flavour differences exist between
different batches of fermented uji and are influenced by the prevailing temperature, humidity, duration of fermentation, method of inoculation (i.e. backslop or spontaneous fermentation), chemical composition of the substrate and its buffering capacity, added ingredients and the compatibility and interactions of the microbial flora. The laboriousness associated with the preparation of uji, inconsistent flavour and unreliability of spontaneous fermentation forces many urban-based and increasingly time conscious consumers to simply add lemon extract to unfermented uji during cooking in order to reproduce a standard sour tasting product. The use of lemon juice as an acidulant is due to its high content of citric acid which however is not a naturally occurring flavour compound of fermented uji.

Extrusion cooking is one of the most efficient and versatile food processing technologies that can be used to produce pre-cooked and dehydrated foods. We have previously reported that extrusion cooking of fermented uji improves in vitro protein and starch digestibility (Onyango et al., 2004b). Improved protein digestibility is due to degradation of complex storage proteins by endogenous and microbial proteases during fermentation and thermal denaturation of protein by extrusion whereas improved starch digestibility results from increased susceptibility of starch to amylase hydrolysis, loss of structural integrity and partial solubilization of starch molecules. Extrusion also influences the amount of dietary fibre and resistant starch (RS) in foods. Unlu and Faller (1998) have reported that adding certain forms of starch or citric acid to corn meal prior to extrusion modifies RS and dietary fibre. Fermentation of sorghum-based foods before extrusion has also been reported to counteract the formation of RS whereas direct acidification does not (Knudsen & Munck, 1985). The possible formation of RS in fermented or directly acidified and extruded uji warrants investigation because consumers value the porridge as a dietary source of highly digestible carbohydrate.

The most important antinutrients in uji prepared from maize–finger millet blend are polyphenols and phytates. Finger millet varieties from eastern Africa have varying amounts of tannins (270–2000 mg/100 g) whereas both maize and finger millet are rich sources of phytic acid (Lorri & Svanberg, 1993; Mbithi-Mwikya et al., 2000; Egli, Davidson, Juillerat, Barclay, & Hurrell, 2002). These antinutrients form complexes with micronutrients such as iron, calcium and zinc and reduce their solubility and bioavailability. Tannins also complex enzymes of the digestive tract adversely affecting utilization of proteins and carbohydrates and resulting in reduced growth, feeding efficiency, metabolizable energy and bioavailability of amino acids. Traditional artisanal technologies such as decortication, soaking, germination and fermentation of cereal-based foods reduce the levels of tannins and phytates, increase bioavailability of amino acids and mineral elements and improve protein and starch digestibility (Lorri & Svanberg, 1993; Mbithi-Mwikya et al., 2000; Mamiro, van Camp, Mbithi-Mwikya, & Huyghebaert, 2001); but these technologies are limited by their laborious and time-demanding nature. The effect of extrusion cooking on phytic acid has not been clearly elucidated. Some authors (Sandberg, Andersson, Kivistö, & Sandström, 1986; Ummadi, Chenoweth, & Uebersax, 1995; Guallberto, Bergman, Kazemzadeh, & Weber, 1997) reported no change whereas Le Francois (1988) reported a decrease in phytic acid content in extruded products. Very little has been published on the effects of extrusion on tannins in cereals (Camire, 2001), but El-hady and Habiba (2003) have reported significant reduction in tannin content after extruding legume seeds at different moisture contents.

Although processing of uji has remained a largely home-based or at best artisanal activity using rudimentary equipments and techniques, untapped potential exists for its commercialization. It is with this background in mind that this study considers the application of a single-screw laboratory extruder to produce ready-to-eat uji from maize–finger millet blend. In order to control the souring process and obtain a standard product, backslop fermentation was replaced with different molarities of citric or lactic acids before extrusion. The effect of these processing conditions on in vitro starch and protein digestibility, amino acid content, phytates, tannins, resistant starch and different fractions of dietary fibre was evaluated.

2. Materials and methods

2.1. Preparation of flour blends and extrusion

Maize (Zea mays) and finger millet (Eleusine coracana) were purchased in Migori district, Kenya. The cereals were cleaned and hammer milled through a mesh having 1000 μm sized pores (KIRDI, Kenya) before blending in 1:1 ratio and sifted through a 600 μm sieve. We have reported the proximate composition of this blend in a previous publication (Onyango et al., 2004b). Moisture content of the blend was adjusted to 19 g/100 g by pipetting appropriate amounts of 0.1, 0.5 and 1.0 mol/l food-grade citric acid monohydrate (Applichem GmbH, Darmstadt, Germany) or lactic acid (Grüssing GmbH, Filsum, Germany) and manually mixing in a wide bowl. The fermented slurry was prepared by adding 66 g flour to 100 ml distilled water. This slurry was inoculated with 10 ml/100 ml of previously fermented maize–finger millet slurry (backslop culture) and incubated in a Memmert Cabinet (Memmert GmbH, Schwabach, Germany) at 30°C for 24 h. The fermented slurry was spread thinly on an
aluminium tray and dried in a Memmert Cabinet at 45 °C to a moisture content of about 10 g/100 g before milling using a pilot scale Retsch Grindomix GM100 (F. Kurt Retsch GmbH, Haan, Germany). The flour was sifted through a 600 μm sieve before adjusting its moisture content to 19 g/100 g with distilled water. The acid treated and fermented flours were sealed in air-tight plastic containers and allowed to equilibrate for 24 h at 5 °C.

