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PROSPECTS IN DEVELOPMENT OF QUALITY RICE FOR HUMAN NUTRITION

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ABSTRACT

Rice in the human diet serves underprivileged populations in Asia as a means of nutritional replenishment for energy and protein as well serving as a vehicle for micronutrient fortification. About 85% of rice consumption is mainly white rice. A possible relationship between white rice consumption and health risk exists. The threat is real enough for the scientific community to promote wholegrain consumption in place of refined grains. In the transitioning food environment, white rice is categorised as a refined grain and is thus implicated in the development of non-communicable diseases (NCDs). There is considerable interest in exploring glycaemic index (GI) in relation to the consumption of different rice varieties. The variable glycaemic response to rice types is better appreciated from the viewpoint of factors that moderate this response. Genetic make-up, physicochemical properties, amylose and dietary fibre content, post-harvesting processing as well as cooking methods are influential factors in determining GI variability. To date, new rice varieties bio-fortified with micronutrients such as iron, zinc and beta-carotene have been produced and useful in ameliorating the micronutrient deficiencies such as iron deficiency anaemia, stunted growth and xerophthalmia affecting children or adults in developing countries. Rice breeding and improvement programs play a major role in safeguarding the food environment, by taking into account traits that will improve rice quality in terms of GI as well as micronutrient capacity.

Key words: Rice, non-communicable diseases, human nutrition, quality, glycaemic index

INTRODUCTION

Rice is a dietary staple, and for most Asian populations, serves as a food crop that is integral with sociocultural identities. Indeed, if the history of rice cultivation is traced, it’s rooting as a food crop was associated with the earliest civilizations of *Homo sapiens* in China and India (Fuller, 2011; Callaway, 2014). The issue of *‘when, where and how’* rice was brought into cultivation and eventually domesticated by humans has been controversial as Fuller *et al.* (2009) claim *‘because rice is embedded within cultural identities within different nations in Asia, everybody wants to have had rice first’* (Liu *et al.,* 2007; Fuller *et al.,* 2009). Recently, similarities in the genomic patterns of wild and domestic strains of *japonica* and *indica* rice subtypes were reported, suggesting early domestications in both China and India occurring between 5000-4000 BC (Gross & Zhao, 2014). It was only in the 1st millennium BC that lowland *indica* rice types were brought to Southeast Asia via trading and kept for cultivation (Fuller, 2011). Today in the 21st century, more than half the global population depends on rice for energy sustenance, with almost 90% of world rice production alone originating from Asian countries, such as China, India, Bangladesh, Indonesia, Myanmar and Thailand (Khush, 2005).

Commercially, more than 2000 varieties of rice are cultivated around the globe (Deepa *et al.,* 2008). About 85% of consumed rice is in the form of polished white rice, with pigmented rice making up the remaining (Deng *et al.,* 2013). Pigmented rice is the dehusked grain, which exhibits a characteristic red, purple or black pigmentation attributable to anthocyanin compounds (Abdel-Aal *et al.,* 2006; Deng *et al.,* 2013). Alternately, brown rice may refer to pigmented rice or non-pigmented rice with the bran intact (Deng *et al.,* 2013).

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Global trade liberalization has paralleled a slow and steady transition in Asian diets away from dietary staples rich in whole grains to ultra-processed foods such as white rice, biscuits, savoury snacks, confectionaries, fast foods, processed meat and sugar-sweetened beverages (Noor, 2002; Zhai *et al.,* 2009; Misra *et al.,* 2011; Baker & Friel, 2014). In this transitioning environment, a significant consumption of white rice categorised as refined grain has been implicated in the development of non-communicable diseases (Hu *et al.,* 2012). As shown in Figure 1a, the relative risk (RR) for development of type 2 diabetes (T2D) is highest for white rice consumption by Asians (RR = 1.55, 95% confidence interval: 1.20-2.01) compared to Western populations, and even higher in comparison to sweetened beverages. Both the quantity and quality of carbohydrates affect overall glycaemic load (GL) burden and a high dietary GL has been implicated in the pathogenesis of non-communicable diseases (NCDs) (Gnagnarella *et al.,* 2008; Livesey *et al.,* 2013; Cai *et al.,* 2015). Of all dietary components, the relative risk of developing T2D is the highest with GL compared to any other food nutrient (Figure 1b). The largest burden of GL undoubtedly comes from cereal consumption and for Asians, the staple cereal is rice (Murakami *et al.,* 2006; Villegas *et al.,* 2007). This contemporary health risk contradicts the early nutritional views that rice if fortified and easily available would combat malnutrition in traditional rice-eating societies as indicated in Figure 2.

This review begins with a brief description of global rice consumption trends over the past five decades and the nutritional contribution of rice in preventing under-nutrition. It will then focus on the importance of glycaemic response as a new metric of rice quality, and will discuss the implications of habitual rice consumption in the development of NCDs. Lastly, we will discuss the potential of brown rice as a healthful grain as opposed to polished white rice in mediating metabolic risk markers in humans.

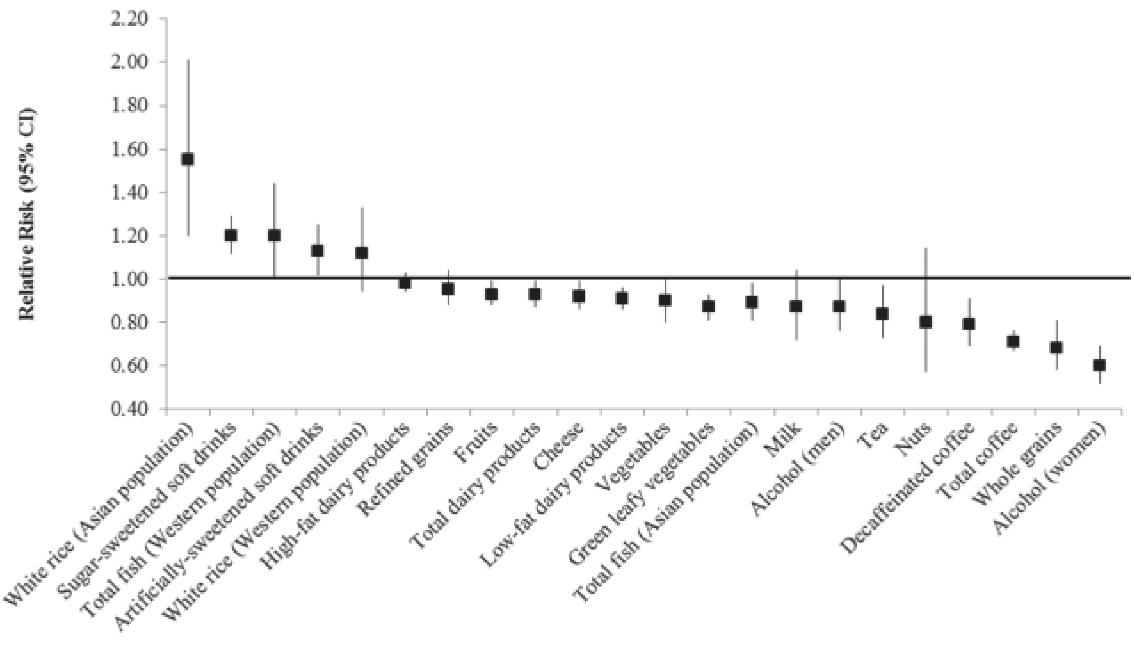

Fig. 1a. Relative risk to develop type 2 diabetes generated from meta-analyses of prospective cohort studies evaluating associations between individual food and beverage items

Footnotes

Abbreviation: CI, confidence interval

Relative risks are derived from comparisons:

(a) between the extreme categories of intakes for: white rice (Hu *et al.,* 2012), total fish (Zheng *et al.,* 2012), decaffeinated coffee and total coffee (Jiang *et al.,* 2014) and tea (Yang *et al.,* 2014);

(b) except for sugar sweetened soft drinks and artificially-sweetened soft drinks (per 330 ml.day^{-1}, Greenwood *et al.,* 2014), dairy products (total, per 400 g.day^{-1}; high-fat type, per 200 g.day^{-1}; low-fat type, per 200 g.day^{-1}; milk, per 200 g.day^{-1}; cheese, per 50 g.day^{-1}, Aune *et al.,* 2013a), refined and whole-grains (per 3 servings.day^{-1}, Aune *et al.,* 2013b), fruits, vegetables and green-leafy vegetables (an increase of 1 serving.day^{-1}, Li *et al.,* 2014a), alcohol (men, 22 g.day^{-1}; women, 24 g.day^{-1}, Baliunas *et al.,* 2009), nuts (1 serving.day^{-1}, Zhou *et al.,* 2014).

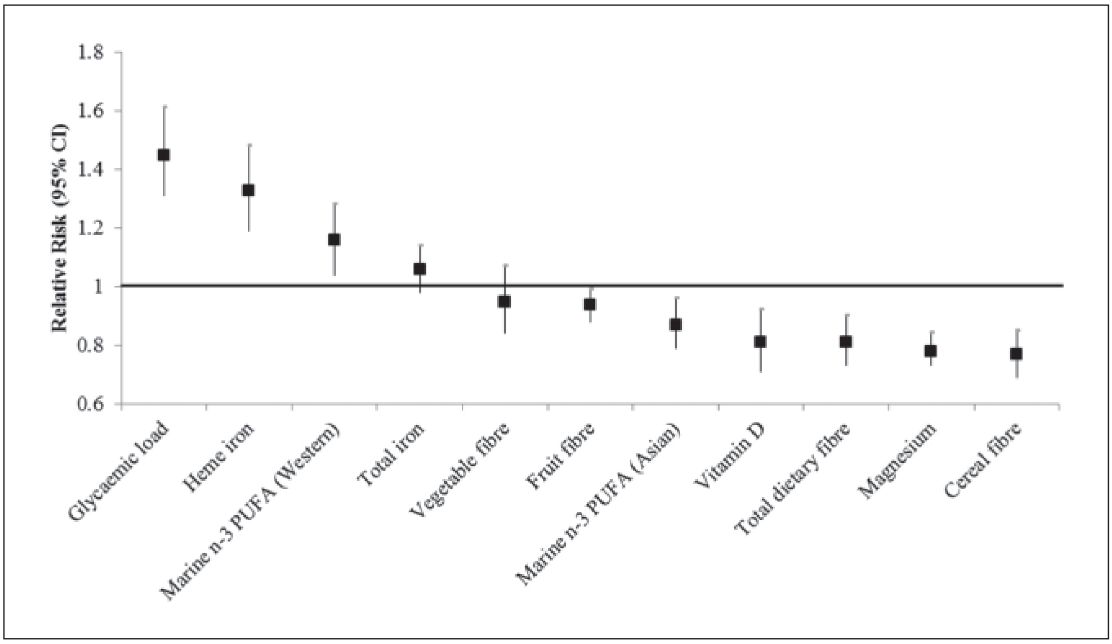

Fig. 1b. Relative risk to develop type 2 diabetes from gylcemic load compared to other single nutrients generated from meta-analyses of prospective cohort studies

Footnotes

Abbreviations: CI, confidence interval; PUFA, polyunsaturated fatty acids

Relative risks are derived from comparisons:

(a) between the extreme categories of intakes for: heme iron and total iron (Bao *et al.,* 2012), marine n-3 PUFA (Zheng *et al.,* 2012), vegetable, fruit, cereal and total dietary fibres (Yao *et al.,* 2014), vitamin D (Khan *et al.,* 2013) and magnesium (Dong *et al.,* 2011);

(b) except for glycaemic load which was as per 100-g increment in GL (Livesey *et al.,* 2013).

