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Retention and Bioaccessibility of β-Carotene in Blended Foods Containing Orange-Fleshed Sweet Potato Flour

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ABSTRACT: The retention and bioaccessibility of β-carotene (BC) in blended foods made with part orange-fleshed sweet potato (OFSP) flour (30%) were examined. Chapatis and porridges were prepared by local processors under field conditions (FC) in Uganda (n = 10). While the retention of *all-trans*-BC in porridges (69 to 93%) and chapatis (70 to 97%) varied between the processors, there was no overall difference between the two products and this was probably because of the variability in FC. BC retention in mandazis was similar to that of chapatis and porridges. Processing in FC significantly increased the amount of cis-isomers, in particular 13-*cis*-BC. The bioaccessibility of the BC as measured by their transfer into micelles was evaluated using an in vitro digestion procedure in various OFSP-derived products. After in vitro digestion, the percentage of micellarized *all-trans*-BC was greater in products cooked with oil, chapati (73%) and mandazi (49%), as compared with the boiled ones, porridge (16%) and puréed from boiled root (10%). In all the products, the incorporation into micelles for 13-*cis*-BC was significantly higher to that of *all-trans*-BC. When taking into account the bioaccessibility of *all-trans*-BC and 13-*cis*-BC isomer, an edible portion of porridge (one mug), boiled root (half a root), mandazis (two), or chapati (one) could provide a significant part of the daily vitamin A requirements of a child under 6 years (respectively 20, 46, 75, or 100%). These data support the promotion/consumption of locally cooked OFSP food products to tackle vitamin A deficiency in sub-Saharan Africa.

KEYWORDS: *Ipomoea batata* (L.) Lam, carotenoids, bioaccessibility, cooking, vitamin A activity, β-carotene

INTRODUCTION

Sweet potato [*Ipomoea batata* (L.) Lam] is a major staple crop in sub-Saharan Africa. Methods of traditional preparation of sweet potato in sub-Saharan Africa include boiling, steaming, roasting, and drying.[1] Sweet potato products are also important for income generation, especially for small businesses and entrepreneurs. In developing countries such as Uganda and other sub-Saharan African countries, dried products (chips, starch, and flour) have been identified as the most promising processed products from sweet potato for household consumption and for business in local markets compared to the many options available.[2,3] The market for these processed products, however, is still underexploited, but there could be opportunities for market development. In particular, Hagenimana and Owori[4] studied the financial viability of chapatis using 30% sweet potato flour and revealed there was a potential for profit in Eastern Uganda.

In combination with business opportunities, there is the potential for nutritional benefits for consumers in sub-Saharan Africa. Orange-fleshed sweet potato (OFSP), containing high concentrations of provitamin A carotenoids, is currently being promoted in Uganda, the second biggest producer of sweet potato in Africa.[5] Consumption of OFSP as an intervention food could potentially tackle vitamin A deficiency, a major public health issue in most developing countries.[6] Processed products containing OFSP have been studied in Kenya[7] and it has been shown that porridge made using OFSP flour was widely accepted by consumers. However, information on how well provitamin A survives processing is still patchy. In OFSP, *all-trans*-BC represents about 80−90% of total carotenoids.[8,9] Bechoff et al.[10,11] investigated provitamin A losses during drying and storage of OFSP in Uganda and Mozambique: drying (sun or solar) had little effect on the provitamin A content in OFSP (less than 20%), while storage had the greatest effect in reducing the level (70% after four months). A further factor is potential losses during cooking. It was noted that addition of flour resulted in favorably higher provitamin A content than with the other types of addition.[12] However, these earlier studies were undertaken in the laboratory. There is a need to explore the variations in carotenoid retention that take into consideration the actual variation in processing conditions that occur in the field. Therefore, more investigations are needed to determine the levels and variability of carotenoid retention after local cooking of sweet potato flour in different commonly consumed products.

Furthermore, an estimate of the carotenoid bioaccessibility of these products produced under field conditions should give a better understanding of how much of the provitamin A is absorbed by the body. The bioaccessibility of fat-soluble nutrients such as carotenoids is the proportion released from the food matrix and solubilized in mixed micelles and therefore available

