# Glycemic Index and Microstructure Evaluation of Four Cereal Grain Foods

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**Abstract:** To determine the glycemic index (GI) of selected cereals and association with their microstructure. The GI of whole grain *pilaf* (WGP), instant brown rice (IBR), whole maize *ugali* (MWU), and refined maize *ugali* (RMU) was assessed in a randomized trial. Fourteen healthy participants with mean age of 25 years were administered 50 g portions of available carbohydrates from glucose and various test foods after an overnight fast on separate occasions. Capillary blood samples of participants were used to measure blood glucose over 2 hr. The GI was calculated as per standard protocol. The microstructure of test foods, determined by scanning electron microscopy was evaluated to understand the measured GI values. The GI (mean ± standard error) of IBR was the highest (87.8 ± 6.8) followed by RMU (74.7 ± 6.5) and WMU (71.4 ± 5.1). WGP had medium GI (58.9 ± 5.1; $P < 0.01$ vs. IBR). Microstructure examination of IBR revealed disruption of bran layer and presence of fissures indicating loss of intactness of bran. Stereozoom images for WGP revealed intact bran and germ. For RMU and WMU, the grain was milled leading to loss of integrity. IBR, RMU, and WMU have high GI values, which is likely due to disruption of bran layer, endosperm modification (IBR), and loss of grain matrix (WMU, RMU). WGP has medium GI probably due to fairly intact bran and germ.

**Keywords:** food processing, grain matrix, microstructure, refined flour, stereozoom, whole grains

**Practical Application:** Wholegrain or whole meal flour may not necessarily be low in glycemic index (GI; low GI < 55; medium 55 to 69 and high GI ≥70). "Ugali" a commonly consumed cereal staple food in Tanzania made from either refined or whole meal maize flour was found to be a high GI food. Intact whole grain foods, such as whole grain pilaf (mixed intact whole grains) is a healthier alternative to milled whole grains such as whole meal maize flour. Instant quick cooking brown rice exhibited a high GI, due to the processing method, suggesting that regular brown rice may be a healthier option.



## Introduction

Dietary carbohydrates are the primary source of blood glucose. The concept of the glycemic index (GI), introduced by Jenkins et al. (1981), is established as a useful tool to assess the quality of carbohydrates in foods. Foods with high GI values elicit a higher peak in postprandial blood glucose during the first 2 hr after consumption of a meal (Foster-Powell, Holt, & Brand-Miller, 2002). Studies have shown a positive association between high GI and glycemic load (GL) diets and the risk of chronic diseases such as type 2 diabetes (T2DM) and cardiovascular disease (Bhupathiraju et al., 2014; Liu et al., 2000). A meta-analysis on low GI diets in the management of diabetes showed that replacing conventional or high GI foods with low GI foods could have clinical advantage on glycemic control (Brand-Miller, Hayne, Petocz, & Colagiuri, 2003).

Cereals form the main staple of diets in most parts of the world, contributing more than 50% of daily dietary calories (Awika, 2011). Refined cereals such as white rice tend to exhibit high GI values compared with whole grains such as brown rice (Shobana et al., 2011, 2017), which are associated with a lower risk of T2DM (Sun et al., 2010). A healthier approach would be to replace refined carbohydrates (refined grains) with intact wholegrains to reduce the GI and GL of the food/meal/diet (Augustin et al., 2015; Jenkins et al., 2014). Intactness of the natural grains matrix and the change in the microstructure created during processing (disruption) can be evaluated by microscopic technique (Parada & Santos, 2016) to better understand the measured GI of various grains. Implementing a diet that is rich in whole grains (preferably intact) in place of refined grains could be a cost-effective, feasible, and a sustainable approach for diabetes prevention, especially in low- and middle-income countries undergoing epidemiological transition (Malik et al., 2019; Mattei et al., 2015; Augustin et al., 2015; Mohan et al., 2014; Hu, Pan, Malik, & Sun, 2012).

*JFDS-2019-0581 Submitted 5/17/2019, Accepted 10/14/2019.* *Authors are with RamyaBai, Shanmugam, Arumugam, Nagarajan, Vasudevan, Gunasekaran, Rajagopal, Anjana, Unnikrishnan, Malleshi, Anjana, Unnikrishnan, Malleshi, Krishnaswamy, Mohan, Sudha are with Madras Diabetes Research Foundation, Dr. Mohan's Diabetes Specialities Centre, WHO Collaborating Centre for Non-Communicable Diseases, Gopalapuram, Chennai, India. Author Spiegelman is with Dept. of Biostatistics, Harvard T.H. Chan School of Public Health, Boston, MA, USA. Authors Spiegelman, Hu, and Willett are with Dept. of Epidemiology, Harvard T.H. Chan School of Public Health, Boston, MA, USA. Authors are with Wedick, Malik, Hu, and Willett are with Dept. of Nutrition, Harvard T.H. Chan School of Public Health, Boston, MA, USA. Author Njelekela is with Dept. of Physiology, Muhimbili Univ. of Health and Allied Sciences, Dar es Salaam, Tanzania. Author Gimbi is with Dept. of Food Science and Nutrition, Sokoine Univ. of Agriculture, Morogoro, Tanzania. Author Henry is with Clinical Nutritional Sciences, Singapore Inst. for Clinical Sciences, Brenner Centre for Molecular Medicine, Medical Drive, Singapore. Direct inquiries to author Sudha (Email: s2r_7@mdrf.in).*

A Publication of the Institute of Food Technologists
Journal of Food Science


doi: 10.1111/1750-3841.14945

This premise led to the development of the Global Nutrition and Epidemiology Transition (GNET) initiative, a collaborative research project launched by researchers from the Departments of Epidemiology and Nutrition at the Harvard T.H. Chan School of Public Health along with nutrition and diabetes investigators across the globe, with the ultimate goal of helping prevent the global diabetes epidemic by improving the carbohydrate quality of staple foods. Hence, low- and middle-income countries with early and ongoing epidemiological transition such as Africa (Tanzania, Nigeria, Kenya), Costa Rica, Puerto Rico, Mexico, Brazil, Iran, India, and Malaysia, were included in the GNET countries. As part of the GNET initiative, to understand the glycemic properties of the local traditional cereal staples choices in these countries and also the contemporary newer whole grain products in the market, the four cereal grains were chosen–"Ugali" with refined and whole grain maize flour, multigrain whole grain "Khashi Pilaf" and "Instant Brown Rice." Determining the glycemic index of these grains will enable us to plan subsequent proof-of-concept dietary intervention studies by replacing refined grains with whole grains and foods with reduced glycemic index and glycemic load for prevention of diabetes. This study focuses on the estimation of GI of selected cereal staples of interest to the GNET countries; and microscopy evaluation was further considered to understand the relation between GI and food microstructure.