Before extrusion, the samples were brought to 25 °C and manually mixed in wide bowls to ensure even moisture distribution. Extrusion was carried out in a Brabender 20 DN single-screw laboratory extruder (Brabender OHG, Duisburg, Germany) having a uniformly tapered screw with a nominal compression ratio of 2:1, diameter 19 mm, length to diameter ratio 20:1, die diameter 3 mm and screw speed at feed inlet was kept constant at 30 rpm. The inner barrel was grooved to ensure conditions of no-slip-at-the-wall. Electrical heating was applied to the three barrel zones along the screw. Barrel wall temperatures at feed, compression and metering sections were kept at 150, 180 and 180 °C, respectively, while screw speed was maintained at 200 rpm. Steady-state conditions were assumed to have been reached when there were no visible drifts in torque, pressure and product temperature at the die. The extrudates were milled using a pilot scale Retsch Grindomix GM100 and sifted through a 600 μm sieve. Two process runs were performed and all chemical analyses were performed in duplicate. The results were subjected to one-way analysis of variance and differences in treatment means identified by Tukey’s Test using Minitab 14 statistical software (Minitab Inc., USA).

2.2. Moisture and pH

Moisture was determined using a Moisture Analyser MA30 (Sartorius AG, Goettingen, Germany). Each blend (10 g) was dissolved in 90 ml distilled water and the suspension agitated for 15 min on a magnetic stirrer before measuring pH using an Inolab pH-meter (Wissenschaftlich-Technische Werkstätten GmbH, Weilheim, Germany).

2.3. Digestible carbohydrate fractions

Total starch was measured using a polarimeter (Carl Zeiss, Jena, Germany). In vitro starch digestibility was determined as previously described (Onyango et al., 2004b). Ethanol soluble starch was determined by adding 2.5 g sample to 50 ml aqueous ethanol (80 ml/100 ml). The suspension was incubated in a water-bath at 35 °C for 30 min with intermittent vortex mixing before centrifugation at 10,000 rpm for 15 min. Starch extract in the supernatant was determined using a Boehringer Mannheim starch kit (Boehringer Mannheim, Darmstadt, Germany).