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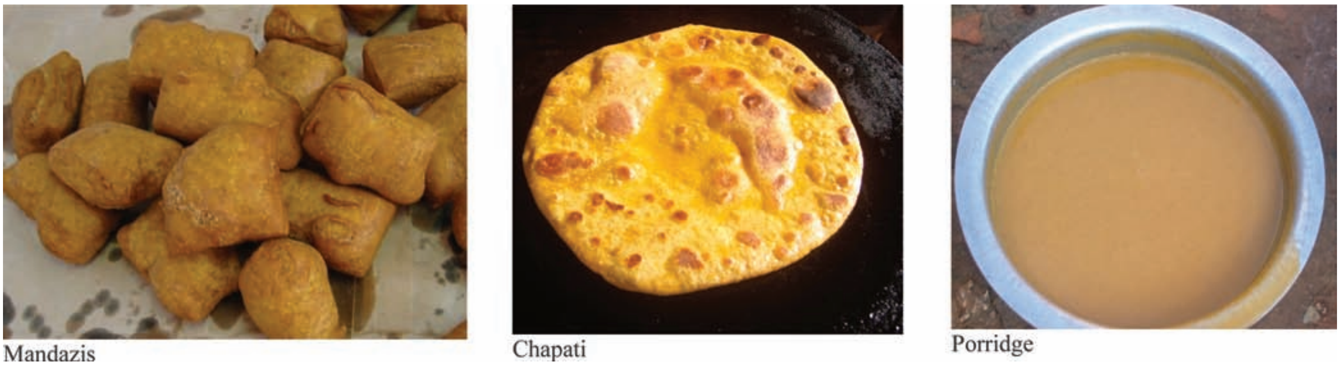

Figure 1. Mandazis, chapatis, and porridge made with 30% OFSP, in Uganda.

for absorption by intestinal cells.[13] The BC bioaccessibility in boiled OFSP was studied by several authors.[14−16] These authors also demonstrated that *all-trans*-BC bioaccessibility was low and appeared to be bound with the matrix. These authors also demonstrated that the addition of oil significantly improved the efficiency of carotenoid micellarization. Although the application of this work was aimed at tackling vitamin A deficiency in Africa, processing was carried out with cultivars different from those of African countries and under controlled laboratory conditions, which differ from the actual conditions encountered in sub-Saharan Africa. Hence, there was a need for more research on the bioaccessibility of BC in OFSP products prepared under local processing conditions and using varieties and products that are commonly consumed in African countries where vitamin A deficiency is an issue.

The present study aims to discover the levels of degradation and BC bioaccessibility in the ready-to-eat OFSP-derived products made under local processing conditions. The preparation (i.e., drying) and cooking process (either by boiling or frying) were conducted under noncontrolled (but monitored) conditions in Uganda. This work aims to promote the marketing and consumption of blended food from OFSP and other locally grown crops, contributing to income generation, the use of locally available crops, and ultimately reducing vitamin A deficiency without the use of medical supplements.

■ MATERIALS AND METHODS

Root Samples. Mature sweet potato roots (Ejumula) (about 80 kg) were purchased from a farmer association (Bagya Basaga Potato Growers and Processors) in Bombo, Luwero. Ejumula is a Ugandan landrace with light skin and orange flesh having a typical *all-trans*-BC content of 60−100 μg g^{-1} on a fresh weight basis.[9] The exact root harvest age was not known, but they were of marketable quality. Roots were processed within 2 days after harvest.

Drying and Milling. Sun/solar (tunnel) dryers were used to dry the sweet potato chips.[10] The flour for making porridge was a blend of OFSP chips (30%), roasted white-yellow maize (35%), and roasted soybean (35%). Soybean and maize were supplied by East African Basic Foods, Kampala, Uganda. The flour for making chapatis and mandazis contained milled OFSP chips (30%) blended with pure wheat flour (70%) (purchased locally at Asam). The choice of the proportion of OFSP flour (30%) was based on previous works.[4,12,17,18]

Processing into OFSP-Derived Products. Chapati volunteer street vendors (n = 10) in the surroundings of Kampala were provided with OFSP-enriched flour and asked to cook chapatis. These were small-scale businesses (one or two persons) that typically made chapatis daily. They all used similar equipment and ingredients—charcoal stove with a frying pan and wheat flour, water, and oil—and mostly sold their product to passers by the road side. For the purpose of our study, each processor was given ingredients to make chapatis, being 500 g of blended wheat:OFSP flour (70:30), oil, and water (according to their needs, up to 200 and 400 mL, respectively). The recipe used by the street vendors was similar to that described by Owori.[18] In our study, pure sunflower oil, which was provided to processors, did not contain vitamin A.[19]

Households (n = 10) in the surroundings of Kampala who normally made porridge were given two 100 g quantities of maize:soybean:OFSP flours (30:35:35) to make porridge. The recipe was similar to that described by Owori et al.[18] All households had similar equipment: charcoal stove, aluminum sauce pan, kettle, and wooden spatula. They all used a similar technique of cooking: mixing flour with cold water and then adding boiling water while the mixture is on the stove

Mandazis were prepared by a local processor who used the same ingredients as for chapatis [wheat:OFSP flour (70:30), water and oil].[18] Mandazis differed from chapatis in that they were smaller and square in shape and they were deep-fried in hot oil preheated at 175 °C for 6 min. While chapatis are similar to large pancakes, mandazis are more like square and spongy cakes (Figure 1). OFSP roots harvested in Uganda (Ejumula variety) were peeled, cut in equal-sized pieces, and boiled 18 min in tap water in a pot without lid. Boiled OFSP were then blended using a Thermomix TM 31 Vorwerk into a homogeneous puree. Samples were stored in amber glass bottles and kept frozen at −20 °C until analysis.