## Materials and Methods

### Subjects

Healthy participants ages 18 to 45 years were recruited from the volunteer registry of the Glycemic Index Testing Centre at the Madras Diabetes Research Foundation (MDRF) in Chennai, India. Overweight and obesity [body mass index (BMI) $\geq 23.0$ kg/m$^2$ as per the Asia Pacific guidelines (WHO, 2000), use of any special diets for therapeutic or other purposes, family history of diabetes, chronic illnesses like CVD, hypertension, cancer, etc., pregnancy and lactation, history of food allergy, concurrent use of any medications (Ranawana, Henry, 2011; Radhika et al., 2010) and fasting blood glucose value >5.6 mmol/L (100 mg/dL) were considered as the exclusion criteria (Alberti & Zimmet, 1998). A total of 15 participants meeting the inclusion criteria volunteered to participate in the study.

Anthropometric measurements including height, weight, and waist circumference were taken in the fasting state using standardized techniques (Deepa et al., 2003). The study was conducted according to the guidelines outlined in the Declaration of Helsinki, and was approved by the Ethics Committee of Madras Diabetes Research Foundation (MDRF). All subjects gave written informed consent before participation. The study has been registered in the Clinical Trial Registry of India (CTRI) and the reference number is REF/2016/11/012671.

### Test foods

Four foods were selected for this study: (1) Kashi 7 whole grain *pilaf* (WGP, a blend of minimally processed whole grains which include oats, long grain brown rice, rye, hard red winter wheat, triticale, buckwheat, barley and sesame seeds cooked to a semi-solid softer texture porridge; commercial market sample); (2) instant brown rice (IBR, Uncle Ben's Whole Grain Fast & Natural Instant Brown Rice [commercial market sample]); (3) refined maize *ugali* (RMU, stiff porridge made from refined maize flour and consumed as a staple in Tanzania and many other parts of East Africa); (4) and whole maize *ugali* (WMU, a whole grain version of the typically consumed staple made from whole maize milled flour). The available carbohydrate contents of these food samples were determined using an enzymatic kit (Megazyme Limited, Ireland which adopts AOAC 2017.16 method for dietary fiber and AOAC 999.03 for sucrose) (AOAC, 2016). The macronutrient compositions were determined by standard American Association of Cereal Chemists methods (AACC 2000). Dietary fiber content was analyzed as per the method of Asp, Johansson, Hallmer, and Siljestroem (1983), and amylose concentration was estimated using the methods of Sowbhagya and Bhattacharya (1979). The amount of available carbohydrate was standardized in all test foods. Participants were provided with a standard portion of test foods containing 50 g of available carbohydrate. The available carbohydrate content (per 100 g) of WMU, RMU, IBR, and WGP were 72, 79, 68, and 65 g, respectively (Table 1). WMU and RMU were prepared using standard cooking methods whereas IBR and WGP were prepared using the cooking instructions provided on the food label as shown in Table 2.

### Experimental protocol

It is a randomized control study, where the participants were randomized using computer-generated randomized tables and were given the test food accordingly. The reference food trial was performed at the first, last, and middle of the sequence of the test foods. The GI protocol was adopted from Brouns et al. (2005) and is in agreement with the procedure recommended by the FAO/WHO. (1998). The protocol was validated with an international laboratory that was involved in an inter laboratory study (Wolever et al., 2008) reported elsewhere (Henry et al., 2008). Participants visited the GI testing centre each day in the morning after a 10- to 12-hr overnight fast. An interviewer-administered questionnaire with details on the previous day's meals (24-hr dietary recall), physical activity, smoking, and consumption of alcohol and caffeine-containing drinks was administered to the participants. Participants were instructed to adhere to their habitual meal pattern on the days prior to the administration of the test foods, and to refrain from any intense physical activity, smoking and consumption of alcohol during the entire period of the study. Fasting capillary blood glucose was estimated twice at an interval of less than 5 min before consumption of the test foods, and the mean of these values served as the baseline value. A Hemocue 201+ glucose analyzer (Hemocue Ltd., Sweden) was used for the measurement of blood glucose. It has been previously validated with the YSI Stat 2300 glucose analyzer, which is considered the gold standard and a reliable method for the measurement of blood glucose (Ranawana, Henry, 2011). Once the fasting blood glucose was estimated, the participants were administered the test food (with the time of first bite considered as 0 min), and the first capillary blood sample was taken exactly 15 min afterwards. Capillary blood samples were further collected at 30, 45, 60, 90, and 120 min. Participants were provided with 200 mL of water along with the test food and an additional 200 mL of water was given during the subsequent 2 hr (Figure 1).

### Reference food

The reference food was 55 g of dextrose (glucose monohydrate-Glucon-D glucose powder, Heinz India (P) Ltd., Mumbai, India) dissolved in 200 mL of water. The reference food was consumed at the beginning, middle, and end of the test food testing period (three visits: days 1, 4, 7). The four test foods (four visits: days 2, 3, 5, 6) were consumed in random order with at least a

**Table 1–Macronutrient content of test foods (g/100 g of uncooked foods).**

| Test food | Moisture (g%) | Protein (g%) | Fat (g%) | Available carbohydrate (g%) | Dietary fiber (g%) | Energy (kcal) | Amylose (g%) |
|---|---|---|---|---|---|---|---|
| Kashi 7 whole grain *pilaf* | 13.2 | 8.4 | 2.6 | 65.0 | 9.0 | 317 | 17.6 |
| Uncle Ben's whole grain fast and natural instant brown rice | 13.0 | 8.0 | 3.0 | 68.0 | 6.0 | 331 | 19.3 |
| Whole maize *ugali* flour | 9.8 | 8.9 | 3.0 | 72.0 | 6.0 | 351 | 22.8 |
| Refined maize *ugali* flour | 9.3 | 5.6 | 1.7 | 79.0 | 4.0 | 354 | 31.1 |

**Table 2–Method of cooking.**[a]

| Test food | Uncooked food sample providing 50 g of available Carbohydrate (g) | Test food to water ratio | Cooking time (min) | Total cooked weight (g) |
|---|---|---|---|---|
| Kashi 7 whole grain "*pilaf*" | 73.5 | 1:2.25[b] | 30 | 160 |
| Uncle Ben's whole grain fast and natural instant brown rice | 76.9 | 1:2[b] | 20 | 193 |
| Refined maize ugali flour | 63.3 | 1:2 flour (g): total water (mL) | 15 | 161 |
| Whole maize ugali flour | 69.4 | 1:2 flour (g): total water (mL) | 15 | 164 |

[a]All of the test foods were prepared by stovetop cooking.
[b]Ratio of test food: Water measured with an Indian household steel cup (steel cup = 120 mL fluid capacity).