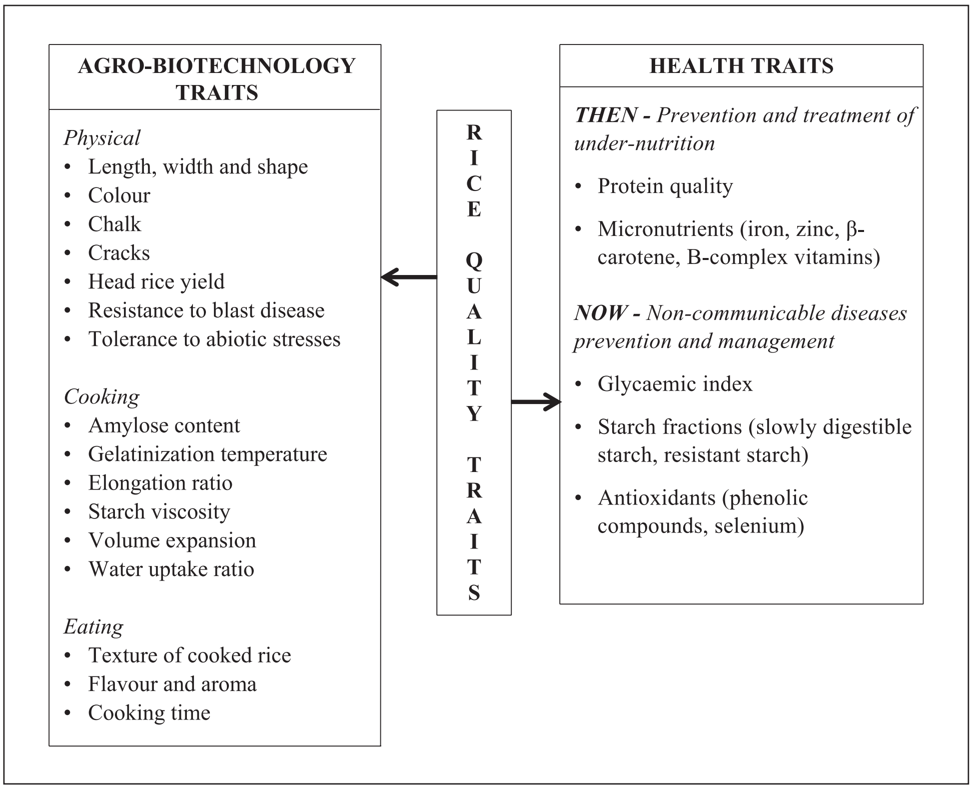

Fig. 2. Algorithm of rice quality traits: then and now

Sources: Juliano (1985); Ramesh *et al.* (2000); Fitzgerald *et al.* (2009); Bhuiyan *et al.* (2011); Bhullar & Gruissem (2013); Calingacion *et al.* (2014, 2015); Li *et al.* (2014b).

RICE CONSUMPTION TRENDS WORLDWIDE, ASIA AND MALAYSIA

Worldwide Trends on Rice Consumption

There is clear indication that the quantity of human rice consumption has steadily increased worldwide over the past half century. The global rice consumption in 2011 was 54 kg/capita/year (FAOSTAT), a 40% increased from 1961 (Figure 3). On the other hand, the global rice demand was projected to grow by 8% in the next decade (Matriz *et al.,* 2010). Expansion of dietary use of rice is mainly due to Asia: the two most populous countries, China and India together account for more than half of the global rice consumption today (Muthayya *et al.,* 2014). Nevertheless, rice consumption in Asia has remained static since the 1990s. Instead, consumption growth data is coming from regions such as Africa and America (Figure 3). This phenomenon is linked to migration of the Asian communities to Western countries (Kubo, 2004) and population growth in Africa (Suwannaporn *et al.,* 2008).

Rice Consumption Trends within Asia

Although rice is a staple food for most Asian countries (Kearney, 2010), diet transformations have taken place impacting dietary patterns reported in some countries. Two distinct phases are involved in diet transformation: (i) income-induced diet diversification and (ii) diet globalization with concomitant Westernization (Pingali, 2006). As the income per capita increases, more diverse food is affordable but traditional dietary practices are still preserved at this stage. However, the dietary pattern begins to shift away from conventional eating habits through the influence of globalization and urbanization. The transformations exhibit several distinctive features, which include (i) decline in rice consumption; (ii) rise in wheat and wheat-based products utilization; (iii) adoption of high protein and energy-dense diets; (iv) increased intake of temperate zone products and (v) increased consumption of convenience food and beverages (Pingali, 2006). Figures 4a and 4b indicate calorie and protein contributions, respectively from rice, are higher in countries with lower national gross domestic product (GDP) rates. In a low-GDP country such as Bangladesh, milled rice consumption in 2011 was 173 kg/capita/year which alone contributed to 71% and 59% of daily energy and protein intakes. This contrasted with Japan, a high-GDP nation, where milled rice consumption of 43 kg/capita/year contributed to 21% and 12% respectively to daily energy and protein intakes (FAOSTAT, 2011). Exceptions are observed for

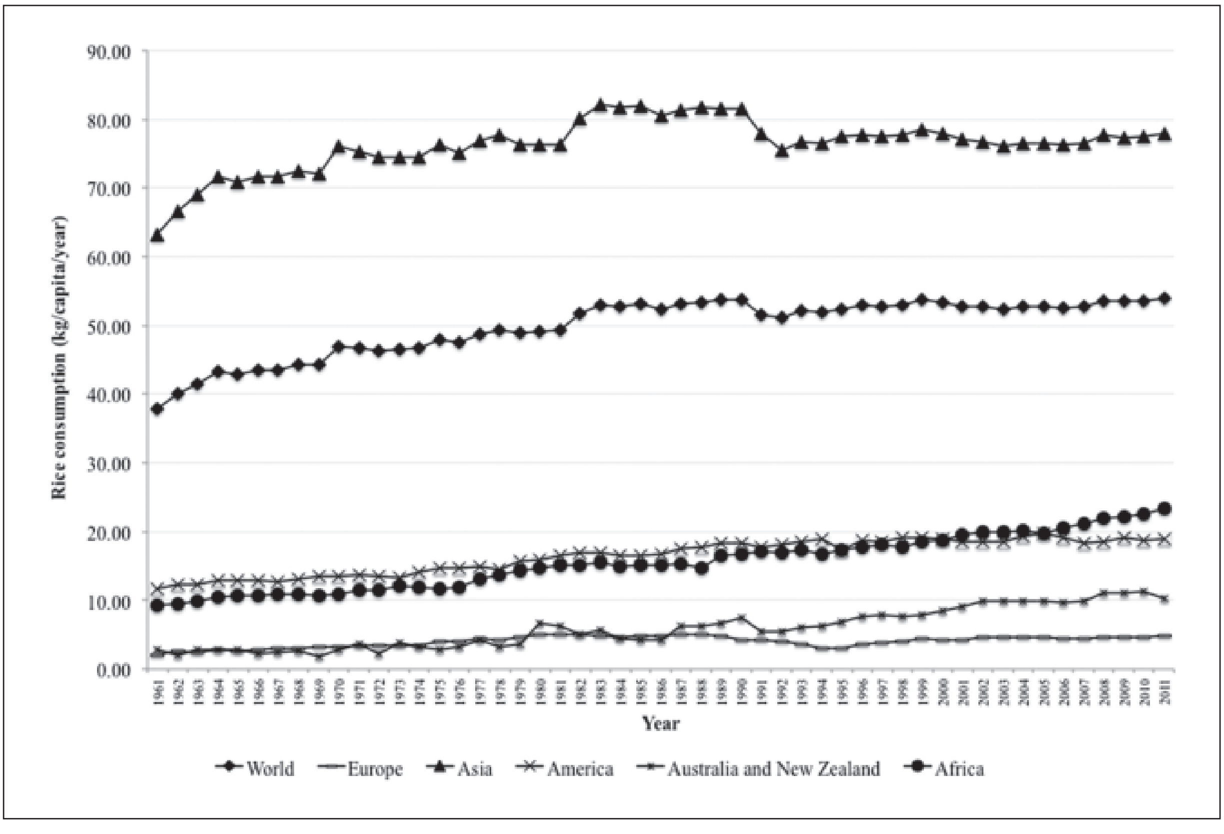

Fig. 3. Global rice consumption trends (in kg/capita/year) from 1961 to 2011.
Data sourced from FAOSTAT (2011).

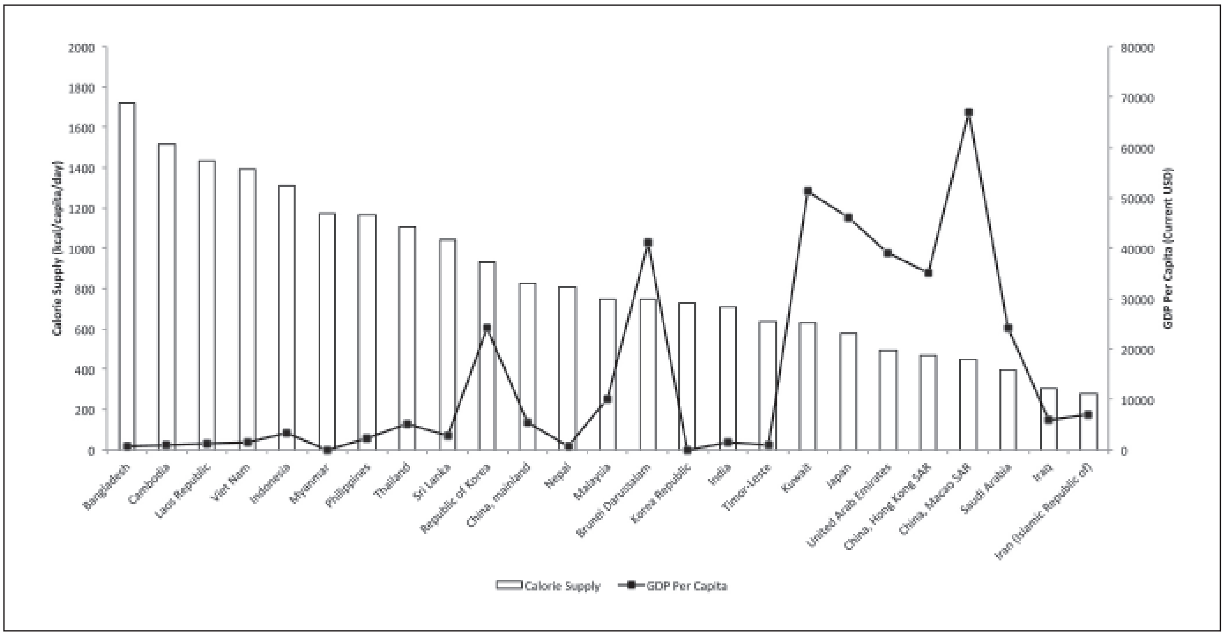

Fig. 4a. Calorie supply from rice in some Asian countries respective to national Gross Domestic Product (USD per capita). Data sourced from FAOSTAT (2011) and World Bank (2011).