Storage of Samples. On location in the field, chapatis (n = 3; the first three chapatis produced by each processor), porridge samples (n = 2; 100 mL, twice per household), and mandazis (n = 3; one processor only) were immediately collected after cooking and transferred to a cool box with frozen gel packs. On the same day at the laboratory, samples were transferred to a freezer. All samples were stored at −20 °C in separate plastic bags during transport between Uganda and Europe (UK and France). Samples were collected for dry matter determination at the same time as for carotenoid analysis. Determinations were made by drying triplicate 5 g samples at 105 °C to a constant weight (minimum 24 h).[20]

In Vitro Digestion. The in vitro digestion system was based on previous studies.[13,21] Triplicate samples (0.5 g for chapati and mandazi, 20 g for porridge, and 3 g for boiled OFSP, respectively) were mixed in saline solution (0.9% NaCl). This mixture was homogenized for 10 min at 37 °C in a shaking water bath. To mimic the gastric digestion, the pH was adjusted to 4.00 ± 0.02 with 1 M NaOH, followed by the addition of 2 mL porcine pepsin (40 g L^{-1} in 0.1 M HCl). The homogenate was incubated at 37 °C in a shaking water bath for 30 min. To mimic the intestinal step, the pH of the partially digested mixture was raised to 6.00 ± 0.02 by adding around 20 mL of 0.45 M sodium bicarbonate pH 6.0. Then a mixture of porcine bile extract and pancreatin (9 mL

Table 1. Characteristics of Chapatis (Made out of 500 g of Part OFSP[a] Flour) per Processor (10)[b]

								individual chapati					
processor	initial temperature (°C)	maximum temperature (°C)	frying time per chapati (min)	amount of water (mL)	amount of oil (mL)	number of chapatis cooked together	total number of chapatis made	weight (g)	thickness (mm)	diameter (mm)	dry matter (%)	*all-trans*-BC ($\mu g\ g^{-1}$ on a fresh weight basis)	TR[c] (%)
1	88	116	3	400	100	1	16	50.7 ± 0.4	2.8 ± 0.4	155.0 ± 5.0	62.5 ± 0.01	30.3 ± 3.2	81.3 ab
2	85	120	2	390	135	1	12	73.3 ± 2.4	2.8 ± 0.4	178.3 ± 4.4	64.4 ± 0.01	30.1 ± 0.3	87.6 ab
3	78	122	1.5	355	90	2	6	141.0 ± 1.0	4.2 ± 0.6	185.0 ± 2.9	60.1 ± 0.00	31.8 ± 0.9	89.0 ab
4	85	139	1	325	90	1	13	68.0 ± 3.1	2.8 ± 0.4	165.0 ± 2.9	63.8 ± 0.00	33.1 ± 2.2	96.9 a
5	90	130	2	350	110	1	10	84.7 ± 0.7	3.3 ± 0.4	163.3 ± 1.7	65.1 ± 0.00	30.4 ± 0.6	85.1 ab
6	61	120	0.6	320	170	5	6	139.3 ± 3.5	3.8 ± 0.4	191.7 ± 1.7	65.4 ± 0.01	27.6 ± 0.1	76.2 b
7	80	190	2	350	100	2	5	156.0 ± 12.2	3.7 ± 0.4	206.7 ± 3.3	65.6 ± 0.01	31.6 ± 0.8	81.5 ab
8	80	183	1	350	100	5	6	139.3 ± 2.7	3.8 ± 0.2	211.7 ± 1.7	64.7 ± 0.01	30.4 ± 0.8	84.0 ab
9	89	134	2	350	100	1	10	86.7 ± 3.7	3.0 ± 0.3	170.0 ± 0.0	62.9 ± 0.01	28.6 ± 1.1	81.8 ab
10	76	178	1	300	170	4	12	64.7 ± 1.8	2.3 ± 0.2	175.0 ± 2.9	72.1 ± 0.01	27.2 ± 1.3	69.7 b
average[d]	81 ± 8	143 ± 29	1.6 ± 0.7	349 ± 30	116 ± 31	2	10 ± 4	100.4 ± 39.1	3.3 ± 0.6	180.2 ± 18.6	64.7 ± 3.1	30.1 ± 1.9	83.3 ± 7.3

[a] Ejumula variety. [b] Weight, thickness, dry matter, *all-trans*-BC, and TR average ± standard deviation were calculated over three chapatis. In the last column, significant differences at $p < 0.05$ (Tukey test; ANOVA) are indicated by different letters. [c] TR = True retention of *all-trans*-BC. [d] Average ± standard deviation over 10 processors.

