Studies on in vitro bioavailability and starch hydrolysis in zinc fortified ready-to-eat parboiled rice (*komal chawal*)

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Abstract Zinc fortified parboiled rice (*komal chawal*) was produced from a low amylose variety of rice by applying ‘brown rice parboiling’ method. In addition to the effect of milling on fortification, the effectiveness of fortification upon the amount of bioaccessible (in vitro digest) and bioavailable (cellular uptake) form of Zn was tested. The effect on glycaemic index was also assessed by employing an in vitro starch hydrolysis assay. The bioaccessible form of Zn in the unmilled fortified rice were ranged in between 4.24 and 11.07 mg/100 g, which was significantly higher ($p < 0.05$) than the milled and unfortified parboiled rice. Similarly, the % absorption of bioavailable Zn was negligible in the unfortified parboiled rice as compared to the fortified rice (14.5–24.5%). The estimated GI of fortified parboiled rice samples was in the range of 50.97–59.79, which was lower than the unfortified parboiled rice (58.80–62.53) and raw rice (78.71–84.64). The results thus demonstrated that Zn fortified *komal chawal* can be a novel and rapidly produced micronutrient enhanced ready-to-eat rice.

Keywords Brown rice parboiling · Zinc fortification · Bioaccessibility · Bioavailability · Glycaemic index

Introduction

Deficiency of micronutrients in the diet is a major global public health concern. In South Asia itself about 95.4% of the people are at risk for Zn deficiency (Hettiarachchi et al. 2004). In developing countries Zn is derived mainly through food grains such as cereals and legumes (Gibson et al. 1998), and deficiency of Zn is believed to be as widespread (Prasad 2003). Zn deficiency affects the immune system, causes various infections, restriction in growth and development in infants, children and various other outcomes in adults and after childbirth (Hotz and Brown 2004). Studies estimated that about 0.4 million deaths occur due to Zn deficiency, especially in South Asia, thereby making it a critical micronutrient deficiency (Black et al. 2008). The common causative factors of Zn deficiency are due to inadequate dietary intake, or presence of Zn inhibitors in the diet. Recently, Zn fortification has been reported in whole rice by paddy parboiling (Prom-u-thai et al. 2010), in whole potato tuber (Erihemu et al. 2015), and in potato chips (Joshi et al. 2016).

Rice is an important staple food among cereal grains, but is not considered as a good source of micronutrients. It can however offer as a good vehicle to eliminate micronutrient deficiency. Fortification during parboiling is one of the methods to enhance micronutrients in rice grains, which is considered as a better alternative to methods such as coating, dusting, supplementation and bio-fortification (Prom-u-thai et al. 2008). Parboiling is a hydrothermal treatment which consists of soaking, steaming and drying (Bhattacharya 2004). In Assam, India, a product named *komal chawal*, meaning soft rice, is produced from a low amylose paddy named *chokuwa* variety simply by paddy parboiling, and after dehulling, the product is consumed by warm water soaking without cooking.

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The product rehydrates in warm water to a texture soft enough for consumption on soaking for 20–25 min (Wahengbam et al. 2019b). In the present study, *chokuwa* rice is used as a carrier for Zn fortification during the production of *komal chawal* by brown rice parboiling method instead of traditional paddy parboiling. Further, the bioaccessibility and bioavailability of Zn in the unfortified parboiled rice and fortified parboiled rice, and subsequent effect on starch hydrolysis were tested.

Materials and methods

Materials

The *chokuwa* rice (a low amylose variety) was obtained from the nearby local farm of Tezpur, Assam, India. Brown rice was obtained by dehusking the paddy in a sheller (RTE-07, A GRAIN, India), and then stored in an air tight container in refrigerated condition before processing. Caco-2 cells were kindly provided by the Cell culture lab of the Institute of Global Food Security, Queen's University, Belfast, UK. Growth media and supplements for cell line studies were obtained from Gibco and Sigma Aldrich, USA, and other chemicals like Zinc sulphate monohydrate ($\text{ZnSO}_4 \cdot \text{H}_2\text{O}$, as zinc source) and enzymes were obtained from Sigma Aldrich, USA.