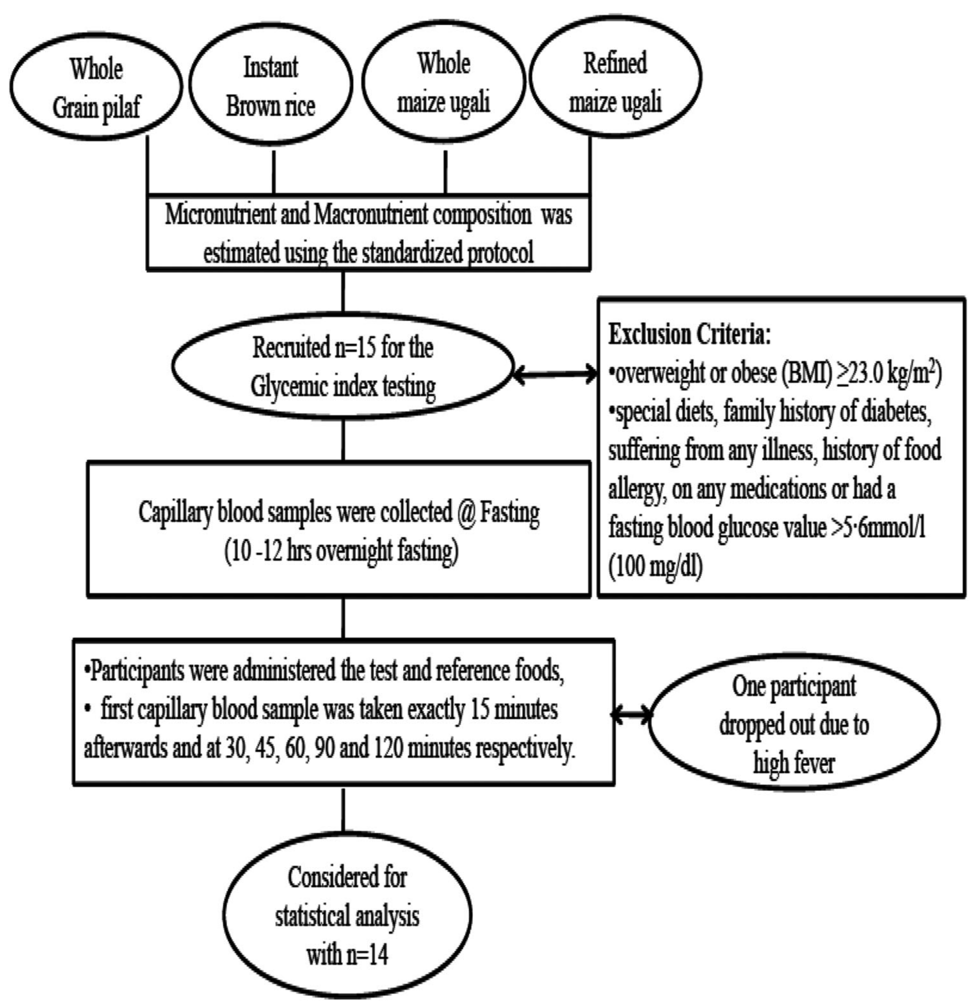


Figure 1–Participant flow diagram. BMI body mass index GI, glycemic index; whole grain pilaf (WGP), instant brown rice (IBR), refined maize ugali and whole maize ugali.

2-day interval between measurements to reduce potential carry-over effects (Brouns et al., 2005).

### Calculation of the GI

The incremental area under the blood glucose response curves (IAUC) of the test and reference foods were calculated geometrically using the trapezoid rule ignoring the area beneath baseline (Brouns et al., 2005). The GI was calculated as the IAUC of a 50 g available carbohydrate portion of the test food expressed as a percent of the response to the same amount of carbohydrate from the reference food taken by the same volunteer.

### Microscopic examination

The IBR kernels were broken open to expose the inner anatomical parts of the grain, mounted on metallic stubs with the aid of a double-sided scotch tape and gold coated (about 100A°) in a KSE 2 AM evaporation Seevac gold sputter (Polaron SEM Sputter Coating System, Hertfordshire, UK). To compare the morphological features, parboiled brown rice (BPT variety, paddy soaked overnight in cold water, steamed at atmospheric pressure for 10 min, dried to 12% moisture, shelled in a rubber roll sheller) was also examined by microscopy as a reference. The samples were scanned using the Carl Zeiss MA15/EVO 18 Scanning Electron Microscope. The bran, aleurone layer of the endosperm, the inner endosperm with special reference to the granular organization of the starch, and the topography of the rice kernels were examined and photographed at different magnifications. Similarly, WMU and RMU flour samples were sprinkled and mounted on metallic stubs and observed using microscopy for the nature of starch and presence or absence of the maize seed coat matter.

All samples were viewed by both scanning electron microscope and stereozoom microscope (Optika, Italy) to study the structural features under high and lower magnifications. However, it was not possible to view WGP by scanning electron microscope due to the mixture of multi whole grains. The microscope analysis was included in this study to enhance the interpretation of the GI values of the test foods.

### Statistical analysis

Of the 15 participants recruited, one dropped out due to unrelated health issues and thus data from 14 participants were considered for the GI estimation and analysis. Descriptive characteristics of the study participants were calculated as mean ± standard deviation for continuous variables and percentages for categorical variables. The GI values were calculated using an in-house GI software based on the method recommended by FAO/WHO (1998). The IAUC mean ± standard error for the reference and four test foods were calculated. Mean differences between the GI of test foods were tested using one-way analysis of variance as the data was normally distributed. Differences in GI between WGP versus IBR/WMU/RMU; IBR versus WMU/RMU; WMU versus RMU were evaluated using paired t-tests. Statistical significance was determined at an alpha level of 0.05. Statistical analysis was performed with SAS software (version 9.1; SAS Inst., Cary, NC, USA).

## Results

The RMU contained the highest amount of available carbohydrate (79 g%) followed by WMU (72 g%), IBR (68 g%), and WGP (65 g%). The reverse order was observed for unavailable carbohydrate or dietary fiber with WGP containing 9 g%, whereas both IBR and WMU contained 6 g% of fiber and RMU, only 4 g%.