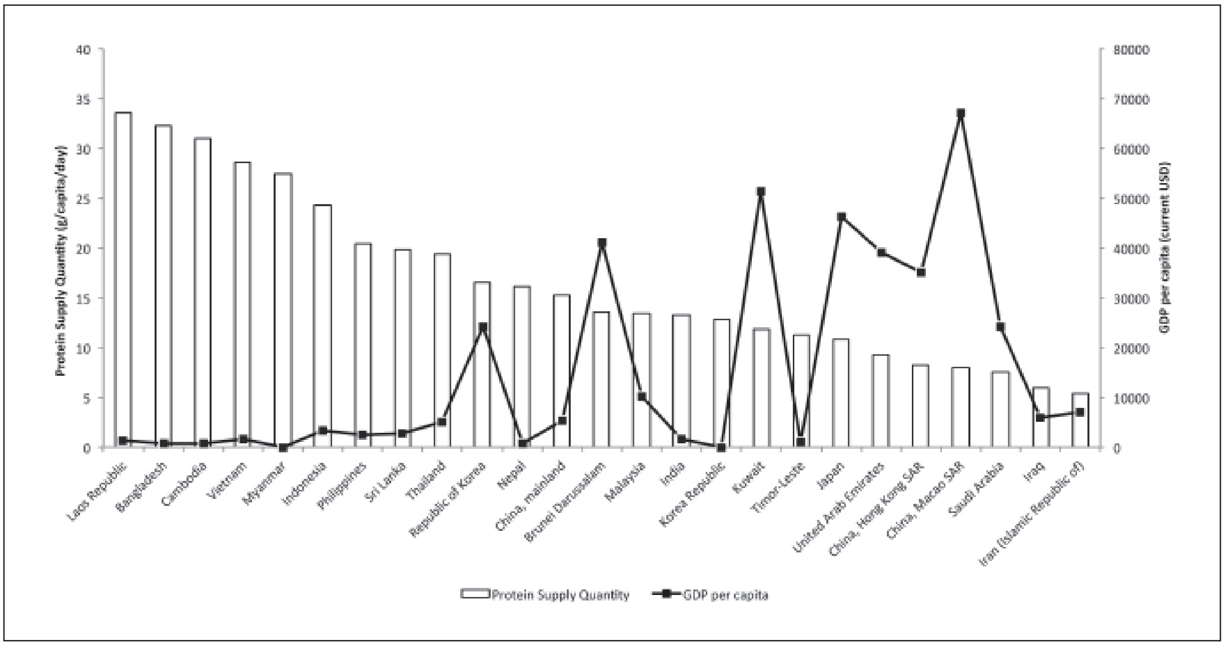

Fig. 4b. Protein supply from rice in some Asian countries respective to national Gross Domestic Product (USD per capita). Data sourced from FAOSTAT (2011) and World Bank (2011).

Korea and Brunei where rice remains popular with the local populations despite a prominent GDP rate (FAOSTAT, 2011).

Rice Consumption Trends in Malaysia

Malaysia is no exception to the influence of diet globalization and Westernization (Noor, 2002). Transformations in food consumption trends have been reported paralleling a rice consumption decline from 1961 to 2011 (FAOSTAT, 2011). In contrast, the intake of wheat and wheat-based products, protein-rich foods and temperate zone products such as dairy products and meat have increased gradually as indicated in Figure 5a. With more women joining the workforce and spending more time outside the home, convenience foods such as bread feature in

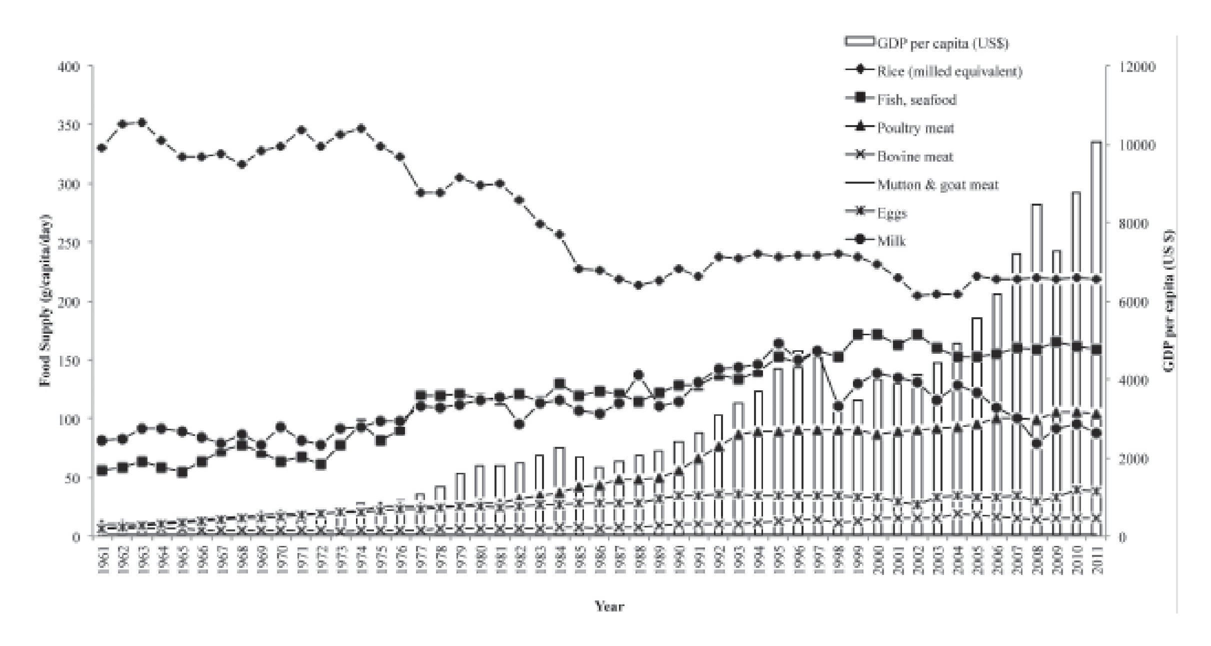

Fig. 5a. Rice and protein-rich foods consumption trends respective to national Gross Domestic Product (USD per capita) in Malaysia from year 1961 to 2011.
Data sourced from FAOSTAT (2011) and World Bank (2011).

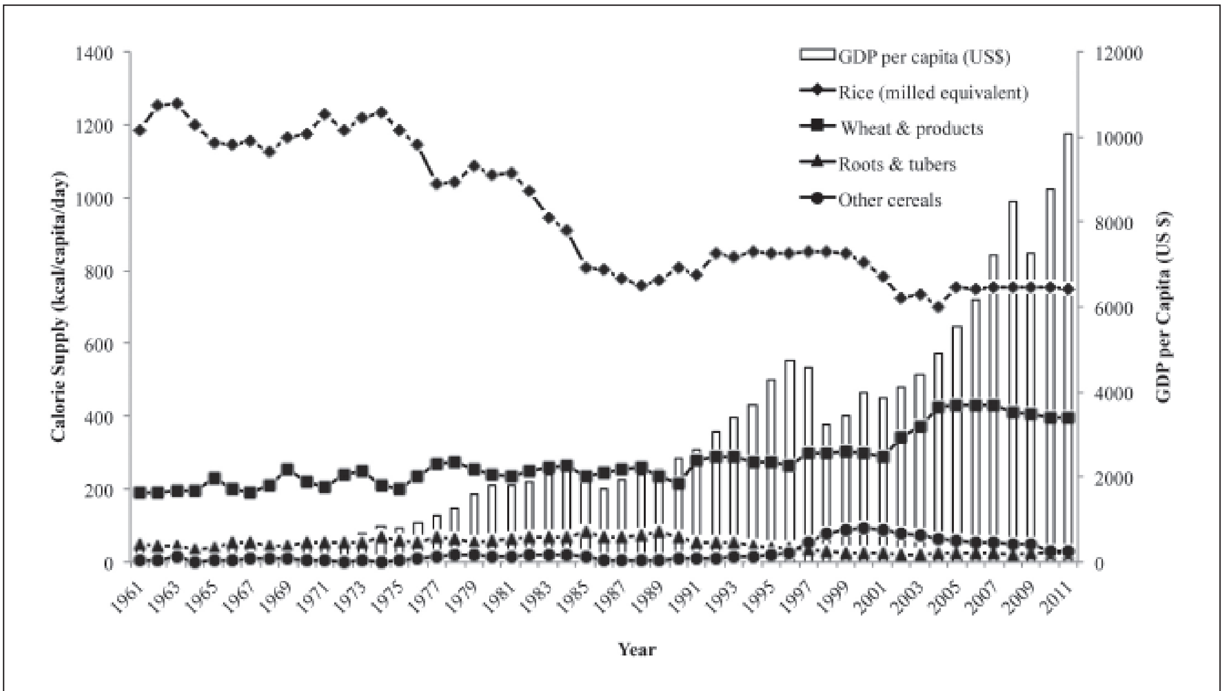

Fig. 5b. Calorie contributions by different types of cereals respective to national Gross Domestic Product (USD per capita) in Malaysia from year 1961 to 2011.
Data sourced from FAOSTAT (2011) and World Bank (2011).

the home menu (Pingali, 2006). Noticeably, calorie contribution from rice consumption from 1975 to 1985 dropped concurrent with the increased consumption of protein and wheat products (Figure 5b). This dietary transformation has been accompanied by a rise in GDP per capita during the period (from 1000 to 2000USD). After 1985, the rice consumption remained relatively constant whereas the protein food consumption continued to increase steadily over time (FAOSTAT, 2011) despite a substantial increment in GDP per capita from 2000 to 10000USD.