Production of zinc fortified parboiled brown rice

The brown rice (100 g) was washed with distilled deionised water and the excess water was drained. Fortification of Zn was carried out separately during the soaking steps of parboiling in 1:2 ratio (w/v) of rice to solution at 60 °C for 90 min, in replicates of three sets ($n = 3$). The concentration ranges of Zn used for fortification is given in Table 1. After soaking, the excess solution was drained, followed by steaming at 1.05 kg/cm^2 for 10 min in a vertical autoclave and drying at 40 °C till 12% moisture. The products thus obtained were milled separately for 30 s (4% degree of milling) and 60 s (8% degree of milling) by using a rice polisher (RTE-08, A GRAIN, India). Before the in vitro study, the unfortified and fortified dried parboiled rice were rehydrated by soaking in water at 60 °C for 25 min to obtain the desired hardness and adhesiveness of cooked condition (Wahengbam et al. 2019b).

In vitro digestibility for assessment of bioassessible Zn

Zn bioaccessibility in the unfortified and fortified parboiled rice was carried out by in vitro simulation digestion via a three-step digestion that included oral, gastric and

intestinal digestion (Wahengbam et al. 2019a). For oral step, 5 g of freeze dried rice powder was mixed with 30 ml of 140 mM NaCl and 5 mM KCl solution. Then 0.5 ml of 1500U/ml α -amylase (A3176-1MU, Sigma, USA, E.C.3.2.1.1) was added, followed by 25 μl of 0.3 M CaCl_2 solution and 500 μl of ascorbic acid (100 mM), and maintained for 2 min at 37 °C in a shaking water bath. For gastric step, 0.5 ml of 11,000U/ml pepsin (P7125, Sigma, USA, E.C.3.4.23.1) solution was added to the orally digested sample and maintained at pH 2 (1 M HCl) for 2 h in a shaking water bath at 37 °C. Then the sample was adjusted to pH 5 (1 M NaHCO_3) and the intestinal step was followed with addition of 2.5 ml of pancreatin-bile solution (0.45 g of bile salts and 0.075 g of pancreatin in 37.5 ml of 0.1 M NaHCO_3). Then 40 μl of 0.3 M CaCl_2 was added and pH was adjusted to 7.0 with 1 M NaOH and incubated for another 2 h in shaking water bath at 37 °C. The digested samples were cooled in ice for 10 min and centrifuged at 4600 rpm for 40 min at 4 °C. The supernatant was separated, snap frozen in liquid nitrogen and stored at -80 °C until further analysis.

Analysis of Zn content

The content of Zn in the supernatant (soluble mineral fraction) was analyzed by inductively coupled plasma optical emission spectroscopy (5100ICP-OES, Agilent Technologies, USA). The % bioaccessibility was then calculated according to Eq. (1) (Hemalatha et al. 2007).

$$\% \text{ bioaccessibility} = \frac{\text{bioaccessible m.f}}{\text{Total m.c}} \times 100 \quad (1)$$

where bioaccessible m.f (mineral fraction) is the soluble Zn fraction obtained after simulated digestion (mg/100 g rice), and total m.c (micronutrient content) is the total Zn content of each dried rice sample (mg/100 g rice) after the parboiling process.

Bioavailability study using Caco-2 cell model

The supernatant obtained after in vitro simulation digestion was used for determining the bioavailable form of Zn by transport through Caco-2 cells (Wahengbam et al. 2019a). Cells were cultured in 75 cm^2 (vessel surface area) flasks and maintained in high glucose (4.5 g/l) minimum essential media (MEM) with 10% (v/v) fetal bovine serum, 1% (v/v) nonessential amino acids, 4 mM L-glutamine, and 1% (v/v) penicillin–streptomycin, and 1% (v/v) sodium pyruvate. The cells were maintained at 37 °C in an incubator with 5% CO_2 , and 95% relative humidity.

For testing the bioavailability, 50,000 cells/ cm^2 (2×10^5 cells/well) were seeded in polyester membrane inserts whose basal compartment contained complete

Table 1 Codings for the samples and range of Zn fortification concentrations

Sample	Milling time (s)	Coding	Total Zn content (mg/100 g rice) ^a
Unfortified rice			
Raw rice	0	R-a	1.56 ± 0.24
	30	R-b	1.23 ± 0.34
	60	R-c	1.02 ± 0.48
Parboiled brown rice	0	PBR-a	1.47 ± 0.69
	30	PBR-b	1.26 ± 0.12
	60	PBR-c	1.03 ± 0.49
Fortified rice			
mg Zn/200 ml water 20	0	Zn-1a	12.36 ± 0.42
	30	Zn-1b	9.89 ± 0.50
	60	Zn-1c	8.12 ± 0.55
40	0	Zn-2a	19.88 ± 0.69
	30	Zn-2b	17.26 ± 0.47
	60	Zn-2c	11.53 ± 0.86
60	0	Zn-3a	27.90 ± 0.74
	30	Zn-3b	24.20 ± 0.52
	60	Zn-3c	19.38 ± 0.32
80	0	Zn-4a	33.84 ± 0.57
	30	Zn-4b	26.41 ± 0.44
	60	Zn-4c	24.68 ± 0.42
100	0	Zn-5a	39.62 ± 0.58
	30	Zn-5b	36.01 ± 0.73
	60	Zn-5c	28.53 ± 0.52