2.4. Nondigestible carbohydrate fractions

Modifications were made to the Englyst enzymatic–colorimetric method for determination of dietary fibre as described by Ceirwyn (1995, Chap. 5). Total nonstarch polysaccharide (NSP, also referred to as total dietary fibre) was determined by weighing 200 mg sample in a 50 ml screw-cap tube. After adding 2 ml dimethyl sulfoxide the suspension was stirred using a magnetic stirrer for 2 min. The tube was placed in a boiling water-bath for 1 h, then removed and without cooling, 8 ml 0.1 mol/l acetate buffer pre-equilibrated at 50 °C was added and vortex mixed. (Acetate buffer, 0.1 mol/l, was prepared using saturated benzoic acid and pH adjusted to 5.2 using acetic acid 10 ml/100 ml. Saturated benzoic acid was prepared by adding 10 g benzoic acid to 1000 ml distilled water; the required volume filtered and diluted 1:1 with distilled water. Four millilitres of 1 mol/l calcium chloride was added per litre of acetate buffer solution to stabilize and activate enzymes.) The tubes were cooled to 35 °C before adding 0.5 ml α-amylase (40 mg/ml tris-maleate buffer, pH 7.0, Sigma A-3176; Sigma-Aldrich Chemie GmbH, Steinheim, Germany) and 0.1 ml pullulanase (Sigma P-2986). The tube was capped and incubated at 42 °C for 24 h with intermittent shaking for the first hour. Absolute ethanol (40 ml) was added, mixed by inversion and left for 1 h at 25 °C. The sample was centrifuged at 6500 rpm for 10 min before removing the supernatant by decantation without disturbing the residue. The residue was washed twice with 45 ml aqueous ethanol (85 ml/100 ml), vortex stirred, centrifuged at 6500 rpm for 10 min and supernatant removed by decantation. This procedure was repeated using 40 ml acetone. Resistant starch was determined in the same way as total NSP but addition of dimethyl sulphoxide was omitted and 10 ml instead of 8 ml acetate buffer was added. Insoluble dietary fibre (IDF) was determined in the same way as total NSP but addition of acetate buffer solution to stabilize and activate enzymes. The tubes were cooled to 35 °C before adding 0.5 ml α-amylase (40 mg/ml tris-maleate buffer, pH 7.0, Sigma A-3176; Sigma-Aldrich Chemie GmbH, Steinheim, Germany) and 0.1 ml pullulanase (Sigma P-2986). The tube was capped and incubated at 42 °C for 24 h with intermittent shaking for the first hour. Absolute ethanol (40 ml) was added, mixed by inversion and left for 1 h at 25 °C. The sample was centrifuged at 6500 rpm for 10 min before removing the supernatant by decantation without disturbing the residue. The residue was washed twice with 45 ml aqueous ethanol (85 ml/100 ml), vortex stirred, centrifuged at 6500 rpm for 10 min and supernatant removed by decantation. This procedure was repeated using 40 ml acetone. Resistant starch was determined in the same way as total NSP but addition of dimethyl sulphoxide was omitted and 10 ml instead of 8 ml acetate buffer was added. Insoluble dietary fibre (IDF) was determined in the same way as total NSP but addition of acetate buffer solution to stabilize and activate enzymes. The tubes were cooled to 35 °C before adding 0.5 ml α-amylase (40 mg/ml tris-maleate buffer, pH 7.0, Sigma A-3176; Sigma-Aldrich Chemie GmbH, Steinheim, Germany) and 0.1 ml pullulanase (Sigma P-2986). The tube was capped and incubated at 42 °C for 24 h with intermittent shaking for the first hour. Absolute ethanol (40 ml) was added, mixed by inversion and left for 1 h at 25 °C. The sample was centrifuged at 6500 rpm for 10 min before removing the supernatant by decantation without disturbing the residue. The residue was washed twice with 45 ml aqueous ethanol (85 ml/100 ml), vortex stirred, centrifuged at 6500 rpm for 10 min and supernatant removed by decantation. This procedure was repeated using 40 ml acetone. Resistant starch was determined in the same way as total NSP but addition of dimethyl sulphoxide was omitted and 10 ml instead of 8 ml acetate buffer was added. Insoluble dietary fibre (IDF) was determined in the same way as total NSP but addition of acetate buffer solution to stabilize and activate enzymes.
appeared dry. Sulphuric acid (2 ml, 12 mol/l) was added to the residue and dispersed by vortex mixing. The tubes were incubated in a water-bath at 35 °C for 1 h with occasional mixing to disperse cellulose before adding water (22 ml), capped, mixed then placed in a boiling water-bath for 2 h with intermittent mixing before cooling to 25 °C. A stock solution was prepared by dissolving 2 g glucose in 500 ml saturated benzoic acid. Standards were prepared by taking 1, 2, 3 and 4 ml of the stock solution and made up to 4 ml with saturated benzoic acid. Four millilitres of 2 mol/l sulphuric acid was added to give standards of 0.5, 1.0, 1.5 and 2.0 mg glucose/ml 1 mol/l sulphuric acid. A suitable number of labelled test tubes were taken and in the first test-tube 1 ml of the blank solution (0 mg sugar/100 ml) was placed and in the next three 1 ml of each of the sugar standards to be measured and in the remaining test-tubes 1 ml of the food hydrolysates to be measured. To each test-tube was added 0.5 ml 3.9 mol/l sodium hydroxide and 2 ml 3,5-dinitrosalicylic acid and vortex mixed. All the tubes were simultaneously immersed in a boiling water-bath and left for 15 min. The tubes were cooled under running tap water before adding 20 ml distilled water and mixing by inversion. Absorbance of the samples was measured at 530 nm using an Ultrospec 1000 (Pharmacia Biotech, Cambridge, UK). A calibration graph of absorbance against concentration of sugar in mg/ml was prepared and total NSP, IDF and RS (g/100 g) calculated as follows:

\[ \text{NSP} = \frac{\text{\(A_t\) \times \(V_t\) \times 100 \times 0.89}}{\text{\(A_s\) \times W_t}}, \]

where \(A_t\) is the absorbance of test solution, \(V_t = 23.5\) the total volume of test solution, \(A_s\) the absorbance corresponding to 1 mg sugar/ml, \(W_t\) the weight of food sample in mg, 0.89 is correction factor to compensate for losses of monosaccharides during acid hydrolysis. Soluble dietary fibre (SDF) = Total NSP−IDF, RS = Total NSP−value obtained for RS.

### 2.5. Protein digestibility and amino acid content

Nitrogen solubility index (NSI), in vitro soluble protein and in vitro insoluble protein digestibility and amino acid composition were determined as previously described (Onyango et al., 2004b).