NUTRITIONAL PROFILE OF RICE

Rice is a good source of energy and protein. It also provides nutritionally significant amounts of vitamins (thiamine, riboflavin, niacin) and minerals (zinc and selenium), which substantially meet the daily nutrient requirement of those populations dependent on rice as a major source of energy (Juliano, 1993). The Malaysian Adult Nutrition Survey, which documented dietary intakes of 6,742 subjects reported that 97% of Malaysians consumed on average 2.5 plates of rice daily, which approximates to 60 grams of carbohydrates (Norimah *et al.,* 2008).

However, not all rice types are similar in nutrient content. Several factors affect the nutritional composition of rice. For instance, the degree of rice processing is a significant factor. As the proportion of nutrients varies in different layers of the rice seed, end products from various degrees of processing will differ in terms of texture, taste and nutrient content (Roy *et al.,* 2011). Brown rice is produced through removing of paddy hull and is composed of bran, endosperm, and embryo. Consequently, the bran layer contains greater amount of fibre, protein, lipid, vitamins and minerals. Further milling removes the bran layer to yield milled or polished rice which will be stripped off the bran-rich nutrients (Fernando, 2013). Therefore, brown rice is considered more nutritious compared to milled rice. For an equivalent amount of carbohydrate, brown rice has a relatively higher content of not just dietary fibre and protein but also micronutrients such as iron, magnesium, zinc, manganese, selenium and B-complex vitamins (Figure 6).

Conventional rice breeding and improvement programs are committed to improving rice quality in terms of yield, grain shape and length, resistance to blast disease, amylose content and aroma (Figure 2). But an early health role for rice came under the ambit of food scientists. To address the prevalence of beriberi in the early 20th century, enrichment of polished rice with the B-vitamins -thiamine, riboflavin and niacin- came about through pre-treatment of milled rice by spray-drying (WHO, 1966). An alternate approach is the parboiling process which entails steeping rice paddy in warm water, steaming and drying. This process forces the B-vitamins to diffuse from the hull into the endosperm (Ayamdoo *et al.,* 2013). But today, research progress has witnessed the production of new rice varieties bio-fortified with micronutrients such as iron, zinc and beta-carotene (Bhullar & Gruissem, 2013). This approach aims to ameliorate micronutrient deficiencies such as iron deficiency anaemia, stunted growth and xerophthalmia affecting children or adults in developing countries.

Nonetheless, brown rice is more susceptible to oxidative deterioration after prolonged storage due to the lipid content in the bran layer (Champagne *et al.,* 1991) while parboiled rice and milled rice can be stored longer and are more resistant to insects (Itoh *et al.,* 1985). Other factors that alter the nutrient content of rice include (i) interspecies differences;

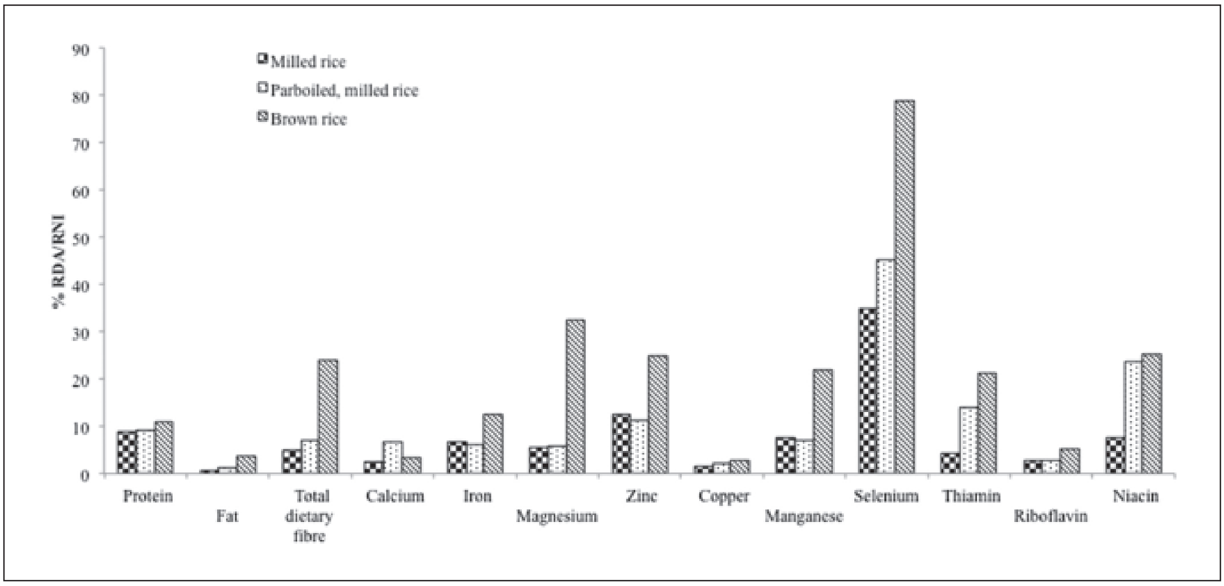

Fig. 6. Nutrient composition based on equivalent carbohydrate content ≈ 60g for milled *vs* parboiled, milled *vs* brown rice varieties compared to the Recommended Daily Allowance (RDA) (Institute of Medicine 2001) or Recommended Nutrient Intakes (RNI) for Malaysians (National Coordinating Committee on Food and Nutrition 2005).

(ii) agriculture practices (soil nitrogen, solar radiation, application of fertilizer and etc.); (iii) storage; (iv) washing and (v) cooking practices (Roy *et al.,* 2011).

RICE BRAN OIL AND CARDIOVASCULAR HEALTH

Rice bran oil (RBO) is oil extracted from the bran of the rice seed (Cicero & Derosa, 2005). Global consumption of this oil has increased 10 times by 2011 from 70000 tonnes in 1961 with most of the supply coming predominantly from China (105000 tonnes) and India (506207 tonnes) with minor productions from Thailand and Vietnam (FAOSTAT, 2011). The fatty acid composition (FAC) profile of RBO is dominated by unsaturated fatty acids such as oleic acid (38.4%), linoleic acid (34.4%) and α-linolenic acid (2.2%) with a smaller fraction from saturated fatty acids, such as palmitic (21.5%) and stearic (2.9%) acids (Cheruvanky & Thummala, 1991). Both animal (Cheruvanky & Thummala, 1991; Wilson *et al.,* 2007) and human studies involving mildly hypercholesterolemic (Lichtenstein *et al.,* 1994; Berger *et al.,* 2005) and type 2 diabetes (Lai *et al.,* 2011) patients have highlighted cholesterol-lowering properties of rice bran oil. In addition, a plant sterol-based spread derived from rice bran oil was efficacious in reducing plasma lipid levels in mildly hypercholesterolemic patients (Eady *et al.,* 2011).

Independent of its favourable FAC profile, the polyphenol-rich content of RBO may also confer cholesterol-lowering effects (Most *et al.,* 2005), namely γ-oryzanol, phytosterols, tocopherols and tocotrienols (Cicero & Derosa, 2005). It is hypothesized that phystosterols and γ-oryzanol reduce cholesterol absorption in the intestines and increase excretion of bile acids, which indirectly results in plasma cholesterol reduction (Cicero & Derosa, 2005; Chou *et al.,* 2009). On the other hand, tocotrienols are reported to regulate cholesterol synthesis and catabolism at transcriptional level by increasing hepatic HMG-CoA reductase, CYP7A1 and LDL-receptor expressions in animal studies (Cicero & Derosa, 2005; Chen & Cheng, 2006). Overall, the application of rice polyphenols to human health remains to be studied.

GLYCAEMIC VARIABILITY OF RICE VARIETIES

Glycaemic index (GI) is a metrological approach to quantifying the human postprandial glucose response immediately after consuming fixed amounts of carbohydrate-rich foods (Jenkins *et al.,* 1981). As rice is a major global staple, there is considerable interest in exploring postprandial glycaemia in relation to the consumption of different rice varieties. The GI values derived from many studies have been published in *The International Tables of GI and GL Values* (Foster-Powell *et al.,* 2002; Atkinson *et al.,* 2008). Epidemiological studies describing the carbohydrate quality in diets consumed by different populations have utilized the GI tables to quantify daily dietary GI and GL to elucidate the diet-disease relationship (Murakami *et al.,* 2006; Villegas *et al.,* 2007; Oba *et al.,* 2010).

There is a wide range in GI values for the same type of rice (Table 1). For instance, the 10 entries for jasmine rice ranged from 48 to 109, whereas six entries for basmati rice ranged from 43 to 69 (Foster-Powell *et al.,* 2002; Atkinson *et al.,* 2008). Generally, GI values for brown rice and white rice averaged 68 and 72, respectively (Foster-Powell *et al.,* 2002). The differences in reported GI values could be attributed to rice preparation techniques (e.g. rice-to-water ratio, cooking time and heat intensity), blood collection method (finger-prick *vs* venous blood) or prandial blood event sampling time frame (Table 1). Therefore, the clinical relevance and application of GI have been questioned (Coulston & Reaven, 1997; Pi-Sunyer, 2002; Wolever, 2013).

A better differentiation of rice characteristics based on extrinsic and intrinsic factors which affect grain digestibility and mediate resultant glycaemic response, would be important in the development of new rice varieties with low GI potential. New brown rice varieties have been reported with low GI such as produced by cross-breeding programs (Karupaiah *et al.,* 2011; Trinidad *et al.,* 2013) or increasing resistant starch content via genetic modification (Li *et al.,* 2010). Therefore, genetic make-up, physicochemical properties, amylose and dietary fibre content, post-harvesting processing as well as cooking methods (Table 1) are influential factors in determining GI variability and will be discussed in the following sections.