^aThe Zn contents represented in this table have been adapted from our previous publication (Wahengbam et al. 2019b)

MEM media. The culture medium was changed every 48 h, till 21 days of initial seeding, after which the growth medium was removed. Then the cell monolayer was washed with Ca^{2+} and Mg^{2+} free Hank's balance salt solution and the basolateral compartments were filled with transport solution (130 mM NaCl, 10 mM KCl, 1 mM MgSO_4 , 5 mM glucose, and 50 mM HEPES (4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid), pH 7.4) and the apical chambers (inserts) were filled with the soluble mineral fraction followed by incubation at 37 °C for 2 h. After then the basolateral compartments were collected for the determination of Zn transport across the cell monolayer. Cell viabilities were assessed by trypan blue exclusion, which were typically 94–98% after 2 h of exposure. The % absorption of bioavailable Zn transport across the cell monolayer was obtained by using Eq. (2).

$$\begin{aligned} & \% \text{ absorption of bioavailable Zn} \\ &= \frac{\text{Transport } x_{\text{basolateral}}}{\text{Bioaccessible } x_{\text{apical}}} \times 100 \end{aligned} \quad (2)$$

where transport x equals the amount of Zn in ppm, transported to the basolateral compartment through the cell

monolayer and bioaccessible x in apical compartment are the amount of bioaccessible Zn in ppm.

A relationship was also derived between the amounts of bioaccessible form with their respective % absorption values (bioavailable form), in order to observe the effect of amount of bioaccessible Zn available for absorption in the intestinal cell.

In-vitro starch hydrolysis assay

This was carried out by following the methodology of Wahengbam et al. (2019a), in which the rate of glucose liberation due to hydrolysis of the solubilized starch was monitored by measuring the activity of α -glucosidase enzyme on rice. Sample was prepared by mixing 300 μl rice starch solution (0.1 g/ml in PBS) with 150 μl of PBS and 20 μl of α -glucosidase enzyme (prepared by mixing intestinal acetone powders from rat (I1630, Merck, UK) with citrate buffer). The liberation of glucose was measured from 0 to 120 min at regular interval of 30 min by using a Microstat portable glucose analyser (P-GM7, Analox Instruments, USA). The area under curve (AUC) for each hydrolysis curve was obtained and the hydrolysis

index (HI) was determined by dividing the AUC of each sample by the corresponding AUC of reference food (Bravo et al. 1998) and the expected glycaemic index (GI) was calculated according to Eq. (3) (Bravo et al. 1998).

$$GI = 39.71 + 0.549 \times HI \quad (3)$$

Statistical analysis

One-way ANOVA was carried out for data analysis and Duncan's mean comparison test applied at a probability of $p = 0.05$ to determine differences among treatments. These were done using the software IBM SPSS Statistics 20.

Results and discussion

In vitro digestibility of Zn fortified rice

The codings of the samples for Zn fortified and unfortified rice are given in Table 1. The content of Zinc in all fractions of rice before and after fortification has been estimated in our previous work (Wahengbam et al. 2019b) and values are included in Table 1. The Zn fraction retained in the supernatant after the in vitro simulation digestion is the bioaccessible form of soluble which is potentially available for absorption in the intestinal cells. The amount of bioaccessible Zn and % bioaccessibility in the unfortified and fortified parboiled (unmilled and milled) rice are shown in Fig. 1a, b, respectively. It was observed that % bioaccessibility was much higher in the fortified samples as compared to PBR, and the bioaccessible Zn in the unmilled fortified rice ranged in between 4.24 and 11.07 mg/100 g.