**Table 3–Demographic and clinical characteristics of the study participants**

| Characteristics | Mean |
|---|---|
| Age (years)[a] | 24.6 ± 0.7 |
| Male (*n*%)[b] | 64 |
| Female (*n*%) [b] | 36 |
| Height (cm) [b] | 164 ± 2.6 |
| Weight (kg) [b] | 55.3 ± 1.7 |
| Body mass index (kg/m$^2$)[a] | 20.3 ± 0.4 |
| Body fat (%) [b] | 20.64 ± 7.94 |
| Waist circumference (cm) [b] | 73.36 ± 8.36 |
| Blood pressure systolic (mmHg) [b] | 111.1 ± 12.6 |
| Diastolic (mmHg) [b] | 66.1 ± 8.2 |
| Fasting blood glucose mmol/L[b] | 87.0 ± 8.0 |

[a]Standard deviation.
[b]Standard error.

**Table 4–Mean IAUC and GI of the test foods ($n$ = 14)**

| Test foods | IAUC mmol/ min mean (SEM) | GI[a] mean (SEM) | GI classification[b] |
|---|---|---|---|
| Kashi 7 whole grain *pilaf* | 181.5 ± 20.8 | 58.9 ± 5.1 | Medium |
| Uncle Ben's whole grain fast and natural instant brown rice | 266.3 ± 25.6 | 87.8 ± 6.8 | High |
| Whole maize *ugali* flour | 212.5 ± 16.7 | 71.4 ± 5.1 | High |
| Refined maize *ugali* flour | 221.3 ± 20.2 | 74.7 ± 6.5 | High |

IAUC, incremental area under the curve; GI, glycemic index.
[a]Reference GI (Glucose) = 100.
[b]GI classification: Low GI ≤ 55; medium GI = 56–69; high GI ≥70, *P* value from analysis of variance 0.012.

The amylose content was highest in RMU (31.1%) compared to WMU (22.8%), IBR (19.3%), and WGP (17.6%; Table 1).

Demographic and clinical characteristics of the participants are shown in Table 3. The mean age of the study participants was 24.6 ± 0.7 years and the mean BMI was 20.3 ± 0.4 kg/m$^2$. Participants had mean fasting blood glucose levels 87.0 ± 8.0 mg/dL. The mean glycemic responses to the four test foods are shown in Figure 2(A, B). IAUC measurements were the lowest for WGP (181.5 ± 20.8 mmol/l·min), followed by WMU (212.5 ± 16.7 mmol/l·min) and RMU (221.3 ± 20.2 mmol/l·min). The highest IAUC value was found for IBR (266.3 ± 25.6 mmol/l·min) as shown in Table 4. Mean GI measures were significantly different among test foods ($P$ = 0.012). GI was the lowest for WGP (58.9 ± 5.1) and the highest for IBR (87.8 ± 6.8). There was a significant difference between the GI of WGP and IBR ($P$ = 0.004) compared to other test foods (Table 5).

Microscopic evaluation of the four foods was conducted to understand the possible relation between the microstructure and the assessed GI. The morphological and microstructural features of IBR and *ugali* flours (from both WMU and RMU) were examined under stereozoom and scanning electron microscopy. The scanning electron photo-micrographs of IBR, WMU and RMU revealed the physical topography and the status of the bran in the food grains and milled maize products used for the study. Disruption of the bran layer and presence of fissures or cracks on the surface and partial damage to germ (Figure 3A to 3C) were clearly visible in the IBR kernels. In contrast, bran layer in the reference

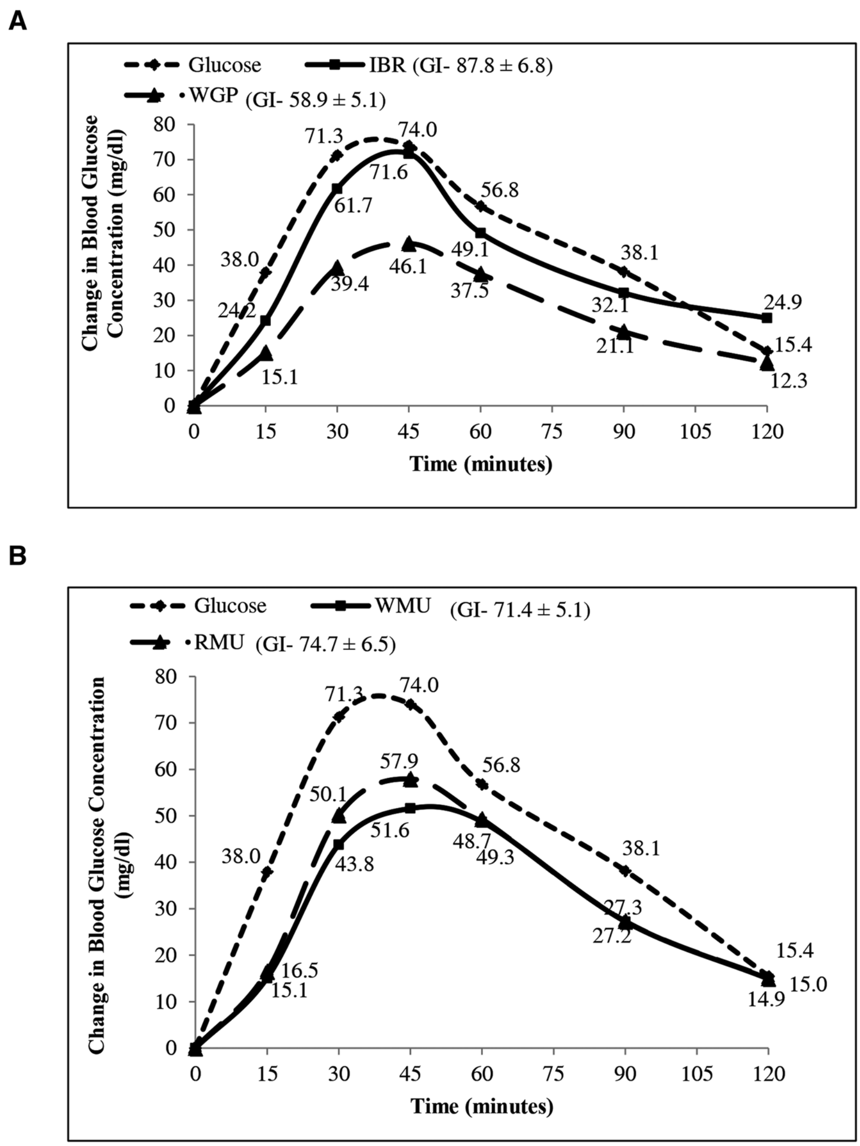


Figure 2–Change in mean glucose concentration (mmol/L) of (A) whole grain *pilaf* and instant brown rice and (B) whole maize *ugali* and refined maize *ugali.*