### 2.6. Antinutrients

Tannins were extracted by shaking 1 g sample in 10 ml acidified methanol (1 ml concentrated hydrochloric acid/100 ml methanol) in centrifuge tubes at 25 °C for 20 min. The sample was centrifuged at 10,000 rpm for 15 min before pipetting 1 ml into a test-tube. Vanillin-hydrochloric acid reagent was prepared by mixing equal portions of vanillin solution (4 g vanillin/100 ml methanol) and acidified methanol (8 ml concentrated hydrochloric acid/100 ml methanol). The vanillin-hydrochloric acid reagent (5 ml) was added to the sample and absorbance read in 1-cm cuvettes using an Ultrospec 1000 spectrophotometer at 500 nm after 20 min against vanillin-hydrochloric acid reagent as blank. To correct for interference of natural pigments, sample blanks were prepared by subjecting the original extract to the conditions of the reaction but without the vanillin-hydrochloric acid reagent (Price, van Scoyoc, & Butler, 1978). A standard curve was prepared by adding 1 g tannic acid (Fluka Chemie AG, Buchs, Switzerland) to 100 ml acidified methanol and this stock solution was used at various dilutions from 1:10 to 1:50.

Phytates were extracted by adding 0.1 g sample to 10 ml 0.2 mol/l hydrochloric acid and shaken for 1 h before centrifuging at 5000 rpm for 15 min. The supernatant (0.5 ml) was pipetted into a test tube fitted with a ground-glass stopper before adding 1 ml acidic ammonium iron (III) sulphate dodecahydrate (0.2 g NH₄Fe(−SO₄)₂·12H₂O in 100 ml 2 mol/l hydrochloric acid and made up to 1000 ml with distilled water). The sample was boiled for 30 min then rapidly cooled to 25 °C in an ice-water-bath. 2,2′-bipyridine solution (10 g 2,2′-bipyridine and 10 ml thiglycolic acid in 1000 ml water) was added (2 ml) to the test tube and the contents mixed. Absorbance was read after 1 min using an Ultrospec 1000 spectrophotometer at 519 nm against distilled water (Haug & Lantzsch, 1983). A standard curve was prepared by adding 125 mg sodium phytate (Sigma Aldrich GmbH, Steinheim, Germany) to 100 ml 0.2 mol/l hydrochloric acid and this stock solution was used at various dilutions to give final phytate phosphorous concentrations of 3–30 μg/ml.

### 3. Results and discussion

#### 3.1. Product characteristics

Moisture content declined from about 19 g/100 g in each blend before extrusion to about 10 g/100 g after extrusion whereas the pH of the blends was minimally affected by extrusion (Table 1). A consistent stream of the expanded product was obtained at the die outlet for all treatments except for the blend extruded with 1 mol/l citric acid. This latter blend tended to disintegrate in to a flaky mass at the die exit and its emergence was accompanied by explosive moisture flash-off. A similar behaviour has been reported with acidified cassava starch (Sriburi & Hill, 2000) and was attributed to loss of structural integrity as the extensively depolymerized starch molecules exit the die. This change, also referred to as starch conversion, appears to be influenced by feed moisture, barrel temperature, mechanical shear and...
chemical environment. Interestingly, the backslup fermented product, whose pH value was close to that of the 1 mol/l citric acid treated blend, maintained its structural integrity as it emerged from the die. This may be because of the chemical environment of the fermented blend, which is exclusively influenced by lactic acid and lacks citric acid—which is not a natural byproduct in fermented uji.

### 3.2. Digestible carbohydrate fractions

Starch content of the raw blend was 76 g/100 g and significantly decreased \((P < 0.05)\) when the unfermented or fermented blend was extruded (Table 2). Starch content of the blends treated with citric or lactic acids, with the exception of 0.1 mol/l citric acid, were also significantly lower \((P < 0.05)\) than in the raw material. Treatment of the blends with increasing concentration of citric acid decreased total starch whereas increasing concentration of lactic acid did not affect starch content. These declines in starch content are associated with thermal and physical hydrolysis of starch (Colonna & Mercier, 1983; Della Valle, Kozlowski, Colonna, & Tated, 1989). Decline in starch content could also be due to formation of irreversible complexes between amylose and monoglycerides and free fatty acids (Björk & Asp, 1983; Camire, 2001) and between amylose and proteins (Björk, Asp, Birkhed, & Lundquist, 1984a; Tester, Karkalas, & Qi, 2004). In an earlier study we found that the accompanying decrease of extractable crude fat, when backslup fermented maize–finger millet blend is extruded, is about 70% (Onyango et al., 2004b).

The absence of ethanol soluble starch in all the extrudates confirmed that extrusion solubilizes starch in its macromolecular form without degradation into maltodextrins and has also been reported by Mercier and Feillet (1975). Solubilization of starch during extrusion is nutritionally desirable since it indicates formation of a product that is more susceptible to amylolytic digestion. In vitro starch digestibility of the raw blend was 20 mg maltose/g starch and increased to 162–246 mg/g after extrusion (Table 2). The ability of pancreatic enzymes to digest raw cereal starch is related to the crystalline arrangement of its starch granules. The short exterior chains of amylpectin molecules (chain length less than 20) in cereal starches favour formation of thermodynamically stable A-type X-ray diffraction patterns that are susceptible to pancreatic amylases (Tester et al., 2004). The starch, in this native state, is also referred to as slowly digestible starch because it can be digested in the small intestine, albeit slowly (Englyst, Kingman, & Cummings, 1992). Starch needs to be gelatinized for efficient hydrolysis since gelatinized starch is more susceptible to enzymatic attack (Akdogan, 1999). In vitro starch digestibility significantly improved \((P < 0.05)\) after the raw blend was extruded, and all the extrudates did not differ significantly from each other \((P > 0.05)\). Extrusion improves starch digestibility by shearing off branches on amylpectin molecules and thereby increasing their accessibility to amylolytic enzymes (Camire, 2001). Other changes that occur in the starch granules and contribute to improved digestibility are hydration, loss of structural integrity and partial solubilization of starch molecules (Björk &