On subsequent milling between 0 s and 30 s, there was loss of about 27.72%, 26.57%, 20.85%, 11.28% and 18.24% in Zn-1b, Zn-2b, Zn-3b, Zn-4b and Zn-5b, respectively. Similarly, in between 0 s and 60 s milling, the % loss of Zn were about 60.63%, 69.71%, 52.73%, 46.47% and 41.97% in Zn-1c, Zn-2c, Zn-3c, Zn-4c and Zn-5c, respectively. This shows that with increase in milling duration, more reduction in Zn content occurs. The % loss was more at lower fortification concentrations (Zn-1 to Zn-3) as compared to higher concentrations (Zn-4 to Zn-5). This might be due to loss of accumulated Zn in the outer surface of kernels (aleurone layer) mainly. Whereas, the less % reduction of Zn in case of parboiled rice soaked in more concentrated Zn solution might be due to diffusion of Zn ions beyond the aleurone layer (Wahengbam et al. 2019b).

The % bioaccessibility of Zn fortified unmilled parboiled rice were in the range of 28–35%, which followed a decreasing trend with increase in concentration. This might be due to the higher total Zn content with increasing concentrations as compared to available soluble Zn content. Thus, variation between bioaccessible form and total Zn content effects the % bioaccessibility. Nearly similar trend of % bioaccessibility was followed in case of 30 s milled fortified samples (25 to 34%), except for Zn-4b, which was slightly more among the 30 s milled samples. However, an increased trend was observed in case of 60 s milled Zn fortified samples (18 to 22%), except for Zn-2c. These increasing trends in 60 s samples may be due to less variation between the total Zn content and bioaccessible Zn form. As in milling maximum Zn from the aleurone layer is removed, only the tightly bound Zn ions remains which gets diffused inside the endosperm portion, and with

Fig. 1 **a** Content of bioaccessible form of Zn (mg/100 g rice), **b** % bioaccessibility of Zn in the unfortified and fortified parboiled rice. Note Similar superscripted alphabets along the bars represent no significant difference ($p < 0.05$)

increasing Zn fortification concentrations, diffusion inside the rice grains also increases. Therefore, in 60 s milled samples increased trend was observed as variation in the available soluble fraction of Zn is minimized. Zinc bioaccessibility of 19.9–63.7% were reported in the vegetables like lettuce, pak choi, cole, and leaf lettuce (Yin et al. 2017) which is under the range of % bioaccessibility of the present study.

Thus, with relatively less Zn concentration in the solution, the diffusion of Zn to the rice grains during the fortification process (soaking) may be distributed to some extent in the aluerone layer and outer portion of endosperm area, thereby resulting in a higher reduction in Zn content due to milling. Subsequently, in spite of the similar soaking period, the % decrease of bioaccessible Zn in 30 s milled was less in the higher concentration fortified samples. This may be attributed to the higher diffusion of Zn ions to the inner endosperm portion of the rice grains (Prom-u-thai et al. 2010).

Bioavailable form of Zn in Caco-2 cell model

The % absorption of bioavailable Zn is represented as the bioaccessible Zn which was absorbed through Caco-2 cell monolayer into the transport medium from the supernatant (soluble fraction) filled in the upper apical chamber. This was very less and negligible in PBR as compared to the fortified samples (Fig. 2). It shows that the bioavailability of micronutrients in unfortified staple crops is typically low (La Frano et al. (2014). For unmilled samples, the % absorption of bioavailable Zn also increased from Zn-1a to Zn-5a, with increase in Zn fortification concentration. However, no significant difference was found ($p < 0.05$)

Fig. 2 The % absorption of bioavailable Zn in the unfortified and fortified parboiled rice. Note Similar superscripted alphabets along the bars represent no significant difference ($p < 0.05$)

between Zn-3a, Zn-4a and Zn-5a. This positive correlation of % bioavailability with increasing coccentration of Zn fortification were also followed for the milled samples.