**Table 5–Difference in GI among test foods ($n = 14$)**

| Test foods | *P* value |
|---|---|
| GI of Kashi *pilaf* vs. Uncle Ben's whole grain fast and natural instant brown rice | 0.004 |
| GI of Kashi 7 whole grain *pilaf* vs. *Ugali* whole | 0.10 |
| GI of Kashi 7 whole grain *pilaf* vs. *Ugali* refined | 0.08 |
| GI of Uncle Ben's whole grain fast and natural instant brown rice vs. of *Ugali* whole | 0.10 |
| GI of Uncle Ben's whole grain fast and natural instant brown rice vs. *Ugali* refined | 0.05 |
| GI of *Ugali* whole vs. *Ugali* refined | 0.70 |

There was a significant difference between Kashi/whole grain "pilaf" and Uncle Ben's whole grain fast and natural instant brown rice (paired "*t*" test).

rice (parboiled brown rice -BPT 5204 variety; Figure 3D) was smooth and undisturbed. The endosperm of the IBR (Figure 3E) shows starch granules compacted inside the endosperm cell walls. The photo-micrographs of the WMU and RMU shown in Figure 4, indicate the starch granules were polygonal and spherical in shape, typical for maize starch. No major differences were observed between WMU (Figure 4A) and RMU (Figure 4B), except for the presence of larger proportions of pericarp in the WMU (Figure 4C). The microstructure of WGP could not be visualized by the scanning electron microscope as it is a multigrain product.

The stereozoom images of IBR reveal horizontal fissures in the grain surface with considerable loss of germ tissue and rupture of bran with oozing of the endosperm matter (Figure 5A). In contrast, Figure 5B shows parboiled brown rice (control) with intact bran and germ constituents. Figure 5C and D indicates that the WMU flour has a higher proportion of pericarp matter as evidenced by the presence of yellow colored specks. In contrast, the image for the RMU flour was practically free from the bran particles. Figure 5E shows the WGP with fairly intact bran and germ constituents indicating that they are whole grains, whereas Brown rice alone had minimal distuption on the bran layer.

## Discussion

This study determined the GI of WGP and IBR, in addition to commonly consumed Tanzanian cereal staple RMU made from refined maize and also the *ugali* made from whole maize (WMU), using a validated GI protocol. WGP was found to exhibit the

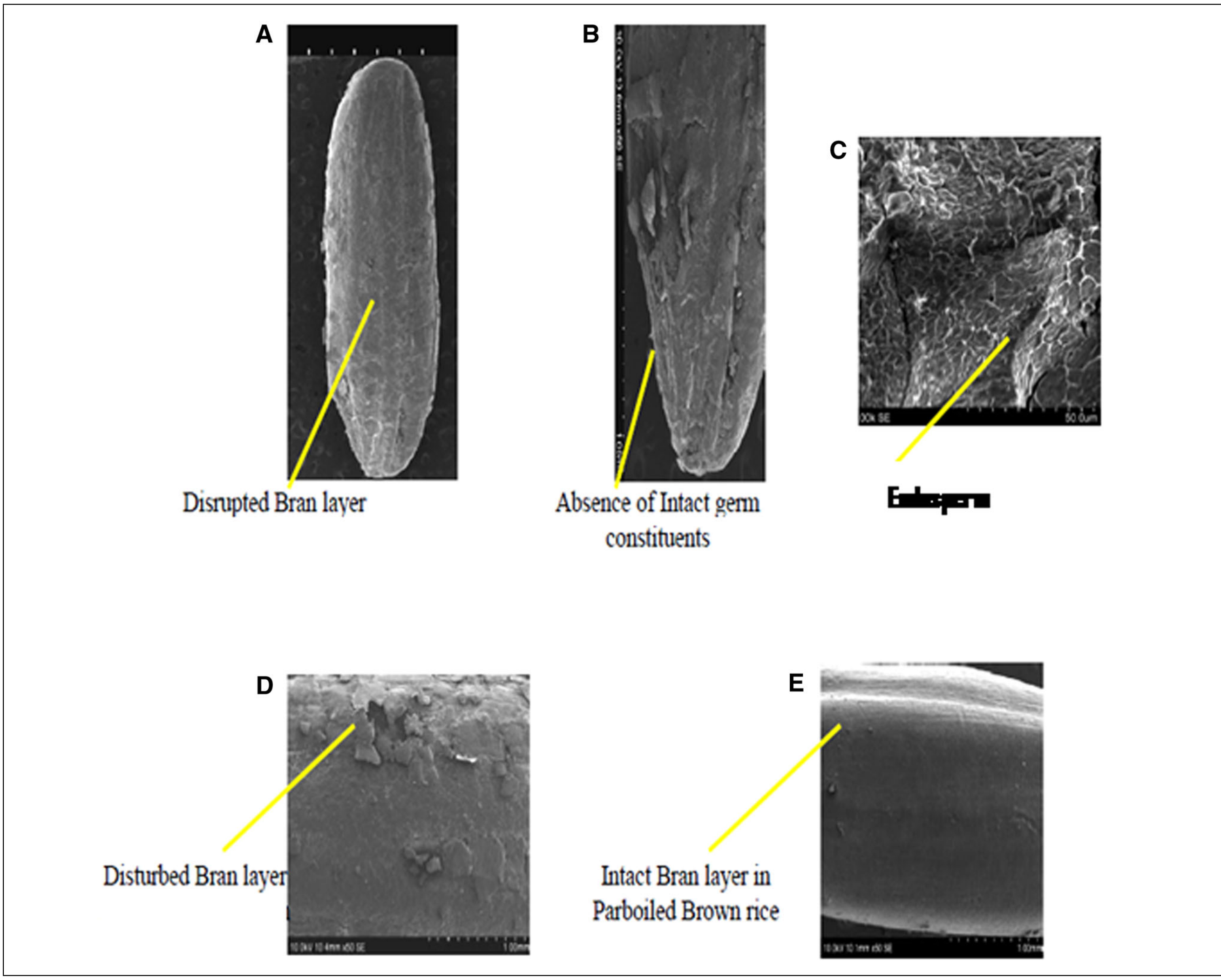


Figure 3–Scanning electron micrograph of IBR. (A) IBR full grain depicting the presence of discrupted bran and germ (11 SE). (B) IBR rice depicting disrupted bran and presence of partial germ (50 k SE). (C) IBR endosperm (1.00 k SE). (D) IBR surface depicting the disrupted bran layer (50 SE). (E) Parboiled brown rice (control sample) surface with intact bran layer (50 SE).

lowest GI among the four foods tested, placing it in the medium GI category. IBR showed the highest GI followed by WMU and RMU; all of these were in the high GI category. Evaluation by stereozoom microscope of WGP showed fairly intact grain constituents and possibly accounting for the resultant medium GI. Similarly, disruption of the bran layer, presence of fissures or cracks on the surface and partial damage to germ of IBR (perhaps due to quick cooking processing methodology) could explain relatively high GI. We found no significant difference in the GI of WMU and RMU (high GI) despite the former being a wholegrain milled flour suggesting the importance of intactness of the grain (Figure 5C and D).