### Table 1

Moisture content\(^a\) and pH of maize–finger millet blend before and after extrusion

<table>
<thead>
<tr>
<th></th>
<th>UF</th>
<th>FTD</th>
<th>Citric acid (mol/l)</th>
<th>Lactic acid (mol/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Moisture</td>
<td>Before extrusion</td>
<td>19.2</td>
<td>19.2</td>
<td>19.4</td>
</tr>
<tr>
<td></td>
<td>After extrusion</td>
<td>10.3</td>
<td>9.1</td>
<td>10.6</td>
</tr>
<tr>
<td>pH</td>
<td>Before extrusion</td>
<td>6.3</td>
<td>4.1</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>After extrusion</td>
<td>6.1</td>
<td>4.2</td>
<td>5.6</td>
</tr>
</tbody>
</table>

UF: unfermented, FTD: fermented. 
\(^a\)g/100 g.

### Table 2

Digestible carbohydrate fractions of extruded maize–finger millet blend

<table>
<thead>
<tr>
<th>Treatment</th>
<th>TS(^a)</th>
<th>IVSD(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw flour (control)</td>
<td>76.0a</td>
<td>20.0b</td>
</tr>
<tr>
<td>Unfermented, extruded</td>
<td>69.9b</td>
<td>226.9a</td>
</tr>
<tr>
<td>Fermented, extruded</td>
<td>66.6c</td>
<td>220.1a</td>
</tr>
<tr>
<td>0.1 mol/l citric acid</td>
<td>71.4a</td>
<td>210.5a</td>
</tr>
<tr>
<td>0.5 mol/l citric acid</td>
<td>69.5b</td>
<td>245.9a</td>
</tr>
<tr>
<td>1.0 mol/l citric acid</td>
<td>66.6c</td>
<td>245.9a</td>
</tr>
<tr>
<td>0.1 mol/l L-lactic acid</td>
<td>68.9b</td>
<td>195.6a</td>
</tr>
<tr>
<td>0.5 mol/l L-lactic acid</td>
<td>68.7b</td>
<td>232.1a</td>
</tr>
<tr>
<td>1.0 mol/l L-lactic acid</td>
<td>69.6b</td>
<td>162.2a</td>
</tr>
</tbody>
</table>

TS: total starch, IVSD: in vitro starch digestibility. Means followed by the same letter in the same column are not significantly different at \(P < 0.05\).

\(^a\)g/100 g dry matter basis.

\(^b\)mg maltose/g starch dry matter basis.
Asp, 1983; Dahlin & Lorenz, 1993; Garcia-Alonso, Jimenez, Martin, Bravo, & Saura, 1999). X-ray diffraction patterns have shown that thermal treatment decreases the amount of A-type crystalline structure and instead new complexes are formed that pack initially in the unstable E-pattern before rearranging to the more stable V-pattern (Fan, Mitchell, & Blanshard, 1996; Sriburi & Hill, 2000).

3.3. Nondigestible carbohydrate fractions

Total NSP decreased from 2.5 g/100 g in the raw blend to 1.5 g/100 g in the unfermented-extruded blend and further to values between 0.9 and 1.4 g/100 g in blends that were fermented or treated with different molarities of lactic or citric acids before extrusion (Fig. 1). Further significant changes in total NSP did not occur with increasing concentrations of either lactic or citric acids. The values ranged from 1.1 to 1.4 g/100 g and 0.8 to 1.0 g/100 g in the blends extruded with lactic and citric acids, respectively. The decrease in total NSP is attributable to the high extrusion temperature and intense mechanical shear that disrupts glycosidic linkages and weak bonds between polysaccharide chains of dietary fibre polysaccharides. Depending on the process conditions, raw materials and the enzyme system used for solubilization of starch, a higher NSP content has been noted after extrusion (Björk, Nyman, & Asp, 1984b). Although amyloglucosidase hydrolyses α-(1→4) and α-(1→6) bonds of amylose and amylopectin, it is not as effective as a combination of α-amylase and amyloglucosidase (Björk et al., 1984b) or α-amylase and pullulanase for in vitro determination of NSP.