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Table 2. Characteristics of Porridge (Made out of 100 g of Part OFSP[a] Flour) from the Household (10)[b]

household	maximum temperature (°C)	duration of cooking per porridge (min)	volume of porridge after cooling (mL)	dry matter (%)	*all-trans*-BC (μg g^{-1} on a fresh weight basis)	TR (%)[c]
1	89	5.0 ± 0.8	875 ± 102	9.9 ± 0.01	5.5 ± 1.5	74.0a
2	88	5.8 ± 0.2	675 ± 20	13.6 ± 0.01	7.6 ± 0.7	80.5a
3	85	4.5 ± 0.8	725 ± 61	13.1 ± 0.02	7.9 ± 3.1	87.4a
4	84	6.5 ± 0.0	625 ± 20	13.3 ± 0.00	7.3 ± 0.0	71.6a
5	81	10.3 ± 1.0	585 ± 29	14.0 ± 0.00	7.8 ± 0.3	71.1a
6	83	9.5 ± 0.0	740 ± 49	11.6 ± 0.01	6.0 ± 1.4	69.2a
7	83	5.8 ± 1.0	775 ± 20	11.5 ± 0.00	6.4 ± 0.1	77.7a
8	83	4.3 ± 0.2	700 ± 41	11.8 ± 0.00	6.7 ± 0.2	74.0a
9	86	6.0 ± 0.0	700 ± 82	14.1 ± 0.00	8.6 ± 1.6	93.0a
10	86	4.5 ± 0.4	825 ± 20	10.6 ± 0.00	6.0 ± 0.5	77.2a
average[d]	83.8 ± 3.7	6.2 ± 2.2	722 ± 107	12.3 ± 1.8	56.4 ± 3.9	77.6 ± 9.5

[a] Ejumula variety. [b] Duration of cooking, volume of porridge, dry matter, *all-trans*-BC and TR average ± standard deviation were calculated over two cooking trials. In the last column, significant differences at $p < 0.05$ (Tukey test; ANOVA) are indicated by different letters. [c] TR = True retention of *all-trans*-BC. [d] Average ± standard deviation over 10 households.

containing 2 g L^{-1} pancreatin and 12 g L^{-1} bile extract in 100 mmol/L trisodium citrate, pH 6.0) and 4 mL of bile extract at 0.1 g/mL were added. Samples were incubated in a shaking water bath at 37 °C for 30 min to complete the digestion process. Micelles were then separated by centrifugation (20 000 rpm for 4 h at 10 °C using a Beckman L755 TST 41-14 SW rotor). The aqueous fraction was collected and then filtered through a 0.22 μm filter (Millipore). Aliquots were stored at −20 °C under nitrogen until analysis.

Carotenoid Analysis. Carotenoid extraction from OFSP flour and cooked products was determined using a method described earlier.[10] True retention (TR) was calculated according to Kidmose et al.[22]

$$\mathrm{TR}\ (\%) = 100 \times \frac{\text{nutrient content per gram of cooked food} \times \text{weight of food after cooking}}{\text{nutrient content per gram of raw food} \times \text{weight of food before cooking}}$$

BC content in the cooked food (mandazi, chapati, or porridge) was expressed relative to the value of BC in the food before cooking (wheat: OFSP flour or maize:soybean:OFSP containing 30% OFSP flour).

To determine the carotenoid retention after in vitro digestion, the filtered micellar phase (10 mL) was extracted three times with 10 mL of hexane (with 0.1% BHT) and 5 mL of ethanol containing 100 μL of recovery standard (β-apo-carotenal). The hexane extracts were evaporated and redissolved in 400 μL of mobile phase [dichloromethane/methyl *tert*-butyl ether (MTBE)/methanol (50:40:10)]. Samples were injected under the analytical conditions described in a previous work.[21] HPLC analyses were performed with an Agilent 1100 System. Carotenoids were separated along a C30 column (250 × 4.6 mm i.d., 5 μm YMC (EUROP GMBH, Germany). The mobile phases were H_2O as eluent A, methanol as eluent B, and MTBE as eluent C. Flow rate was fixed at 1 mL min^{-1}. Absorbance (450 nm) was measured using an Agilent 1100 photodiode array detector.

Fat Content Determination. The fat content was measured in 2 g of freeze-dried mandazi or chapati using accelerated solvent extraction (ASE350-Dionex model)−solid/liquid extraction with PE.[23] Quantification of fat was made gravimetrically after solvent evaporation. Briefly, 2 g of freeze-dried sample was weighed and introduced into a 350ASE cell (22 mL). Extraction was carried out under 100 bar pressure for a duration of 15 min with solvent. After evaporation sample was weighed and the percentage of fat content based on weight difference was calculated.

Statistical Analyses. Data were processed on SPSS (PASW Statistics 17.0) software for Windows using analysis of variance (ANOVA). Differences between factor levels were assessed by a Tukey HSD test ($p < 0.05$). Correlations ($p < 0.01$ and $p < 0.05$) were tested using Pearson tests (two-tailed). Residual distribution plots confirmed the appropriateness of the parametric tests.