## GI of whole grain *pilaf*

The pilaf contained six kinds of cereals (oats, brown rice, rye, triticale, buckwheat and barley and an oil seed [sesame]). The visual observation of the cereals indicated that the grains were processed to separate out the nonedible seed coat or husk portions from oats, barley, rye, rough rice (paddy), triticale, and buckwheat; whereas the sesame seeds were just dehulled to get rid of the coarse seed coat matter and hence WGP consisted of mostly intact grains. The brown rice in WGP had abrasions indicating discontinuous bran (Figure 5E), potentially a reason for medium GI category (GI value of 58.9) despite most of the individual wholegrains in the WGP having low GI (Atkinson, Foster-Powell, & Brand-Miller, 2008). The intact dietary fiber (from bran, germ and cell walls in the case of unprocessed wholegrains) offers physical protection to the starch granules during cooking and reduces the digestibility. Soluble fiber (predominantly from oats and barley in WGP), lowers the GI of food by increasing its viscosity (Bjorck & Elmstahl, 2003). The mechanism includes increased thickness of the undigested slurry in the small intestine, inhibition of intestinal motility, and delayed gastric emptying resulting in a decrease in the postprandial glucose and insulin response (Brennan, 2005). WGP has a mixture of soluble and insoluble dietary fiber contributed from different grains, and hence the glycemic outcome could be influenced. Our earlier study showed that intact wholegrain brown rice containing predominantly insoluble fiber had a medium GI (Shobana et al., 2017). Blending of whole grains with other grains of similar physical properties such as hardness and particle size with similar cooking characteristics may be advantageous for preparation of whole grain mixtures similar to *pilaf.* Uniformly cooked grains with comparable gelatinization characteristics and grain texture for one single cooking method could positively impact the GI

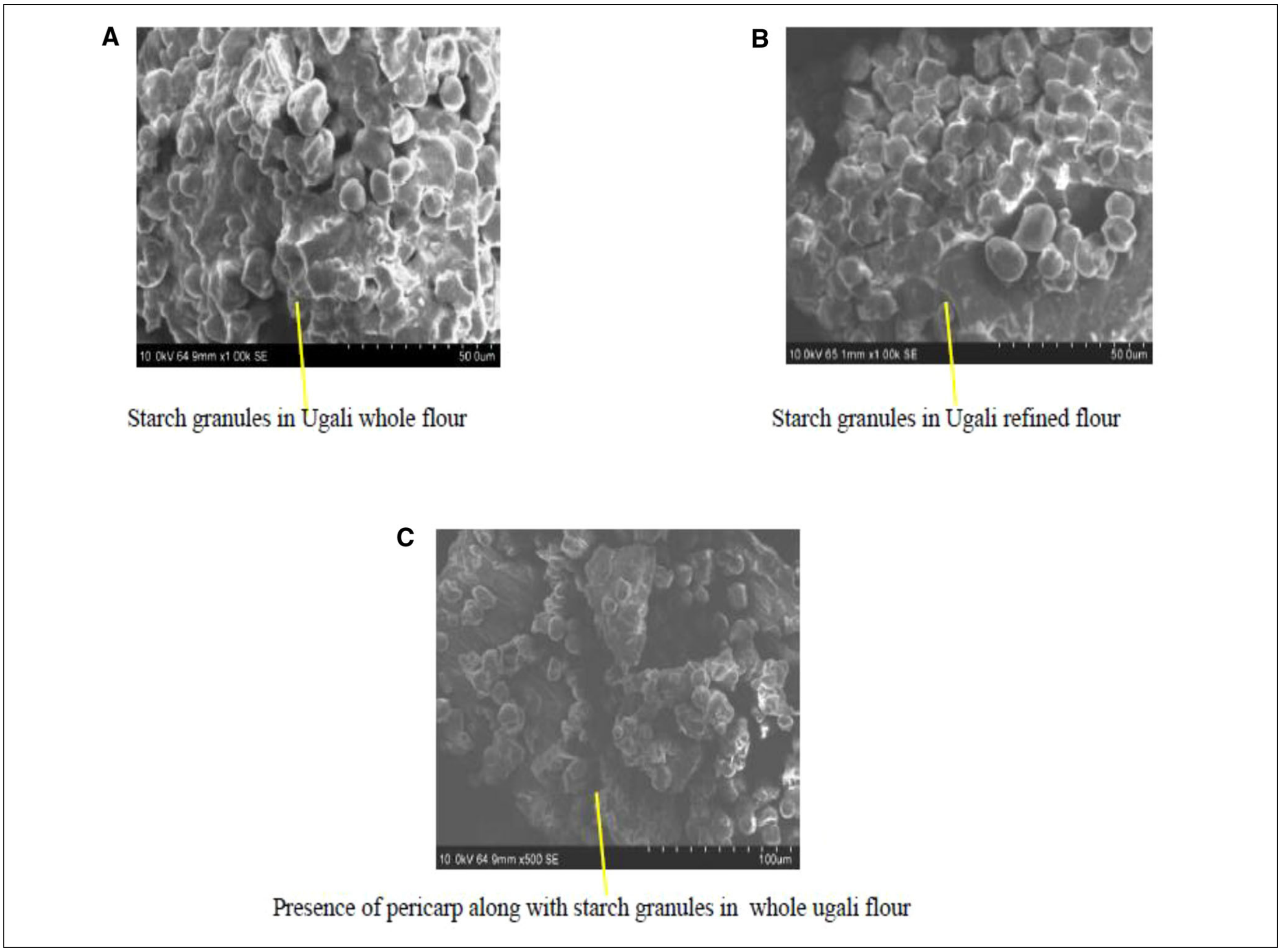


Figure 4–Scanning electron photomicrographs of maize *ugali* frour (whole and refined). (A) Starch granules in whole maize ugaliflour (1.00k SE). (B) Starch granules in refined maize ugaliflour (1.00 k SE). (C) Presence of pericarp along with starch granules in wholemzise ugali flour (500SE).

of food. Similar to our GI finding for WGP, international GI tables (Atkinson et al., 2008) had reported a medium GI value of 55 for a multigrain porridge, containing rolled oats, wheat, triticale, rye, barley, and rice, cooked with water.