Amylose to Amylopectin Ratio

Common to all cereals, rice starch is differentiated into two starch subtypes, the longer straight, minimally-branched chain amylose polymer and the relatively shorter and highly-branched amylopectin (Juliano, 2003); but it is their distributional content that determines rice eating and cooking qualities (Tan & Corke, 2002). Milled rice can be grouped into *waxy* (1-2% amylose), *very low* (2-9% amylose), *low* (10-20% amylose), *intermediate* (20-25%) and *high* (25-33% amylose) categories (Juliano, 2003). A higher amylose content in rice translates into greater volume expansion and

Table 1. Studies evaluating glycaemic index of different rice varieties in healthy populations[a]

Country	Participants' characteristics	Tested rice	Reference food	Rice cooking method	Blood sampling method	(Item no.) GI[b]	References
New Zealand	n=14; Age, 31 ± 11 years; BMI, 25.0 ± 4.6 kg/m^2; FPG, 5.10 ± 0.48 mmol/L	1. Parboiled white, long-grain (Uncle Ben's)	Dextrose (50g available CHO) in 400mL water	According to manufacturer's instructions	Venous blood (2-h period)	(1) 56 ± 7	Perry *et al.* (2000)
Australia	n=12 (6 Asian/ 6 Caucasian)	1. Broken rice 2. Glutinous rice 3. Jasmine rice, long-grain	Glucose (50g available CHO) in 250mL water	Cooked in a rice cooker using 2 volumes of water for each weight of rice	Finger-prick (2-h period)	(1) 86 ± 8 (2) 94 ± 6 (3) 109 ± 10	Chan *et al.* (2000)
Malaysia	n=10; 7 males; Age, 25 ± 4 years; BMI, 23.6 ± 2.3 kg/m^2	1. High fibre rice A 2. High fibre rice B 3. High fibre rice C 4. White rice D 5. White rice E 6. White rice F 7. Fragrant rice G 8. Fragrant rice H	Glucose (50g available CHO) in 250mL water	According to manufacturer's instructions	Finger-prick (2-h period)	(1) 81 ± 7 (2) 60 ± 6 (3) 87 ± 9 (4) 72 ± 9 (5) 61 ± 6 (6) 69 ± 8 (7) 79 ± 8 (8) 80 ± 6	Barakatun Nisak *et al.* (2005)
United Kingdom	n=8-10; Age, 18-55 years; BMI, ≤25 kg/m^2; FPG, <6.1 mmol/L	1. Basmati, Indian, boiled 8 min 2. Basmati, Indian, easy-cook, boiled 9 min 3. Basmati, boiled 12 min 4. Basmati, organic, boiled 10 min	Glucose (50g available CHO) in 200mL water	According to manufacturer's instructions	Finger-prick (2-h period)	(1) 69 ± 6 (2) 67 ± 11 (3) 52 ± 11 (4) 57 ± 10	Henry *et al.* (2005)
Canada	n=10; 7 females; Age, 33 ± 3 years	IR42, high-amylose 29.1% 1. Dehulled (brown, BR) 2. Polished (white, WR)	White bread (50g available CHO) with 250mL or 500mL water	BR boiled in 275g water for 30 min on controlled heat settings; WR boiled in 172g water for 22 min on controlled heat settings	Finger-prick (1-h period)	WR-based (1) 83 ± 11 (2) 94 ± 11 GLU-based (1) 58 (2) 66	Panlasigui & Thompson (2006)
China	n=8-12; Age, 20-45 years; BMI, 18.5-25 kg/m^2	1. White rice 2. Brown rice 3. Sticky rice A 4. Sticky rice B 5. Sticky rice C (higher amylose) 6. Instant rice, in hot water 3min 7. Instant rice, cooked 6min	Glucose (50g available CHO) in 200mL water	Cooked by "traditional method" used in Chinese's daily lives	Venous blood (2-h period)	(1) 83 ± 3 (2) 87 ± 5 (3) 87 ± 7 (4) 88 ± 6 (5) 50 ± 6 (6) 46 ± 9 (7) 87 ± 6	Yang *et al.* (2006)
United Kingdom	n=10	1. Basmati, regular 2. Basmati, easy-cook 3. American, easy-cook	Glucose 50g available CHO) (in 250mL water	According to manufacturer's instructions	Finger-prick (2-h period)	(1) 43 ± 8 (2) 68 ± 8 (3) 49 ± 12	Aston *et al.* (2008)
Iran	n=30; Age, 35 ± 2 years; BMI, 23.0 ± 0.8 kg/m^2; FPG, 89 ± 7 mg/dL	1. Sonna Pearl, white 2. Kazema, white 3. Basmati, white	Dextrose (50g available CHO) – *volume of water not mentioned*	Cooked with 2% salt and without any oil *(rice: water ratio not mentioned)*	Venous blood (2-h period)	(1) 52 ± 1 (2) 68 ± 2 (3) 61 ± 1	Zarrati *et al.* (2008)

United Kingdom	n=14; 6 males; Age, 38 ± 16 years; BMI 21.3 ± 2.3 kg/m^2	1. Basmati, white 2. Basmati, brown 3. Mixed basmati white and brown 4. Mixed basmati white and wild rice 5. Basmati, easy-cook 6. Long-grain rice, easy-cook 7. Thai red rice 8. Thai glutinous rice	Glucose (50g available CHO) in 200mL water	Cooked individually in 850mL water	Finger-prick (2-h period)	(1) 50 ± 6 (2) 75 ± 8 (3) 59 ± 9 (4) 63 ± 8 (5) 80 ± 8 (6) 47 ± 6 (7) 76 ± 8 (8) 92 ± 8	Ranawana *et al.* (2009)
Bangladesh	n=10; 5 males; Age, 29 ± 6 years; BMI, 22.5 ± 2.5 kg/m^2	Bangladesh, high-amylose (AM) varieties 1. BR-14 (27% AM) 2. BR-19 (29% AM) 3. BR-44 (27% AM)	Glucose (50g available CHO) in 250mL water	*Boiled with sufficient water until it got to appropriate softness. Water was drained after boiling.*	Venous blood (2-h period)	(1) 55 ± 5 (2) 50 ± 6 (3) 43 ± 12	Fatema *et al.* (2010)
China	n=16; 9 males; Age, (men) 24 ± 1 years (women) 25 ± 1 years; BMI, 18-24 kg/m^2	1. Genetically-modified resistant starch-enriched rice (8.05g RS/40g available CHO) 2. Regular, wild-type rice (0.97g RS/40g available CHO)	Glucose (40g available CHO) in 300mL water	Not mentioned	Venous blood (4-h period)	(1) 48 ± 5 (2) 77 ± 9	Li *et al.* (2010)
Sri Lanka	n=10; Age, 25-45 years; normal BMI	<u>*Unparboiled white rice*</u> 1. Bg 300 2. Bg 352 3. Bg 358 4. Bg 406 5. LD 356 6. Rathkaral 7. Wedaheenati 8. Heendikwel <u>*Parboiled white rice*</u> 9. Bg 352 10. Bg 358 11. Bg 406 12. LD 356	Glucose (50g available CHO) in 250mL water	Cooked with similar quantity of water and rice (rice: water ratio 1:1)	Finger-prick (2-h period)	(1) 61 ± 3 (2) 67 ± 3 (3) 67 ± 6 (4) 73 ± 2 (5) 70 ± 2 (6) 60 ± 2 (7) 57 ± 1 (8) 62 ± 2 (9) 60 ± 2 (10) 62 ± 2 (11) 64 ± 5 (12) 71 ± 2	Pathiraje *et al.* (2010)
United Kingdom	n=13; 7 females; Age, 30 ± 2 years, BMI, 25.6 ± 1.0 kg/m^2; FPG, 5.0 ± 0.1 mmol/L	1. Hassawi rice 2. Parboiled rice (Uncle Ben's)	Glucose (25g available CHO) in 250mL water	Cooked in "traditional ways" with rice: water ratio 1:2	Finger-prick (2-h period)	(1) 59 ± 5 (2) 54 ± 7	Al-Mssallem *et al.* (2011)
Malaysia	n=9; Age, 23 ± 3 years; BMI, 22.9 ± 3.4 kg/m^2; FPG 4.65 ± 0.26 mmol/L	1. Transgressive red rice (dehulled) 2. Transgressive red rice (polished) 3. White rice	Glucose (50g available CHO) in 250mL water	Cooked individually in a rice cooker with 2 mL water/g rice	Venous blood (3-h period)	(1) 51 ± 8 (2) 79 ± 14 (3) 86 ± 14	Karupaiah *et al.* (2011)
India	n=23; 12 males; Age, 23 ± 2 years; BMI, 20.7 ± 1.3 kg/m^2; FPG 4.7 ± 0.3 mmol/L	1. Sona Masuri, white 2. Ponni, white 3. Surti Kolam, white	Dextrose (50g available CHO) in 200mL water	Cooked in a rice cooker with rice: water ratio 1:3.5	Finger-prick (2-h period)	(1) 72 ± 5 (2) 70 ± 4 (3) 77 ± 4	Shobana *et al.* (2012)

United States of America	n=21; 12 males; Age, 22-57 years; BMI, 18.5-30.1 kg/m^2	1. High resistant starch rice (4.4g RS/50g available CHO) 2. Low resistant starch rice (0.4g RS/50g available CHO)	Glucose (50g available CHO) – *volume of water not mentioned*	<u>*High RS rice*</u> Refrigerated long grain rice prepared with rice cooker for 20-30 min (rice: water ratio 1:1.5) <u>*Low RS rice*</u> Refrigerated short grain rice prepared with pressure cooker for 6 min (rice: water ratio 1:4) *– excess water was drained*	Finger-prick (2-h period)	(1) 84 ± 7 (2) 78 ± 11	Chiu & Stewart (2013)

New Zealand	<u>*Chinese group*</u>
	n=32; 17 males;
	Age, 33 ± 8 years;
	BMI, 22.9 ± 2.7 kg/m^2;
	FPG, 4.80 ± 0.38 mmol/L
	
	<u>*European group*</u>
	n=31; 15 males;
	Age, 34 ± 8 years;
	BMI, 25.8 ± 4.8 kg/m^2;
	FPG, 4.80 ± 0.44 mmol/L
		1. Jasmine white, Sun Rice
		2. Basmati, Sun Rice
		3. Brown, Sun Rice
		4. Doongara, Sun Rice
		5. Parboiled, Uncle Ben's
			Carbotest 50-g glucose drink	Cooked in a rice cooker with the same rice: water ratio – *not specified*	Finger-prick (2-h period)	<u>*Chinese*</u>
						(1) 80 ± 1
						(2) 67 ± 1
						(3) 78 ± 1
						(4) 67 ± 1
						(5) 72 ± 1
						
						<u>*European*</u>
						(1) 68 ± 1
						(2) 57 ± 1
						(3) 65 ± 1
						(4) 55 ± 1
						(5) 57 ± 1
							Kataoka *et al.* (2013)

India	n=83 (only 70 was included in final analysis); 64 males; Age, 26 ± 5 years	1. Thermally treated basmati	Dextrose (50g available CHO) in 200mL water	Cooked in a rice cooker with rice: water ratio 1:1.5	Finger-prick (2-h period)	(1) 55 ± 1	Srinivasa *et al.* (2013)
Philippines	n=10; Age, 27-55 years	<u>*Milled rice*</u> 1. Sinandomeng 2. IR64 3. IMS 2 4. NSIC Rc160 5. PSB Rc18 6. PSB Rc12 7. PSB rc10 <u>*Brown rice*</u> 8. Sinandomeng 9. IR64	Glucose drink (Medic Orange) 50g glucose in 240mL	<u>*Milled rice*</u> Cooked in rice cooker with water: rice ratio from 1.2-1.8 to achieve similar Intron hardness <u>*Brown rice*</u> Uses ratio 1.75-2.0 and pre-soaked for 30min to achieve similar Intron hardness	Finger-prick (2-h period)	(1) 75 ± 4 (2) 57 ± 3 (3) 63 ± 2 (4) 70 ± 4 (5) 59 ± 4 (6) 63 ± 3 (7) 50 ± 3 (8) 55 ± 2 (9) 51 ± 1	Trinidad *et al.* (2013)
United States of America	n=12; 9 females; Age, 29 ± 6 years; BMI, 23 ± 3 kg/m^2; FPG, 93.4 ± 10.3 mg/dL	1. Della US jasmine 2. Jazzmen US jasmine 3. Reindeer Thai jasmine 4. Mahatma Thai jasmine	Glucose (50g available CHO) in 250mL water	Cooked individually in a rice cooker with rice: water ratio 1:1	Finger-prick (2-h period)	(1) 96 ± 17 (2) 106 ± 13 (3) 115 ± 11 (4) 116 ± 7	Truong *et al.* (2014)

BMI, body mass index; CHO, carbohydrate; FPG, fasting plasma glucose; RS, resistant starch.

flakiness but cook dry, are less fluffy and turn hard after cooling. On the contrary, cooked low-amylose rice grains are moist and sticky. Intermediate-amylose rice is therefore preferred in most rice-cultivating areas of the world, except where low-amylose *japonica* varieties are grown (Calingacion *et al.,* 2014).