RESULTS AND DISCUSSION

The research study was divided in two parts. In the first part, processing was assessed under field conditions using the two most common blended foods, chapatis and porridges. The aim was to understand the effect of variable processing conditions (that differed between processors) on variability in BC content and true retention under field conditions for two contrasting products. BC retention was calculated for mandazis for one vendor only at this stage because it contained similar ingredients to chapati. In the second part, an in vitro bioaccessibility study was carried out using a wider range of OFSP-derived products from Uganda; mandazi and boiled and pureed sweet potato were included in addition to chapati and porridge.

Effect of Processing Conditions on BC True Retention in Chapatis, Mandazis, and Porridges. The characteristics of the chapatis made by 10 different processors (eight men and two women) from three different locations (Bwaise, Kawanda village, Kawanda road side) near Kampala, Uganda, are given in Table 1. True retention of *all-trans*-BC (TR) varied between 69.7 and 96.9% among the 10 chapati processors. The size or weight of chapatis did not influence on TR ($p < 0.05$) and this was probably due to the very similar sizes of the chapati in our study. Kidmose et al.,[22] who worked on the effect of stir frying on TR in several fried vegetables, reported that there was an effect of size on TR only when there were great differences in sizes. There were no significant correlations between the maximum temperature (143 °C in average) and *all-trans*-BC content or TR. Moreover, there were no clear correlations between frying time and TR. Kidmose et al.[22] similarly reported that TR was not affected by frying time. This was believed to result from similar and short frying times, 0.5−2 min used for the vegetables, and agreed with

Table 3. Content of *all-trans*, Epoxy, and *cis*-BC (μg g^{-1} on a Fresh Weight Basis) and Percentage[a] of BC in the Flour (OFSP or Composite) and in the Products Porridge, Chapati, and Mandazi after Cooking[b]

		all-trans		5,6-epoxy		5,8-epoxy		13-*cis*		9-*cis*	
	N[c]	content	%	content	%	content	%	content	%	content	%
maize:soybean:OFSP flour[d]	3	65.0 ± 11.0	89.8	3.9 ± 0.6	5.4	1.1 ± 0.2	1.6	1.6 ± 0.3	2.2	0.7 ± 0.2	1.0
porridge	20	7.0 ± 1.4	77.5	0.4 ± 0.1	4.8	0.3 ± 0.1	3.3	1.0 ± 0.2	11.2	0.3 ± 0.1	3.2
wheat:OFSP flour[d]	3	60.5 ± 4.3	90.4	3.8 ± 0.3	5.7	0.9 ± 0.1	1.3	1.1 ± 0.1	1.6	0.6 ± 0.1	0.9
chapati	30	30.1 ± 2.2	80.9	1.9 ± 0.1	5.0	1.2 ± 0.2	3.1	3.1 ± 0.7	8.2	1.0 ± 0.2	2.8
mandazi	3	32.9 ± 1.7	80.4	1.7 ± 0.3	4.2	1.4 ± 0.3	3.4	3.6 ± 0.4	8.8	1.3 ± 0.2	3.2

[a] The percentage of BC was calculated as the compound content over the total BC content (that included *all-trans*-BC + 5,6-epoxy-BC- + 5,8-epoxy-BC + 13-*cis*-BC + 9-*cis*-BC). [b] For the same compound, significant differences (ANOVA Tukey test; $p < 0.05$) are indicated by different letters. [c] N = number of carotenoid extractions from the product. Average ± standard deviation. [d] Blend containing 30% OFSP.

our results (1.6 min in average). While the amount of water added to the dough did not influence TR, the dry matter of the cooked chapati was correlated to TR ($R = -0.681$, $p < 0.05$). The dry matter content of the product was also correlated to the quantity of oil ($R = 0.724$, $p < 0.05$). This correlation could be explained by substitution of the moisture in the product by oil during frying.[17] In addition, the *all-trans*-BC content and TR in chapatis were negatively correlated to the quantity of oil used ($R = -0.816$, $p < 0.05$ and $R = -0.723$, $p < 0.01$ respectively). A significant degradation of carotenoids in oil was previously reported[24] working with pure BC in a deep-frying controlled system, but the frying times were longer (up to 30 min at 180 °C and up to 120 min at 120 °C). Another more probable explanation[22] would be that some of the carotenoids are lost by transfer into the oil, since they are fat soluble. The wide TR variation between the processors could be mainly attributed to variations in oil and water contents.