The % absorption of bioavailable Zn (14.5 to 24.5%) in 0 s milled fortified samples were more as compared to the milled samples. The amount of bioavailable Zn decreased with increasing milling time; but were more than PBR. The % absorption of bioavailable Zn ranged from 12.0 to 23.4% for 30 s milled and 9.8 to 20.0% for 60 s milled fortified rice as shown in Fig. 2. The deviation between the unmilled and 30 s milled % absorption of Zn-1 to Zn-2 fortified samples was however less significant ($p < 0.05$). Jou et al. (2012) also observed the % absorption of bioavailable Zn by rat pups model in milled (42%) and undermilled (40%) bio-fortified rice, which were less significant among milled and undermilled rice. The amount of % absorption of Zn in the present study is comparable with the findings of Islam et al. (2013) who found the % absorption of 20.1 (human isotope model) and 30.1 (mathematical model) in the milled high zinc content rice. Similarly, % absorption of bioavailable Zn was reported in bio-fortified wheat flour (15%) by Rosado et al. (2009). About 8.7–24.2% absorption was reported in Zn fortified white bread and 5.7–11.3% in fortified whole meal bread by a radionuclide technique and whole-body counting by Sandström et al. (1980). While in white bread combined with animal protein sources, the % absorption of bioavailable Zn of about 6.9–25.3% (for white bread, milk, cheese meal) and 5.6–14.4% (for whole meal bread, milk sources) were reported by Sandström et al. (1980). These variations in bioavailability of nutrient may be due to different digestion methods used, variation in the amount of release from the food matrix, intestinal cells absorption, and transport to body cells (Etcheverry et al. 2012), thereby affecting the overall % absorption.

A close linear relationship between bioaccessible Zn and the transport of Zn in the form of % absorption were also found, as shown in Fig. 3. The goodness of fit ($R = 0.96$) of linear relationship between bioaccessible Zn and its % absorption were well fitted. The results show that increasing the bioaccessible form gave slightly more % absorption.

In vitro assay simulating glycaemic index

The glucose liberation rate from 0 to 120 min after hydrolysis by α -glucosidase enzyme were checked for all the test groups. Figure 4a, b, c shows the 0 s, 30 s milled and 60 s milled samples test groups, respectively. The variation in HI values of all samples are shown in Fig. 4d. Likewise, the estimated GI of all milled and unmilled raw, PBR, and Zn fortified parboiled rice test groups are given in Table 2. The rate of starch hydrolysis (glucose liberation

Fig. 3 Plot showing the relationship between concentration of bioaccessible Zn and % absorption of bioavailable Zn

rate) increased with increase in enzyme reaction time and milling time. This rate was higher in R than the unfortified and fortified parboiled rice. This effect may be due to variation in the crystallites of the starch. Raw rice has A-type starch, which in parboiled rice gets converted into B-type or/and V-type or mixed pattern (Prasert and Suwannaporn 2009). This was also observed in our previous study by XRD analysis (Wahengbam et al. 2019b). The presence of A-type starches in raw rice attributes to higher hydrolysis rate than the parboiled rice. This is because the A-type starches are shorter double helices and more readily digestible, whereas B-type starches are often contain a high amount of resistant starch (Jane et al. 1997). Tetens et al. (1997) also observed low starch digestibility in parboiled rice, which is in support to our observations.

For unmilled (0 s) processed rice samples (Fig. 4a), at same time interval of hydrolysis, the rate of glucose liberation increases with time. R-a sample showed higher glucose liberation rate as compared to unmilled processed samples. The decreased in glucose liberation rate of Zn

Fig. 4 Glucose liberation rate of **a** 0 s milled, **b** 30 s milled, **c** 60 s milled and **d** estimated HI of raw, unfortified and Zn-fortified parboiled rice samples. Note Similar superscripted alphabets along the bars represent no significant difference ($p < 0.05$)

Table 2 Estimated glycemic index (GI) of the samples

Sample code	GI for Zn fortified test groups
R-a	78.71 ± 1.15 ^j
PBR-a	58.80 ± 0.81 ^h
Zn-1a	57.62 ± 1.14 ^{gh}
Zn-2a	55.02 ± 0.58 ^{def}
Zn-3a	58.46 ± 1.13 ^h
Zn-4a	51.67 ± 1.22 ^{ab}
Zn-5a	50.97 ± 0.53 ^a
R-b	80.59 ± 1.46 ^j
PBR-b	59.35 ± 1.30 ^h
Zn-1b	55.89 ± 1.33 ^{efg}
Zn-2b	54.01 ± 1.89 ^{cde}
Zn-3b	58.74 ± 1.19 ^h
Zn-4b	53.43 ± 1.35 ^{bcd}
Zn-5b	52.25 ± 0.46 ^{abc}
R-c	84.64 ± 0.80 ^k
PBR-c	62.53 ± 1.13 ⁱ
Zn-1c	59.21 ± 1.67 ^h
Zn-2c	56.32 ± 1.69 ^{fg}
Zn-3c	59.79 ± 1.26 ^h
Zn-4c	53.86 ± 1.11 ^{cde}
Zn-5c	59.50 ± 1.16 ^h