The relationship between amylose content of rice and postprandial glycaemia is inconsistent. Goddard *et al.* (1984) reported that consumption of high-amylose (23-25%) rice resulted in significantly lower glycaemic and insulin responses compared to low (14-17%) and waxy (0%) rice varieties. This observation was attributed to greater amylose-lipid complex in high-amylose rice, which resulted in delayed starch hydrolysis. Amylose-lipid complex has been shown to restrict granule swelling during cooking (Tester & Morrison 1990), which impedes the accessibility of amylase enzymes into the granules. However, Panlasigui *et al.* (1991) reported that three high-amylose (26.7–27.0%) rice varieties differed significantly in *in vitro* starch digestion rate and *in vivo* glycaemic response (GI, 55 vs 65 vs 81). Despite having similar amylose content, these rice varieties exhibited varied physicochemical properties relating to gel consistency, gelatinization temperature and amylograph viscosity. This finding concurred with Dhital *et al.* (2015) who showed clearly that amylose content is not a rate-limiting factor to assess *in vitro* starches' susceptibilities to amylase enzymes. Other rice properties relating to morphology or presence of intact non-polysaccharides (fibre) or lipid and protein matrices, could potentially encapsulate starch granules and thus lower starch digestibility (Dhital *et al.,* 2015).

In a pooled analysis of 235 varieties of rice evaluating GI, Fitzgerald *et al.* (2011) concluded that amylose is the major grain constituent which negatively associates with its GI. But this analysis could not explain as to why GI variability was evident within each category of amylose content. Fitzgerald *et al.* (2011) hypothesize that rice GI effect would be best attributed to the interaction between other loci within the *Waxy* gene of the grain.

Post-Harvesting Technologies and Thermal Processing

Rice can be prepared for human consumption using a wide range of cooking methods, depending on the country of origin, culinary and cultural backgrounds. These include boiling, parboiling, steaming, pressure cooking, straining, baking as well as techniques inherent to the recipes such as the Chinese-styled stir-frying, Middle Eastern-styled pilaf and Italian-styled risotto (Rashmi & Urooj, 2003; Hensperger & Kaufmann, 2012). Basically, during cooking, rice starch undergoes gelatinization, loses its crystalline structure and organization and becomes susceptible to hydrolysis by α-amylases. Steamed rice has the lowest rapidly digestible starch (RDS) and highest slowly digestible starch (SDS) contents whilst boiling and pressure cooking significantly elevates RDS values irrespective of rice type (Rashmi & Urooj, 2003). *In vitro* digestibility of rice starch with higher resistant starch (RS) and SDS content produces lower *rapidly available glucose* (RAG) and a lower *starch digestible index* (SDI) (Rashmi & Urooj, 2003). These metrics have been proposed as a surrogate indicator of rice GI (Englyst *et al.,* 1996).

A greater degree of gelatinization occurs in cooked rice after pressure cooking compared to cooking by either electric cooker or microwave oven (Lee *et al.,* 2005). Greater gelatinization consequently led to greater *in vitro* starch hydrolysis rates and postprandial plasma glucose in rats (Lee *et al.,* 2005). Further, reducing the rice:water ratio from 1:2 to 1:1 significantly increased the RS content in both freshly prepared and cooled after cooking rice samples (Kim *et al.,* 2006). Additional water used in cooking allows a greater swelling and disruption of the starch granules, which contributes to greater RS formation when starch retrogrades (Sagum & Arcot, 2000). Reed *et al.* (2013) reported that compared to steamed and pilaf rice, stir-frying rice resulted in the slowest starch hydrolysis rates and this could be attributed increased amounts of retrograded starch after chilling as well as formation of amylose-lipid complexes and lipid coating of the starch after stir-frying with oil. The utility of the *in vitro* approach in determining starch digestibility suggests a validation process should compare this method with the *in vivo* approach of human postprandial glycaemic testing.

Anti-nutrients

Anti-nutrients are the natural or synthetic compounds which potentially impede or reduce the absorption of other nutrients in the gastrointestinal tract (Zhou & Erdman, 1995). Phytic acid, or inositol hexophosphate (IP6) is often deemed as an anti-nutrient due to its strong affinity to chelate divalent metal cations (calcium, zinc, iron, copper), precipitate and form insoluble salts which renders these minerals unavailable for absorption (Zhou & Erdman, 1995). A cross-sectional analysis of phytate content in several Malaysian rice samples reported a range of 36-92 mg/100g raw rice (Norhaizan & Nor Faizadatul Ain, 2009). These values are lower than values reported in China [55-183 mg/100g] (Ma *et al.,* 2005) and Korea [160-955 mg/100g] (Joung *et al.,* 2004).

Yoon *et al.* (1983) found that increased phytate intake from cereal and leguminous foods negatively correlated with GI. Phytate alters starch digestibility via three mechanisms: [i] binding to starch by hydrogen bonding; [ii] indirectly bonding to starch proteins or [iii] binding to α-amylase or enzyme cofactors such as calcium which would delay digestion and absorption of ingested starch (Jenab & Thompson, 2002). In fact, phytate has been shown to inhibit the α-glucosidase and α-amylase in a dose-dependent manner (*in vitro*) as well as lowering glycated haemoglobin and lipid peroxidation in diabetic rats (*in vivo*) after treatment with IP6 rice for 28 days (Kuppusamy *et al.,* 2011). In line with this, Omoruyi *et al.* (2013) highlight a reduction in intestinal amylase activity in diabetic rats fed with phytate supplement (4% of rodent chow) compared to a control group.

Although the direction of research indicates the potential of higher phytate in modulating glycaemic response to rice, its interference with micronutrient absorption should be considered from the point of overall health. In fact, crop science has expanded to developing new rice varieties with low phytate content (Feng & Yoshida, 2004; Ali *et al.,* 2013).

Non-starch polysaccharides (Dietary fibre)

Non-starch polysaccharides (NSPs) or commonly known as dietary fibre relates to the *edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine* (American Association of Cereal Chemists, 2001). Dietary fibre includes two major classes based on solubility which are [i] soluble fibre such as pectins, gums and β-glucans and [ii] insoluble fibre, which includes cellulose, lignin and hemicelluloses. Fibre itself does not have a GI value as it does not contain any glycaemic carbohydrate, but addition of fibre to carbohydrate-rich foods contributes to the GI-lowering effect of the food (Jenkins *et al.,* 1986). Jenkins *et al.* (2002) proposed a model called *Glycemic Reduction Index Potential* (GRIP) to quantify the anticipated reduction in GI units/gram of fibre, when fibre is added to a food.

Panlasigui and Thompson (2006) compared the *in vitro* digestion rate and postprandial glycaemic response of brown and polished rice of the same variety in healthy and diabetic subjects. The GIs of brown rice were significantly lowered by 12.1% in healthy volunteers whilst in diabetic patients, the reduction approximated 36%. Similarly, removing the bran layer was found to increase the GI value of a crossbred red rice variant from 51 (dehusked) to 79 (polished) (Karupaiah *et al.,* 2011). In Philippines, a brown rice variant called *Sinandomeng* was categorised as low GI (=55) whilst the milled version had a high GI value (=75) (Trinidad *et al.,* 2013). These studies suggest that the bran which encapsulates the rice kernels serves as a physical barrier which deters water absorption and delays the swelling of starch granules during thermal processing (Panlasigui & Thompson, 2006; Karupaiah *et al.,* 2011; Trinidad *et al.,* 2013) as well as reduces the accessibility of hydrolytic enzymes (Sasaki & Kohyama, 2011; Dhital *et al.,* 2015). Some studies, however, could not establish a link between GI and dietary fibre in rice (Barakatun Nisak *et al.,* 2005; Yang *et al.,* 2006; Ranawana *et al.,* 2009).

Polyphenols

Polyphenols include phenolic acids, flavonoids, anthocyanins, stilbenes, lignans and polymeric lignin found in plant-based foods, such as whole grains, cereals, fruits, vegetables, legumes, cocoa, tea, coffee and wine (Pandey & Rizvi, 2009). Plant-based polyphenols have been hypothesized to regulate and improve glycaemia through 4 mechanisms [i] inhibition of intestinal α-amylase and α-glucosidase; [ii] reduction of gluconeogenesis and increase of glycogenesis and glycolysis; [iii] increase of peripheral insulin sensitivity and glucose uptake and [iv] exerting anti-oxidative properties which improve β-cell function and insulin secretion (Hanhineva *et al.,* 2010; Bahadoran *et al.,* 2013).

Ferulic acid, a predominant phenolic acid found in most rice types (Sompong *et al.,* 2011; Fasahat *et al.,* 2012; Deng *et al.,* 2013) suppresses blood glucose by enhancing glucokinase activity, promoting glycogenesis and stimulating plasma insulin secretions in diabetic rats (Jung *et al.,* 2007). A 4-week intervention using anthocyanin-rich extract derived from black rice ameliorated glucose intolerance and insulin resistance in rats fed with high-fructose diet (Guo *et al.,* 2007). In addition, black rice exhibited the highest α-glucosidase inhibitory activity compared to red and purple rice, and this was attributed to the relatively greater total phenolic and anthocyanin contents in black rice (Yao *et al.,* 2010).

Current evidence based on *in vitro* and animal studies indicate the potential of polyphenols to retard starch digestion and delay postprandial glycaemia. Extrapolation with human clinical studies is needed to confirm if polyphenol-rich pigmented rice is able to regulate postprandial glucose homeostasis. Further, a dose-response relationship of polyphenols should be explored in these studies.