The average *all-trans*-BC content in chapatis was 30.1 μg g^{-1} with an average TR of 83.3% over 10 processors. As a comparison, the retention of BC in mandazi (made from the same ingredients as chapati) by only one processor was 85% (varying from 80 to 89%). There is clear evidence in some reports[12,25,26] that the cooking process for bread, mandazi, and chapati can reduce the level of carotenoids in the products eaten by consumers. Nonetheless, Hagenimana et al.[12] indicated that the amount of provitamin A after making chapatis and mandazis made either out of raw−grated or boiled−mashed OFSP or OFSP flour was still significant (15, 11, and 23 μg g^{-1}, respectively, for chapatis and 15, 16, and 21 μg g^{-1}, respectively, for mandazis on a fresh weight basis), and this was in agreement with our study.

The characteristics of the porridges made by 10 different households (10 women) from Kawanda village are given in Table 2. Cooking porridges resulted in a similar level of *all-trans*-BC retention (77.6% in average) to that of chapatis ($p < 0.05$), and this was probably because of the variability in retentions obtained under field conditions. Our porridge was reported to have similar cooking time (6 min on average) to the millet porridge, whereas the maize porridge, the most commonly consumed in this area, took longer (typically 30 min). The maximum temperature (85 °C) and duration of cooking without oil did not significantly affect TR, although there was a trend. The volume of porridge did not affect TR but dry matter did: porridges with lower dry matter contents retained less *all-trans*-BC ($R = 0.532$, $p < 0.05$ over 20 cooking trials, two per household). The lower retention in more liquid porridges could possibly be explained by increased heat damage to carotenoids caused by their greater dispersion in boiling water.

Changes in *all-trans*-BC and Minor Carotenoids after Processing of Porridges and Mandazi. Table 3 reports levels of *all-trans*-BC in the 30% OFSP flour and in the cooked products. There were no significant differences between the contents in *all-trans*-BC of composite flour [maize:soybean: OFSP (35:35:30)] and of OFSP flour [wheat:OFSP (70:30)] and between mostly other minor compounds, 5,6 epoxy-BC, 5, 8-epoxy-BC, and 9-*cis*-BC. The lack of difference between the BC contents in both blended flours confirmed that the proportion of 30% OFSP flour was consistent in the composite flour and the addition of soybean and maize did not make a significant impact on the level of these compounds.

The percentages of *all-trans-* and of 5,6-epoxy-BC over total BC were significantly lowered after processing into porridge, chapatis, and mandazi. These trends were in accordance with earlier papers[11,27] that showed that *all-trans*-BC and 5,6-epoxy-BC were affected during the storage of dried chips at ambient temperature with 5,6-epoxy-BC having a slower degradation rate than *all-trans-β*-carotene.

In contrast, percentages of 5,8-epoxy-BC, 13-*cis*-BC, and 9-*cis*-BC significantly increased after processing into porridge and into chapatis and mandazis (Table 3). These results under field conditions demonstrated that processing favors cis-isomerization and formation of 5,8-epoxy-BC. It was demonstrated under laboratory conditions[28] that the preferentially formed cis-isomers from *all-trans-β*-carotene in the orange-fleshed sweet potato variety Jewel (raw, 90 μg g^{-1} on a fresh weight basis) are 13-*cis*-BC and 9-*cis*-BC. When applying various processes (blanching, canning, lye peeling, pureeing, dehydrating, microwaving, baking), 13-*cis*-BC was found to be predominant, in accordance with this field study. The higher proportion of cis-isomers in porridge as compared with chapati and mandazi might have resulted from longer cooking. Nonetheless, working on storage of dried orange-fleshed sweet potato, authors[11] observed that 5,8-epoxy-, 13-*cis*-, and 9-*cis*-BC decreased with time, but at a lower rate than *all-trans*-BC and 5,6-epoxy-BC. Therefore, evolution of cis-isomers and 5,8-epoxy in dried sweet potato is different when processed into porridge or chapati or when stored. Cis-isomerization is reported to occur in provitamin A carotenoids at temperatures above 35 °C.[29]

Bioaccessibility of *β*-Carotene in Various OFSP Food Products. Bioaccessibility of carotenoids, as measured by their transfer into micelles, was evaluated using an in vitro digestion procedure. Fat matter, BC content, and bioaccessibility in OFSP food products are reported in Table 4. Chapati and mandazi

Table 4. Fat Percentage, BC Content in OFSP[a] Food Products, BC Bioaccessibility of *all-trans*- and 13-*cis*-BC during Simulated Digestion, and Estimation of Vitamin A Activity in Products Cooked from OFSP Flour To Take into Account in Vitro Digestion