## GI of instant brown rice

The international tables of GI values have reported a wide range (47 to 109) for various types of rice including white, brown, and instant rice (Atkinson et al., 2008; Kaur, Ranawana, Teh, & Henry, 2015). Whole grains, such as brown rice, have kernels with intact bran and germ containing a relatively higher level of fat, which can hinder water absorption and increase the duration of cooking (Desikachar, Raghavendra Rao, & Ananthachar, 1965). Intact bran also limits the swelling and fissuring of the starch granules thereby slowing down the starch digestibility, but cooking time remains a challenge. Instant brown rice with minimal cooking time typically undergoes hydrothermal treatment (Champagne et al., 1999), and there are reports on hydrothermal processing for preparation of instant jasmine rice as well (Prasert & Suwannaporn, 2009). This process involves raising the moisture content of kernels and subjecting them to controlled high-temperature short-time treatment (HTST), which results in cracks or fissures in the kernel as shown in the case of IBR (Figure 3D and 5A). This allows the rapid hydration and gelatinization of starch and also swelling of the starch granules, thereby reducing cooking time (Prasert & Suwannaporn, 2009) and enhances digestibility. Although the details of the specific treatments given to the IBR were not available, scanning electron micrographs and stereozoom images distinctly showed disrupted bran layers and the partial presence of germ constituents compared to the reference brown rice (Figure 3A to E, 5A), which likely decreased the cooking time. Our previous study (Shobana et al., 2017) found higher GI and 24-hr glucose responses for minimally polished rice (which is similar to IBR with disrupted bran) as compared to brown rice prepared from the same variety. Thus brown rice with intact bran and germ constituents can be a healthier choice with low to medium GI values (Atkinson et al., 2008; Shobana et al., 2017) over instant brown rice with disrupted bran, germ, and fissures and high GI.

Hydrothermal treatment would have also induced changes such as pregelatinization in the starch, as evident by the scanning electron microscope images (Figure 3C), which in turn could have affected the cooking time, textural features, and ultimately the higher GI of IBR in this study. However, the GI of brown rice has been shown to vary from low to medium to high for a number of reasons, including amylose content, degree of gelatinization, amylose-to-amylopectin ratio, and cooking time (both quick cooking and very long cooking time; Kaur, Ranawana, & Henry, 2016, Kaur et al., 2015; Ranawana, Henry, Lightowler, & Wang, 2009). Ranawana et al. (2009) have attributed the higher GI values of brown basmati rice to a longer cooking time.

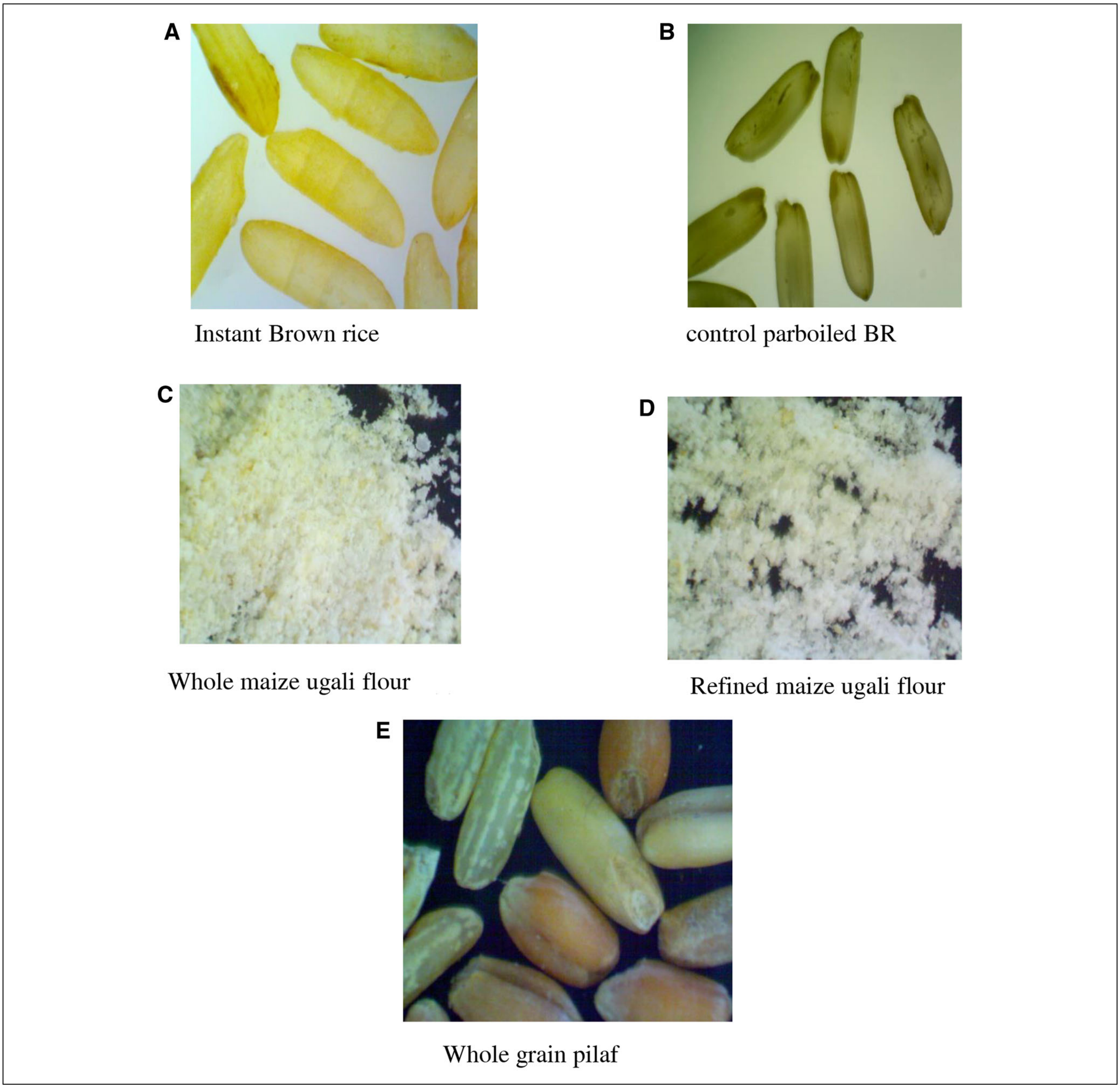


**Figure 5–Stereozoom images. (A) Instant brown rice. (B) Parboiled brown rice (control). (C) Whole maize ugali flour. (D) Refined maize ugali flour. (E) Whole grain pilaf.**

## GI of refined and unrefined *ugali*

As part of the GNET initiative in Africa, substitution of brown rice for *ugali,* a maize-based African cereal staple, has been studied by Akarolo-Anthony et al. (2013). Fine grits of maize almost free from seed coat matter is typically used for *ugali* preparation. This study assessed the differences between the GI of "ugali" made from refined and whole maize meal to support the recommendation of using whole grain flour in this and other staple foods.