The decrease in total NSP after extrusion was accompanied by a redistribution of SDF to IDF fractions in all the blends (Fig. 1). The proportion of SDF in the raw blend was 39% and increased to 52% in the unfermented-extruded blend. Increased SDF fraction after extrusion or canning is associated with solubilization of some IDF fractions, disruption of ligno-cellulose links in the cell walls and disintegration of larger molecules of fibre resulting in the formation of low molecular weight soluble fragments such as arabinose, xylose, galactose and glucose (Björk et al., 1984b; Fornal, Soral-Smietana, Smietana, & Szpadowski, 1987; Periago, Englyst, & Hudson, 1996; Periago, Ros, & Casas, 1997). Solubilization of fibre is negatively correlated to the moisture content of the feed material whereas extrusion temperature and screw speed have minimal influence (Ralet, Thibault, & Della Valle, 1990). Solubilization of fibre increases its availability to bacterial flora in the colon making it easier to ferment than insoluble fibre. Soluble dietary fibre fractions are important in foods because they trap fatty substances in the gastro-intestinal tract and therefore reduce cholesterol levels in the blood and lower the risk of heart disease. The ability of SDF to retard absorption of glucose in the small intestine is also a desirable characteristic in the development of foods for diabetic individuals. In contrast to the unfermented sample, SDF

![Fig. 1. Distribution of total NSP, IDF, SDF and RS in extruded maize-finger millet blend.](image-url)
fractions in the fermented, lactic or citric acid treated blends decreased on extrusion. The proportion of SDF in total NSP decreased from 39% in the raw blend to 19% when the blend was fermented before extrusion. The ratio of SDF in total NSP decreased from 30% to 19% and 45% to 30% with increasing molarities of citric and lactic acids, respectively. Extrusion at acidic conditions facilitates conversion of SDF to IDF by polymerization of the short chain fibre fragments to form large insoluble complexes or Maillard compounds that are consequently analysed as lignin (Camire, 2001). It is also possible that the diverse bacterial and yeast flora in the backslop fermented blend may have utilized some SDF for their metabolic processes. The decrease in SDF and increase in IDF fractions means increased fibre availability for faecal bulking and water binding in the colon resulting in more frequent and softer bowel motions, reduced risk of constipation and increased volume of waste material.

Resistant starch was not detected in the raw blend and only a minimal amount (0.6g/100g) was formed when the unfermented blend was extruded. Formation of RS was counteracted when the pH of the blends was lowered either by fermentation or increasing molarities of lactic or citric acids. Similar results have been noted with sorghum, another important cereal crop in eastern Africa. Resistant starch was formed when unfermented sorghum was cooked but fermentation or acidification before cooking counteracted the formation of RS (Knudsen & Munck, 1985). Blends extruded with lactic acid had RS contents in the range of 0.3–0.5g/100g whereas citric acid treated blends had RS contents less than 0.1g/100g. Formation of RS is associated with retrogradation of amylose (Englyst et al., 1992; Shamai, Bianco-Peled, & Shimoni, 2003) during which enzyme resistant amylose–amylose linkages are formed. This implies that starchy foods with high amylose contents are expected to have high RS contents after extrusion. An example is high amylose corn (maize) starch that has about three times more RS than boiled millet and six times more RS than cornflakes extruded from normal maize (Englyst et al., 1992). Unlu and Faller (1998) have also reported that when high amylose corn starch (74% amylose) is extruded with increasing concentrations of citric acid up to 7.5g/100g (equivalent to 0.35mol/l) there is a corresponding increase in the formation of RS and fibre.

Göni, Garcia-Diz, Manas, and Saura-Calixto (1996) have classified the RS content of several raw and processed starch-rich foods, with values ranging from less than 1g/100g (i.e. negligible) to more than 15g/100g (i.e. very high). Using this classification we can conclude that our extrudates had negligible amounts of RS. These amounts can be considered nutritionally insignificant and cannot adversely affect the energy digestibility of extruded uji. Research on RS in the developed world is geared towards the need to increase nondigestible fractions and reduce digestible starch with the aim of producing functional foods for the treatment of obesity, diabetes, colon cancer and coronary heart disease (Unlu & Faller, 1998; Camire, 2001). By contrast, in a developing country such as Kenya, the need for highly digestible starch in foods supersedes the need for RS-rich foods. Uji is an important source of energy for weaning age children, refugees and generally the poor meaning that it should be able to supply the consumer with maximum amount of highly digestible starch. A reduction in energy content due to the formation of RS would therefore be undesirable.