Organic Acid

The use of organic acids is common in some Asian culinary practices, such as adding vinegar in *sushi* (Japan) or tamarind in *puliyodharai* (India).

Sugiyama *et al.* (2003) observed a GI-lowering effect when acetic acid (the main component of vinegar) was added to white rice (GI = 80) in the making of *sushi* (GI = 67), even at low concentrations (0.2-1.5 $g.100g^{-1}$). An initially proposed mechanism was, addition of acetic acid in a meal could delay the gastric emptying, and hence decelerate postprandial glucose release (Liljeberg & Bjorck, 1998). But it was recently reported that acid and heat-moisture treated rice starches, irrespective of amylose content, had significantly greater RS content (30.1-39.0%) compared to native rice starches (6.3-10.2%) or heat-moisture treated rice starches (18.5-23.9%); and this effect became enhanced with acid treatment in the order of citric > lactic > acetic acids (Hung *et al.,* 2015). An explanation is that the production of low-molecular-weight starch fractions from acid hydrolysis promotes retrogradation and realignment of starch to form double helices during heat-moisture treatment (Chung *et al.,* 2009). Further, the cross-linkages and novel crystallites formed as a result of esterification between organic acids and rice starch may render a greater resistance to enzymatic digestion (Shin *et al.,* 2009; Hung *et al.,* 2015), which in turn leads to lower starch digestibility. Future studies should explore the mechanisms of food acid addition to rice preparation in relation to human postprandial glycaemic response.

Chewing Degree

Chewing or mastication is a process in which ingested foods are ground and broken down by teeth into smaller particles to prepare for further digestion in the gastrointestinal tract (Pereira *et al.,* 2007). This process increases the surface area of the chewed bolus, allowing greater accessibility to digestive enzymes, therefore resulting in an increased rate of digestion (Read *et al.,* 1986; Hoebler *et al.,* 2000; Ranawana *et al.,* 2010).

The relationship between chewing rate and postprandial glycaemia was first tested and reported by Read *et al.* (1986). Ingesting and swallowing rice whole, instead of chewing thoroughly, significantly reduced peak glucose response (5.3 *vs* 7.1 $mmol.L^{-1}$) and area under the blood glucose curve (86 *vs* 244 $mmol.min^{-1}$) in healthy, young adults (Read *et al.,* 1986). This study suggested particle size of rice is partly accountable for postprandial digestibility. However, these findings lack clinical practicality as swallowing foods whole increases choking risk, reduces the pleasure of eating as well as potentiates abdominal discomfort and distension due to incomplete digestion. It was then reported that habitual mastication and eating behaviour differs between individuals, and these may account for individual variability in postprandial glycaemic response (Ranawana *et al.,* 2010). In a recent study by Ranawana *et al.* (2014), chewing rice thoroughly (30 chews per mouthful, CPM) significantly elicited greater overall glycaemic response (184 *vs* 155 mmol $min.L^{-1}$), peak glucose concentration (2.8 *vs* 2.4 $mmol.L^{-1}$) and GI (88 *vs* 68) compared to usual chewing (15 CPM). Interestingly, in an exploratory, crossover study evaluating the impact of eating methods on glycaemic response, Sun *et al.* (2015) discovered that glycaemic response to white rice eating with chopsticks (GI, 68) was significantly lower than using spoon (GI, 81), but not with using fingers. Eating with chopsticks lowers the GI of rice by 16% due to smaller mouthfuls, increased chewing and longer time taken to consume the entire portion of rice. Another study reports that compared to usual chewing (10 CPM), thorough chewing (31 CPM) resulted in lower food ingestion rate (24 *vs* 11 $g.min^{-1}$), voluntary food intake (358 *vs* 313 g) and longer meal duration (15 *vs* 29 min) (Smit *et al.,* 2011).

These findings, however, may not be applicable in individuals with glucose tolerance abnormalities. Suzuki *et al.* (2005) compared the effects of usual and thorough mastication on 3-hour postprandial plasma glucose (PPG) concentrations in subjects with normal glucose tolerance (NGT) or predisposed to type 2 diabetes using a crossover design trial. Thorough mastication lowered PPG at 90- and 120-min in the NGT group, which could be partly explained by an early-phase insulin secretion, as indicated by higher insulinogenic index (ratio of incremental serum insulin to plasma glucose concentration 30-min post-meal). However early-phase insulin secretion was not observed in the predisposed group after thorough mastication and this led to significantly elevated PPG concentrations.

HABITUAL RICE CONSUMPTION AND CHRONIC DISEASE DEVELOPMENT

A large-scale epidemiological study of middle-aged Chinese women (n=64277) showed a 78% greater risk of developing type 2 diabetes (T2D) in the highest quartile of cooked rice intake (≥750 $g.day^{-1}$) compared with the lowest quartile (<500 $g.day^{-1}$) (Villegas et al., 2007) (Table 2). In Japan, a 65% increase in risk of T2D was noted only in women (n= 33794) and not men (n=25494) (Nanri *et al.,* 2010). These observations are also consistent with Caucasian populations in the United States with the highest quartile of white rice eaters been 17% more likely to develop T2D than those in the lowest intake quartile (Sun *et al.,* 2010). It must be noted that Asians consume more rice than Caucasians (≥113 $g.day^{-1}$) in these studies (Table 2). A meta-analysis concluded pooled relative risk for

Table 2. Observational studies relating habitual rice consumption and chronic disease[a]

Country/ Study	Participants' characteristics	Follow-up period (y)	Rice intake assessment		Assessed outcomes (cases)	Magnitude[b]	Quality score (%)[c]	References
			Tool	Intake				
Cohort								
Australia/ Melbourne Collaborative Cohort Study	n=31,641 Sex, 59% women Age, 40-69y	4	FFQ, 121-item, validated for this particular cohort	Q1: <1x/wk Q2: 1.0-1.4x/wk Q3: 1.5-2.4x/wk Q4: ≥2.5x/wk	New T2D cases (365)	Adjusted OR (95% CI) = 0.93 (0.68-1.27) in Q4 *vs* Q1.	91.7	Hodge *et al.* (2004)
China/ Shanghai Women's Health Study	n=64,227 Sex, 100% women Age, 40-70y	4.6	FFQ, 77-item, validated for this particular cohort	Q1: <500 g/d Q2: 500-624 g/d Q3: 625-749 g/d Q4: ≥750 g/d	New T2D cases (1,608)	RR (95% CI) = 1.78 (1.48-2.15) in Q4 *vs* Q1.*	91.7	Villegas *et al.* (2007)
Japan/ Japan Public Health Centre-based Prospective Study	n=59,288 Sex, 57% women Age, 45-75y	5	FFQ, 147-item, validated	Men Q1: 280 g/d Q2: 420 g/d Q3: 560 g/d Q4: 700 g/d Women Q1: 165 g/d Q2: 315 g/d Q3: 420 g/d Q4: 560 g/d	New T2D cases (1,103)	Men RR (95% CI) = 1.19 (0.85-1.68) in Q4 *vs* Q1. Women RR (95% CI) = 1.65 (1.06-2.57) in Q4 *vs* Q1.**	91.7	Nanri *et al.* (2010)
Japan/ Takayama Study	n=27,862 Sex, 55% women Age, 53.7±12.1y (men); 54.9±13.0y (women)	7	FFQ, 169-item, validated for this particular cohort	Men[d] Q1: 2.3 srvg/d Q2: 3.2 srvg/d Q3: 3.7 srvg/d Q4: 4.0 srvg/d Women Q1: 1.9 srvg/d Q2: 2.3 srvg/d Q3: 2.7 srvg/d Q4: 3.2 srvg/d	Stroke mortality as per subtypes: ischemic (126) and haemorrhagic strokes (94)	*Haemorrhagic stroke* Men HR (95% CI) = 0.71 (0.34-1.49) in Q4 *vs* Q1. Women HR (95% CI) = 2.36 (0.92-6.03) in Q4 *vs* Q1.* *Ischemic stroke* Men HR (95% CI) = 1.21 (0.61-2.37) in Q4 *vs* Q1. Women HR (95% CI) = 1.67 (0.69-4.07) in Q4 *vs* Q1.	83.3	Oba *et al.* (2010)

USA/ Health Professional Follow-up Study	n=39,765 Sex, 100% men Age, 32-87y	20	FFQ, 116-item, validated for this particular cohort	White rice Q1: <1 srvg/mo Q2: 1-3 srvg/mo Q3: 1 srvg/wk Q4: 2-4 srvg/wk Q5: ≥5 srvg/wk Brown rice T1: <1 srvg/mo T2: 1 srvg/mo – 1 srvg/wk T3: ≥2 srvg/wk	New T2DM cases (2,648)	White rice RR (95% CI) = 1.02 (0.77-1.34) in Q5 *vs* Q1. Brown rice RR (95%CI) = 0.96 (0.82-1.12) in T3 *vs* T1.	91.7	Sun *et al.* (2010)
USA/ Nurses' Health Study	n=69,120 Sex, 100% women Age, 37-65y	22	FFQ, 116-item, validated	Same as above	New T2DM cases (5,500)	White rice RR (95% CI) = 1.11 (0.87-1.43) in Q5 *vs* Q1.* Brown rice RR (95%CI) = 0.83 (0.72-0.96) in T3 *vs* T1.**	91.7	Sun *et al.* (2010)
USA/ Nurses' Health Study II	n=88,343 Sex, 100% women Age, 26-45y	14	FFQ, 116-item, validated	Same as above	New T2DM cases (2,539)	White rice RR (95% CI) = 1.40 (1.09-1.80) in Q5 *vs* Q1.* Brown rice RR (95%CI) = 0.89 (0.75-1.07) in T3 *vs* T1.	91.7	Sun *et al.* (2010)
Japan/ Japan Collaborative Cohort Study	n=83,752 Sex, 58% women Age, 40-79y	14.1	FFQ, 40-item, validated for this particular cohort	Men Q1: 280 g/d Q2: 420 g/d Q3: 449 g/d Q4: 583 g/d Q5: 711 g/d Women Q1: 279 g/d Q2: 359 g/d Q3: 420 g/d Q4: 453 g/d Q5: 560 g/d	CVD mortality (3,514)	Men RR (95% CI) = 0.82 (0.70-0.97) in Q5 *vs* Q1.** Women RR (95% CI) = 1.07 (0.88-1.34) in Q5 *vs* Q1.	83.3	Eshak *et al.* (2011)
China/ Jiangsu Nutrition Study	n=1,231 Sex, 59% women Age, 49.0±13.2y	5	FFQ, 149-item, validated	T1: 0-200 g/d T2: 201-400 g/d T3: ≥401 g/d	MetS cases (181)	*Abnormal glucose tolerance* RR (95% CI) = 2.50 (1.37-4.57) in T3 *vs* T1.** *High blood pressure* RR (95% CI) = 0.58 (0.36-0.93) in T3 *vs* T1.** *MetS prevalence* RR (95% CI) = 0.76 (0.43-1.36) in T3 *vs* T1.	83.3	Shi *et al.* (2012)