							recommended daily allowance (RDA)[d]					
		BC content (μg g^{-1})[b]		BC bioaccessibility (%)[c]			classical estimate[e]			estimate taking into account bioaccessibility (in vitro digestion of product)[f]		
OFSP[a] product	fat percentage (%)[b]	*all-trans*	13-*cis*	*all-trans*	13-*cis*	unit	μg RAE per unit	%RDA child <6 years (to meet 400RE)	%RDA pregnant/lactating mother (to meet 800RE)	μg RE per unit after in vitro digestion	%RDA child <6 years (to meet 400RE)	%RDA pregnant/lactating mother (to meet 800RE)
boiled OFSP	–	95.0 ± 2.4	7.4 ± 0.2	9.9 ± 0.1	43.5 ± 4.5	puree portion (100 g)	816.2	204	102	183.7	46	23
porridge	–	8.7 ± 0.3	1.2 ± 0.1	16.3 ± 0.9	30.3 ± 6.1	1 mug (300 g)	232.2	58	29	80.0	20	10
chapati	7.4 ± 1.0	31.5 ± 1.4	2.5 ± 0.5	72.7 ± 5.4	96.2 ± 5.9	1 chapati (100 g)	272.9	68	34	401.7	100	50
mandazi	3.3 ± 0.2	32.9 ± 1.7	3.7 ± 0.4	49.0 ± 3.0	98.1 ± 7.7	~2 mandazis (90 g)	289.6	73	36	289.6	75	34

[a] Ejumula variety. [b] Average ± standard deviation (over three extractions). Fat percentage and BC content are expressed on a fresh weight basis. [c] Micellarized carotenoids. Average ± standard deviation (over nine replicates: three extractions and three digestions per extraction). [d] RDA: recommended daily allowance. Source: ref 37. [e] RAE: retinol activity equivalent. Classical estimate = [*all-trans*-BC content/12 + 13-*cis*-BC content/24] × unit (g). [f] RE: retinol equivalent. Estimate taking into account bioaccessibility = [(*all-trans*-BC content × % bioaccessibility/6) + (13-*cis*-BC content × % bioaccessibility/12)] × unit (g).

presented similar contents of *all-trans*-BC (31.5 and 32.9 μg g^{-1}), whereas that of porridge was only 8.7 μg g^{-1}. Between the different OFSP products, boiled OFSP had the highest *all-trans*-BC content (95.0 μg g^{-1}). In terms of relative area percentage, the 13-cis-isomer represented between 8 and 14% in the cooked products, including boiled sweet potato, and this was in agreement with van Jaarsveld et al.,[30] who found that *all-trans*-BC content remains relatively high in boiled mashed sweet potato (TR = 83–92%) and the 13-cis-isomer represented 12%.

After in vitro digestion, the percentage of micellarized *all-trans*-BC from boiled OFSP was the lowest (9.9%) as compared with the others products. The relatively poor in vitro bioaccessibility of *all-trans*-BC from boiled OFSP was in line with previous studies on OFSP.[14–16] Failla et al.[14] investigated the bioaccessibility of BC from eight OFSP cultivars. It was reported that *all-trans*-BC micellarization during simulated digestion of boiled OFSP was very low, varying between 0.5 and 3% in the different cultivars, and was independent of the amount of BC and this was believed to result specifically from the food matrix structure of OFSP. Although the matrix of OFSP may limit the bioaccessibility, the higher micellarization efficiency of *all-trans*-BC found in our study was probably due to the varietal specificity of the Ejumula cultivar. Working with an Israeli cultivar under the same conditions, we found that BC bioaccessibility was only 3% (data not shown). BC bioaccessibility of the Israeli cultivar was 3 times less than that obtained with the Ejumula cultivar, and this could have possibly resulted from a different food matrix and higher moisture content.

The micellarization efficiency was better for 13-*cis*-BC than for *all-trans*-BC (43.5% and 9.9% in average, respectively). This more efficient incorporation of 13-*cis*-BC as compared with the all-trans form was previously observed[31] and is also in agreement with authors who worked with OFSP.[14,15]

With reference to cooking methods, the efficiency of micellarization of *all-trans*-BC was greater in products cooked with oil, chapati (73%) and mandazi (49%), as compared with the boiled ones, porridge (16%) and purée (9.9%). It clearly appears that the presence of fat during the preparation of chapati and mandazi improves the bioaccessibility of BC isomers. The fact that addition of oil prior in vitro digestion enhances carotenoids micellarization is widely supported by several authors. According to the study,[16] the addition of fat prior to cooking or during cooking porridge did increase incorporation of BC, whereas the addition of oil after cooking porridge did not. In our study, oil was added during cooking. The stir-frying procedure in particular seems to enhance carotenoid micellarization. Garrett et al.[32] observed that stir-frying compared to cooking without oil enhanced the micellarization of lycopene from tomato paste. More recently, Veda et al.[33] reported that the stir-frying method showed the maximum increase in the bioaccessibility of β-carotene from carrot (81%) compared to open–pan boiling (36%). Among the two products cooked with oil, BC bioaccessibility was higher in chapati (72.7%) than in mandazi (49%) and could be explained by the difference in fat matter content determined in the food product: chapatis contained the most fat (7.4%) followed by mandazi (3.3%).

all-trans-BC bioaccessibility of porridge was slightly higher than in purée from boiled OFSP (Table 4). The percentage of micellarization of *all-trans*-BC for OFSP porridge found here was similar to that found in porridge prepared from maize flour[34] (16.3% and 16.7%, respectively). In our study, *all-trans*-BC from porridge made from OFSP flour was more bioaccessible than that from boiled OFSP. The difference in bioaccessibility could also possibly be explained by the damaging effect of drying on sweet potato cell: a close relationship between OFSP cell integrity and bioaccessibility has been recently demonstrated by Bengsston et al.[16] by comparing boiled OFSP and freeze-dried samples made into porridge.