3.4. Protein digestibility and amino acid content

The slight improvement of protein content after fermentation and extrusion (Table 3) is attributable to the decrease of carbon ratio in the total mass during fermentation. Microorganisms utilize carbohydrates as an energy source and produce carbon dioxide as a byproduct. This causes the nitrogen in the fermented slurry to be concentrated and thus the proportion of protein in the total mass increases. The extent of protein denaturation is assessed by changes of protein solubility in water and is measured as NSI (Camire, 2001). We have previously reported that NSI declines when unfermented maize–finger millet blend is extruded (Onyango et al., 2004b). The same effect was observed when the blends were treated with lactic or citric acid before extrusion. These changes are due to denaturation of proteins. Extrusion denatures proteins by opening up their quaternary and tertiary structures, thus inducing polymerization, cross-linking and reorientation to fibrous insoluble structures (Akdogan, 1999). By contrast, the 20% increase in NSI when the blend was

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Protein&lt;sup&gt;b&lt;/sup&gt;</th>
<th>NSI</th>
<th>IVSP</th>
<th>IVISP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw flour (control)</td>
<td>8.5b</td>
<td>11.8b</td>
<td>61.7b</td>
<td>56.7d</td>
</tr>
<tr>
<td>Unfermented, extruded</td>
<td>8.5b</td>
<td>5.4c</td>
<td>65.0b</td>
<td>63.0c</td>
</tr>
<tr>
<td>Fermented, extruded</td>
<td>8.7a</td>
<td>14.5a</td>
<td>70.9a</td>
<td>66.0b</td>
</tr>
<tr>
<td>0.1 mol/l 1-citric acid</td>
<td>8.5b</td>
<td>5.8c</td>
<td>67.6b</td>
<td>65.9b</td>
</tr>
<tr>
<td>0.5 mol/l 1-citric acid</td>
<td>8.5b</td>
<td>6.1c</td>
<td>72.0a</td>
<td>70.0a</td>
</tr>
<tr>
<td>1.0 mol/l 1-citric acid</td>
<td>8.4b</td>
<td>6.8c</td>
<td>69.8a</td>
<td>68.0a</td>
</tr>
<tr>
<td>0.1 mol/l 1-lactic acid</td>
<td>8.6a,b</td>
<td>6.2c</td>
<td>65.0b</td>
<td>62.3c</td>
</tr>
<tr>
<td>0.5 mol/l 1-lactic acid</td>
<td>8.5b</td>
<td>5.8c</td>
<td>67.0b</td>
<td>65.2b</td>
</tr>
<tr>
<td>1.0 mol/l 1-lactic acid</td>
<td>8.5b</td>
<td>6.1c</td>
<td>71.5a</td>
<td>69.3a</td>
</tr>
</tbody>
</table>

NSI: nitrogen solubility index; IVSP: in vitro soluble protein digestibility; IVISP: in vitro insoluble protein digestibility. Means followed by the same letter in the same column are not significantly different at P<0.05.

<sup>a</sup>Dry weight basis.

<sup>b</sup>N × 6.25.
fermented before extrusion is attributable to the fermentation process during which microbial enzymes degrade proteins in to low molecular weight water-soluble nitrogenous substances and amino acids. Some soluble proteins may also be released when the high extrusion temperatures and intensive mechanical shear break down protein–polyphenol complexes.

Soluble and insoluble protein digestibilities improved when the blends were fermented or treated with increasing concentrations of citric or lactic acids before extrusion (Table 3). Fermentation improves protein digestibility by inducing degradation of proteins by microbial and endogenous enzymes. High temperatures, intense mechanical shear and low pH further promote structural changes and denaturation of storage proteins and increase their accessibility to proteolytic enzymes. Thermal inactivation of protease inhibitors and anti-physiological factors such as polyphenols also contribute to improved protein digestibility (Björk & Asp, 1983).

The maize–finger millet blend used in this study has a low protein content (Onyango et al., 2004b), and consistent consumption of porridge prepared from this blend is a major cause of protein deficiency among weaning-age children in eastern Africa. Distribution of the constituent amino acids in the raw and extruded blends is shown in Table 4. Glutamic acid had the highest content followed by leucine and proline whereas cystine was not detected in all the samples. Considerable decline in amino acid contents occurred only with respect to histidine, lysine and arginine in the fermented-extruded blend, and lysine in the blend extruded with 1 mol/l citric acid. Loss of these amino acids in the backslop fermented blend is due to their utilization by lactic acid bacteria during fermentation and further losses may have been caused by their participation in Maillard reactions during extrusion. The considerable lysine losses in all the extrudates is related to its free ε-amino group that make it highly susceptible to Maillard reactions.

3.5. Antinutrients

The high tannin content (1677 mg/100 g) of the raw material (Fig. 2) is due to the finger millet variety used since maize does not have detectable amounts of tannins (Lorri & Svanberg, 1993). Tannin contents of finger millet varieties from eastern Africa vary widely from 270 mg/100 g (Mbithi-Mwikya et al., 2000) to 2000 mg/100 g (Lorri & Svanberg, 1993). The adverse effects of tannins in foods result from their ability to complex enzymes of the digestive tract and so reduce protein and starch digestibility. An inverse relationship between tannin content and in vitro protein digestibility has been reported for germinated finger millet (Mbithi-Mwikya et al., 2000). The physiological consequences of consuming tannin-rich foods are reduced growth, feeding efficiency, metabolizable energy and bioavailability of amino acids. Tannin content decreased to 697 mg/100 g after extrusion of the unfermented blend and further to 551 mg/100 g after fermentation and extrusion. Extrusion of the blends with lactic or citric acids counteracted thermal degradation of tannins and the values ranged from