Values with common superscripted letters are not significantly different (Duncan's multiple range test at $p < 0.05$)

fortified unmilled samples was observed with increase in Zn fortification concentration except for Zn-3a. The lowest glucose liberation rate was observed for fortified parboiled rice with highest Zn concentration (Zn-5a). The glucose liberation rate of Zn fortified samples were lower than the unfortified parboiled rice (PBR-a). This shows an inhibitory or suppressive action on α -glucosidase activity with increasing Zn concentration. This might be due to the effect of Zn ions on the active sites for enzymes, which causes inhibitory action. Similar observations have been reported by Yoshikawa et al. (2006) and Zeng et al. (2012). Yoshikawa et al. (2006), who observed inhibitory action of Zn ions due to effect on Cys residues on the active site for α -glucosidase enzyme. Zeng et al. (2012) reported that the α -glucosidase activity is directly related to levels of plasma glucose, which regulates glucose absorption in patients with type 2 diabetes mellitus. So, the inhibitory effect of this Zn fortified rice on α -glucosidase activity can be considered as an effective way to reduce glucose response.

The hydrolysis rate of milled rice was slightly higher than the unmilled (0 s) parboiled rice samples. Variations in glucose rate were more prominent between the unfortified unmilled (0 s) and milled parboiled rice samples. This

may be due hindrance towards the enzyme to act on the starch substrate caused by the physical barrier of the bran (Panlasigui and Thompson 2006), or due to the presence of fats and protein interaction with starch in the bran portion (Ezeogu et al. 2008). Among the fortified samples, the 60 s milled rice had higher hydrolysis rate as compared to 30 s milled. Thus, Zn fortified parboiled rice were found to have comparatively lower hydrolysis rate as compared to PBR.

Among 30 s milled Zn fortified samples, except for Zn-3b, the hydrolysis rates were almost similar up to 30 min interval, following which differences in rate were observed among Zn fortified samples (Fig. 4b). For 60 s milled samples (Fig. 4c), slight variations were observed after 60 min interval, however variation was very less. This may be due to removal of bran layer as well as reduction in Zn content due to milling, therefore, the enzyme activity action is somewhat equally distributed, and thus variation in rate is minimized.

The average HI for PBR and Zn fortified samples showed a positive correlation ($R = 0.89$) with the milling time. The highest hydrolysis rate of 60 s milled raw rice (R-c) gave the highest HI (81), and thus the highest estimated GI (84.64). Overall, the HI of Zn fortified parboiled samples were lower than the PBR, despite similar processing condition. The lowest HI (20.52) and GI (50.97) were observed in the most concentrated unmilled Zn fortified parboiled rice (Zn-5a). Overall, the 60 s milled samples showed higher HI (Fig. 4d). Variations in processing and compositional and accompaniment factors may be attributed to the observed variation in GI (Kaur et al. 2016). Except for Zn-3a, the estimated HI and GI of PBR were higher than the Zn fortified parboiled brown rice. The results obtained in this in vitro GI study tallies with report of Wolever et al. (1986), who observed GI of 67 for white parboiled rice and 54 for parboiled rice. Our observations are nearly similar to the report of Larsen et al. (2000) who observed the GI on traditional (46) and pressure (39) parboiled rice. Thus, it was observed that the estimated GI of present study was under the low (less than 55) and medium (56–70) range.

The lower GI in Zn fortified rice might be due to inhibition of α -glucosidase enzyme activity and may also associated with the formation of steric hindrances due to reassociation of starch molecules due to parboiling, which causes more mass transfer resistances. These observations are supported by the report of Sanromán et al. (1996). Guha et al. (1997) also reported that the decrease in starch hydrolysis rate or lower digestibility of starch is associated with starch protein interaction, formation of amylose–lipid complex and water availability limitation. Even the extent of retrogradation due to formation of the resistant starch greatly influences enzyme hydrolysis (Hu et al. 2004).

Conclusion

The production of Zn fortified ready-to-eat parboiled rice (*komal chawal*) through the brown rice parboiling method was investigated as a potential to implement micronutrient fortification. The fortification process resulted in a good amount of bioaccessibility and bioavailability, and lower rate of starch hydrolysis. Low to intermediate range of GI values were also observed for the fortified rice. Thus, *komal chawal* can be considered as a value added product, and can be further investigated for obtaining other micronutrients rich ready-to-eat form of rice.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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