Estimation of Vitamin A Activity in OFSP-Derived Products To Meet Nutritional Requirements. Estimation of vitamin A activity in OFSP food products consumed in Uganda are presented in Table 4. Using a classical estimate from food, retinol activity equivalent (RAE) was calculated using the conversion factor 12 μg g^{-1} *all-trans*-BC or 24 μg g^{-1} minor carotenoids corresponding to 1 RAE g^{-1}.[35] When bioaccessibility was taken into account, the conversion factor applied was that of retinol equivalents (RE): 6 μg g^{-1} *all-trans*-BC or 12 μg g^{-1} minor carotenoids correspond to 1 RE g^{-1}. That is because in the calculation of RAE, bioavailability was already included.

Using the classical estimate, one mug of porridge (300 g) and one chapati (100 g) would bring similar amounts of vitamin A activity to the diet, respectively 58% and 68% of the RDA of a child under six year old (400 RAE) and 29% and 34% of the RDA for pregnant and lactating mothers (800 RAE). On the other hand, when bioaccessibility was considered, estimates for porridges and chapatis were different: respectively 20% and 100% of the RDA for children and 10% and 50% of that for mothers. An exception is mandazi, however: using the classical estimate or the estimate taking into account bioaccessibility did not affect much the calculation of RDA. This was due to the fact that the BC bioaccessibility of mandazi was 50%. Altogether these results showed that classical estimates of RAE were overestimated for boiled OFSP and porridge but were underestimated for chapati and highlighted that BC bioaccessibility is critical in the process of establishing the vitamin A activity of a particular food product.

Estimate taking account of bioaccessibility indicates that a 100 g portion of the OFSP purée without added fat could provide 46% of the daily vitamin A requirement of a child under 6 years. Comparatively, 100 g of porridge ($^1/_3$ cup) would only provide 6%. These results suggest that consuming a purée made from 100% OFSP is more profitable for a child than consuming porridge made with 30% OFSP flour.

In a review of current published work, Burri[6] extrapolated on how much OFSP would be required to meet the needs of different class ages in vitamin A in developing countries. The calculation took into account the losses after processing, bioaccessibility, and vitamin A status of the individuals (well or poorly nourished). However, as compared with our results, the amounts of OFSP predicted by Burri[6] to meet 100% RDA were underestimated (about 50 g for children who require 400 μg g^{-1} day^{-1}). This shows that model predictions based on average losses are very difficult to make.

In our work, the quantities of OFSP consumed in order to meet the RDA requirements are based on well-nourished individuals. Nevertheless, Howe and Tanumihardjo[36] and Burri [6] reported that poorly nourished people convert more β-carotene and therefore their OFSP intake requirements shall be lower. Further investigation is needed to estimate what would be the nutritional requirements of poorly nourished people for these OFSP-derived products.

This study examined the "natural" variability of β-carotene retention on products made by different local processors and households in Uganda. True retention (TR) was similar for chapatis and porridges, in spite of the difference in the processing technique. As regard to porridges, the more liquid samples had lower TR; therefore, the thicker porridges should be preferred. In addition, a higher concentration of flour in the porridge would increase the *all-trans*-BC content. Oil had a dual effect. There was a negative correlation between oil addition and TR. On one hand, using less oil could help retain more carotenoids in the product and also reduce costs (oil is the most expensive ingredient in the preparation of chapatis). On the other hand, BC bioaccessibility was enhanced in products containing more oil.

The BC bioaccessibility in fried products (chapatis and mandazis) was a lot greater than that in boiled products (porridge and puree). The average RDA for an adult is intermediate between those of children and pregnant/lactating mothers, being about 600 RE.[37] It was reported that the average adult consumption in Kampala is two mugs of porridge and two chapatis (G. Menya, personal communication). This consumption would equal to more than the recommended daily allowance (RDA) (150%) in the case of chapatis and to 30% of RDA in the case of porridge. With a preference for chapatis, however, both of these commonly consumed products could bring a significant vitamin A intake to the diet of people in Uganda.

In conclusion, these results highlight the importance of OFSP flour-derived products as a significant source of vitamin A. This study suggested that promotion/marketing of products made with flour from locally grown OFSP in Uganda could contribute to decreasing vitamin A deficiency.

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DISCLOSURE

The views expressed are those of the authors.

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