![Table 4](image)

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Amino acid content of extruded maize–finger millet blend</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amino acid</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Aspartic acid</td>
<td>5.0±0.4</td>
</tr>
<tr>
<td>Threonine</td>
<td>2.9±0.2</td>
</tr>
<tr>
<td>Serine</td>
<td>3.2±0.3</td>
</tr>
<tr>
<td>Glutamic acid</td>
<td>15.7±1.2</td>
</tr>
<tr>
<td>Proline</td>
<td>6.2±0.1</td>
</tr>
<tr>
<td>Glycine</td>
<td>2.6±0.5</td>
</tr>
<tr>
<td>Alanine</td>
<td>4.2±0.3</td>
</tr>
<tr>
<td>Valine</td>
<td>4.0±0.3</td>
</tr>
<tr>
<td>Methionine</td>
<td>1.3±0.1</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>2.7±0.1</td>
</tr>
<tr>
<td>Leucine</td>
<td>7.9±0.5</td>
</tr>
<tr>
<td>Tyrosine</td>
<td>2.7±0.2</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>3.6±0.2</td>
</tr>
<tr>
<td>Histidine</td>
<td>2.1±0.3</td>
</tr>
<tr>
<td>Lysine</td>
<td>2.2±0.3</td>
</tr>
<tr>
<td>Arginine</td>
<td>3.2±0.1</td>
</tr>
</tbody>
</table>

aDry weight basis, amino acid content g/16 g N, mean±SEM (n = 2); RNF: raw blend (control), UF: unfermented-extruded, FTD: fermented-extruded.
bPercent of corresponding value in raw material.
861–1093 mg/100 g and 777–817 mg/100 g for blends extruded with lactic and citric acids, respectively.

Fermentation or treatment of the blends with lactic or citric acids before extrusion had no effect on phytic acid content, which ranged from 247 to 286 mg/100 g. The amount of phytic acid in the unfermented-extruded blend also remained unchanged (Fig. 2). The inability of extrusion cooking to degrade phytic acid has also been reported in wheat, rice and oat bran (Gualberto et al., 1997), legumes (Ummadi et al., 1995) and a high-fibre cereal (Sandberg et al., 1986). Furthermore, deactivation of phytase during extrusion cooking could impair mineral absorption in the stomach and small intestine. It is speculated that this enzyme plays a role in phytate hydrolysis in the gastrointestinal tract and therefore its activity should be retained even after processing (Lopez, Leenhardt, Coudray, & Remesy, 2002). Literature research shows that activation of endogenous phytases by germination is one of the most effective ways to reduce phytate in cereals (Sandberg & Svanberg, 1991; Mbithi-Mwikya et al., 2000; Mamiro et al., 2001; Egli et al., 2002). Another effective alternative method involves use of exogenous phytases (Sandberg & Svanberg, 1991; Hurrell, Reddy, Juillerat, & Cook, 2003). Nevertheless even germination or use of exogenous phytases cannot reduce phytates to levels that have almost no inhibitory effect on in vivo mineral iron absorption (Hurrell et al., 2003). Residual phytate levels should be less than 0.5 μmol/g in order to eliminate any inhibitory effect on iron availability (Sandberg & Svanberg, 1991).

4. Conclusion

Although uji is an important source of energy and dietary proteins for many poor people in eastern Africa there has been no major progress in improving its nutritional quality and processing technique. Extrusion technology presents a new exciting opportunity to process uji at the industrial instead of the household level. The dehydrated ready-to-eat product could serve as an inexpensive source of food for the poor and refugees because its dehydrated nature dispenses with the need for refrigeration during transport and storage; and since the porridge is already pre-cooked, less energy would be required at the household level for its reconstitution. This study has therefore considered (a) acidification with citric or lactic acids as alternative souring techniques to backslop fermentation and (b) extrusion as a means of producing a pre-cooked and shelf-stable product. Treatment of maize–finger millet blends with lactic or citric acids before extrusion had no adverse effects on in vitro starch and protein digestibility when compared to backslop fermented and extruded blend. The overall amino acid balance was poorer in the fermented-extruded blend than in the blends treated with lactic or citric acids before extrusion. The reduction of lysine in particular is of concern because lysine is a limiting essential amino acid in cereals and insufficient amounts can impair growth in young children. Extrusion of the unfermented blend increased SDF and reduced IDF whereas extrusion of
the fermented or acidified blends reduced SDF and increased IDF fractions. Based on the extrusion conditions used in this study, it is possible to produce ready-to-eat uji without a significant increase in RS content or loss of digestible energy. Extruding the fermented blend was effective in lowering tannin content, whereas addition of citric or lactic acids countered the thermal destruction of tannins. Fermentation or treatment of the blends with lactic or citric acids before extrusion had no influence on phytic acid.

Acknowledgements

This work has been financially supported by Deutscher Akademischer Austauschdienst (DAAD). The authors are grateful to Frau Karla Schlosser for the amino acid analysis.

References