The GI of *ugali* in our study did not significantly differ whether prepared from whole maize or refined maize flour. The intactness of the anatomical components of the grain plays a vital role in the digestibility of the carbohydrate (Parada, Aguilera, 2011; Ranawana et al., 2009). As the whole grain maize is milled to flour, the grain matrix, and the dietary fiber (from seed coat and cell wall constituents) are disrupted. Because of the loss of structural integrity of the grain components during the process of milling, the starch granules embedded inside cell walls get exposed leading to increased surface area in the flour. This enables increased water uptake, starch granular swelling and gelatinization during cooking; all of which could raise the GI. Aforementioned, intact dietary fibers are more functional by providing physical protection to starch granules and decreasing the starch digestibility. Similarly, whole grain based preparations such as wheat flour-based pancakes and barley flour bread have also been shown to have high GI values of 80 and 74, respectively (Foster-Powell et al., 2002). Although RMU, being a refined grain, contained higher amounts of dietary amylose, which is known to lower the GI, this was probably offset by its smaller particle size when used as flour. These could help explain why both the whole and refined maize *ugali* showed comparable glycemic properties even though WMU contained higher levels of dietary fiber. These findings are consistent with the data published in the International GI Table for refined and unrefined maize meal porridge (Atkinson et al., 2008).

To our knowledge, this study is the first of its kind to evaluate the GI of instant brown rice and a commonly consumed breakfast cereal WGP, in addition to ugali prepared from whole and refined maize flour, a staple in many East African countries. The strength of the study lies in its methodology. We have used a standardized recommended GI estimation protocol in line with the international methodology outlined by FAO/WHO (1998) to study the glycemic properties of all the food samples. In addition, the amount of available carbohydrate was directly measured as recommended for GI estimation, rather than by using the conventional method of deriving total carbohydrate minus dietary fiber (Brouns et al., 2005). A unique feature of this study was the use of scanning electron microscopy and stereozoom pictures to augment our investigation of the glycemic properties of the foods. However, the study also has some limitations. Anatomical changes in the grain constituents during cooking and the nature of starch and dietary fiber present in the cooked test foods have not been evaluated and such studies are needed to further substantiate our findings. Studies of GI are only able to evaluate an acute 2-hr glycemic response, thus longer term intervention trials are required to establish the effects of whole grains, including the foods that we considered, on the prevention of diabetes or long-term glycemic control among those with diabetes. There are scientists who believe that GI is a useful way to categorize foods according to their blood glucose raising potential and thus feel it can be helpful in guiding consumers to choose foods with a lower glycemic response. This group believes the data is supported by epidemiologic studies and trials linking low GI diets or dietary patterns to reduced risk of cardio metabolic conditions compared to higher GI patterns (Bhupathiraju et al., 2014, Augustin et al., 2015). However, there are other scientists who believe that glycemic index and glycemic load may not be related to measures of insulin sensitivity, insulin secretion, and adiposity (Liese et al., 2005; Pi-Sunyer, 2002). Indeed, Matthan, Ausman, Meng, Tighiouart, and Lichtenstein (2016) have shown that there is considerable variability of individual responses to GI value even among healthy individuals contributing to the variability of GI estimates and thus they believe that GI is unlikely to be a good approach for guiding food choices. Many developing low- and middle-income countries continue to have diets culturally high in carbohydrate. Thus, reducing the dietary glycemic load of food or meal by decreasing the GI for such population may be culturally acceptable to improve the quality of high carbohydrate diets. Therefore in this part of the world industry should focus on developing more intact whole grains or grains with minimal disruption to the grain matrix. For example, use of grits (broken grains) could be encouraged instead of flour-based preparations. The cereal grain industry should also focus on developing products containing whole grains of uniform size with similar physical properties to achieve uniform cooking times and a lower glycemic impact. Another option would be to add functional ingredients such as soluble fiber, which could help with reconstruction of the matrix and reduce the rate of starch digestibility. For clinical purposes, dietitians and physicians could advise patients how to replace high GI foods with lower GI options or to add low GI options to the meal to reduce the overall GL of the meal. However as a counter argument to this view, a recent review by Livesey et al. (2019), show that the nature of dietary fiber or wholegrains cannot effectively predict GI values, which underscores the need to develop country specific GI databases.

## Conclusion

In this study, we have described the GI of the selected four cereal grains, where wholegrain pilaf despite containing intact fiber showed only a medium GI while, instant brown rice showed a high GI owing to the "quick cooking" processing conditions and lower amylose content. The study also highlights that the whole grain cereal which was milled to flour of a finer particle size exhibited a similarly high GI as the flour made from refined grain in "Ugali" preparations. This study also showed that WGP with a medium GI may be a better whole grain alternative among the cereal grains studied. It is thus important to recommend intact whole grain foods that elicit a lower glycemic response than whole meal flour preparations. Well-designed randomized controlled clinical trials are needed to substantiate our findings.


## Acknowledgments

The Dept. of Nutrition of the Harvard T.H. Chan School of Public Health funded this study.


## Authors' Contributions

D.S. and W.W. conceived the study, its design, and were involved in implementation of the study, interpretation of the data, and helped to draft and revise the manuscript. S.V., M.R.B., K.A., L.P., and G.G. were involved in the design and coordination of the study. S.S. conducted the microscopic examinations. V.M., S.V., C.J.K.H., K.K., R.M.A., R.U., S.S., and N.G.M. were involved in the interpretation of the data. M.R.B. initiated the draft manuscript along with NMW. All authors revised the manuscript critically and approved the final manuscript.

## Conflicts of Interest

The authors declare no conflicts of interest.

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