Iran/ Tehran Lipid and Glucose Study	n=1,476 Sex, 61% women Age, 37.8±12.3y	3	FFQ, 168-item, validated	Q1: 93 ± 59 g/d Q2: 209 ± 58 g/d Q3: 262 ± 60 g/d Q4: 432 ± 224 g/d	MetS cases (253)	RR (95% CI) = 1.66 (1.48-2.15) in Q4 *vs* Q1.*	83.3	Bahadoran *et al.* (2014)
Japan/ Japan Public Health Centre-based	n=92,223 Sex, 53% women Age, 40-69y	10	FFQ, 138-item, validated	Q1: 251 ± 83 g/d Q2: 326 ± 89 g/d Q3: 377 ± 88 g/d Q4: 430 ± 89 g/d Q5: 542 ± 127 g/d	New stroke (4,395) and IHD (1,088) cases and CVD mortality (2,705)	*CVD incidence* Total stroke HR (95% CI) = 1.01 (0.90-1.14) in Q5 *vs* Q1. IHD HR (95% CI) = 1.08 (0.84-1.38) in Q5 *vs* Q1. *CVD mortality* Total stroke HR (95% CI) = 1.03 (0.82-1.30) in Q5 *vs* Q1. Total CVD HR (95% CI) = 0.97 (0.84-1.13) in Q5 *vs* Q1.	91.7	Eshak *et al.* (2014)
USA/ NHS I, NHS II, HPFS	n=207,556 Sex, 80% women	NHS: 26 NHSII: 20 HPFS: 24	FFQ, 118- item, validated	Q1: <1 servings/wk Q2: 1 servings/wk Q3: 2-4 servings/wk Q4: ≥5 servings/wk	New CVD cases (12,391)	Adjusted HR (95% CI) = 0.98 (0.84-1.14) for white rice; 1.01 (0.79-1.28) for brown rice; 0.99 (0.90-1.08) for total rice in Q5 *vs* Q1.	91.7	Muraki *et al.* (2015)
Case-control								
China	n=838 Sex, 43% women Age, 69.6±8.0y (cases); 68.7±7.0y (controls)	–	FFQ, 125-item, validated	Q1: <1100 g/wk Q2: 1100-1449 g/wk Q3: 1450-2449 Q4: ≥2450 g/wk	Incident ischemic stroke cases (374)	Adjusted OR (95% CI) = 2.73 (1.31-5.69) in Q4 *vs* Q1.**	76.9	Liang *et al.* (2010)
Cross-sectional								
Iran	n=3,006 Sex, 100% men Age, 39.0±15.2y (WR intake <7x /wk); 34.5±13.2y (WR intake 7-14x/wk)	–	FFQ, 49-item, validated	G1: <7x/wk G2: 7-14x/wk	MetS cases[e]	Adjusted OR (95% CI) = 1.25 (0.72-2.18) in G2 *vs* G1.	62.5	Khosravi-Boroujeni *et al.* (2013)
Singapore	n=2,728 Age, 48.7±11.5y	–	FFQ, 169-item, validated	Q1: 0.98 portions/d Q2: 1.40 portions/d Q3: 1.75 portions/d Q4: 2.15 portions/d Q5: 2.79 portions/d	Degree of insulin resistance (HOMA-IR)	*% change per portion* Adjusted OR (95% CI) = 4.62 (1.29-8.07)	87.5	Zuniga *et al.* (2014)

[a] CI, confidence interval; CVD, cardiovascular disease; d, day; FFQ, food frequency questionnaire; HOMA-IR, homeostatic model assessment – insulin resistance; HPFS, Health Professionals Follow-up Study; HR, hazard ratio; IHD, ischemic heart disease; MetS, metabolic syndrome; OR, odds ratio; RR, relative risk; T2D, type 2 diabetes; wk, week; y, years. [b] P-for-trend, *<0.05, **<0.01
[c] The quality of the studies were assessed by adapting a scoring system by Lievense *et al.* (2001). [d] Classification was based on quartiles of dietary GI. [e] Prevalence of MetS in the studied population was not reported.

T2D was 1.55 for Asian populations compared to 1.12 for Western populations (Hu *et al.,* 2012). A dose-response analysis further indicated an 11% greater risk of T2D for each serving per day increment of white rice intake (Hu *et al.,* 2012). Particularly, one study noted women consuming ≥2 servings of brown rice weekly were 17% less likely to develop T2D compared to infrequent brown rice consumers (<1 serving.month^{-1}) (Sun *et al.,* 2010).

Rice consumption and cardiovascular death risk has also been explored. In the Japan Collaborative Cohort Study (n=83752), middle-aged Japanese men in the highest quintile had an 18% lower risk for CVD mortality compared to the lowest quintile (Eshak *et al.,* 2011). However, in the Japan Public Health Centre-based Study (n=92223), Eshak *et al.* (2014) reported rice consumption was not associated with risk of CVD morbidity or mortality. These findings contrasted with those of Oba *et al.* (2010), who found a positive trend between rice and haemorrhagic stroke in Japanese women (adjusted HR = 2.36; 95% CI 0.92-6.03). A more recent analysis of pooled data from three US cohort studies found no association between white and brown rice consumption with CVD incidence (Muraki *et al.,* 2015). This could be partly explained by the higher proportion of women (>80%) and relatively lower intake of rice in the Caucasian populations. In a recent meta-analysis which included 7 prospective cohort studies (n=225000), higher dietary glycaemic load, rather than glycaemic index and total carbohydrate intake was significantly associated with 19% greater risk for stroke (Cai *et al.,* 2015).

Metabolic syndrome (MetS), as characterized by insulin resistance and systemic inflammation (DeFronzo, 2010), was suggested as an underlying pathway contributory to T2D and CVD (Wilson *et al.,* 2005; Meigs *et al.,* 2006). The Jiangsu Nutrition Study in China documented significantly greater risk for abnormal glucose tolerance and lower risk for blood pressure were associated with ≥401 g.day^{-1} of cooked rice consumption (Shi *et al.,* 2012). However, MetS prevalence was not linked to rice intake in this Chinese population. In contrast, Iranian data (Bahadoran *et al.,* 2014) showed a positive link between higher white rice intake and risk of MetS. However, the results were not adjusted for confounders such as baseline serum high-density lipoprotein cholesterol, systolic and diastolic blood pressure, which were reported to be significantly different across the white rice intake quartiles.

Overall the form in which rice is habitually consumed may explain the development of chronic disease. In China, increased consumption of cooked rice (adjusted odds ratio [aOR] = 2.73, 95% CI 1.31-5.69), congee (aOR = 2.93, 95% CI 1.68-5.13) and rice noodle (aOR = 2.03, 95% CI 1.40-2.94) were associated with a higher risk for ischemic stroke in a case-control study involving 374 incident ischemic stroke patients and 464 hospital-based controls (Liang *et al.,* 2010). Further, there is preliminary evidence on the gender differences in mediating the possible beneficial or detrimental effects of rice consumption on glycaemic and lipid markers (Nanri *et al.,* 2010; Sun *et al.,* 2010; Eshak *et al.,* 2011).

Given these limited observations, a possible relationship between white rice consumption and health risks exists. Most studies do not specify the type of rice consumed respective to white, brown or pigmented rice varieties. Furthermore, the hypothetical detrimental effects of habitual rice consumption appear to be offset when rice is included as part of a "balanced and healthy" prudent dietary pattern, which typically reflects adequate intakes of fruits, vegetables, legumes and lean protein choices (Dugee *et al.,* 2009; Yu *et al.,* 2011; Ahn *et al.,* 2013; Khosravi-Boroujeni *et al.,* 2013). Therefore, a well-designed, randomized controlled trial may serve to answer the health-mediating effects of long-term polished white rice consumption or substitution with minimally-processed pigmented rice in humans.

TARGETING RICE QUALITY FOR DISEASE PREVENTION AND MANAGEMENT

Current evidence from epidemiological studies suggests that adhering to diets high in whole grains is postulated to lower risk of developing obesity, T2D and cardiovascular disease (Ye *et al.,* 2012; Aune *et al.,* 2013b; Cho *et al.,* 2013; Parker *et al.,* 2013). In recognition of the association between diet and non-communicable diseases, the resonating message of most national dietary guidelines is to advocate the choice of whole grains over refined grains (Malaysian Dietary Guidelines, 2010; Australian Dietary Guidelines, 2013; Dietary Guidelines for Americans, 2015). The paradigm shift for healthy eating in the 21st century should deliberately focus on the overall diet quality rather than single-nutrient (such as fat or carbohydrate) or food group intakes (Willett & Stampfer, 2013). Diet quality is assessed using a scoring system which reflects a person's general food intake pattern in alignment with national dietary guidelines and diversity of healthy choices within each individual food group (Wirt & Collins, 2009).The deliberate choice of whole grains, for example, has been shown to improve diet quality of U.S. adults (O'Neil *et al.,* 2010). Further, by using a 10-year predictive mathematical model, Sar and Marks (2015) projected that increment in Cambodian diabetes incidence will be reduced by 27% if the population switches from a high-GI rice type (Phka Rumduol; GI, 88) to a low-GI type (IR66; GI, 54). Similarly, reducing 25% of current rice consumption levels was also predicted to reduce diabetes burden by 26% (Sar & Marks, 2015).

However, evidence is inconsistent in relation to clinical benefits from replacing white rice with brown rice (Table 3). Replacing half of the usual portion of white rice (total dietary fibre, TDF 1.9 $g.100g^{-1}$) with high-fibre rice (TDF 4 $g.100g^{-1}$) for 4 weeks significantly reduced body weight, body mass index, low-density lipoprotein cholesterol (LDL-C) and triacylglycerol in Korean overweight adults (Lee *et al.,* 2006). Substituting white rice with brown rice for 16 weeks in middle-aged Chinese men and women did not result in favourable reductions in serum glycaemic and lipid markers (Zhang *et al.,* 2011). Reductions in body weight and LDL-C level and improvement in antioxidant status of overweight and obese Korean women were achieved with brown or black rice substitution in a very-low calorie diet (~800 $kcal.day^{-1}$) (Kim *et al.,* 2008). A slight reduction in high-sensitivity C-reactive protein, an inflammatory marker, occurred in non-diabetic overweight women 6 weeks after replacing brown rice for white rice without changing fasting blood glucose and lipid profile (Kazemzadeh *et al.,* 2014). Comparatively, consumption of >80 g whole grains per day led to lower but non-significant trends in interleukin-10 and C-reactive protein levels in adults with low habitual whole grains (<24 g.day-1) intake (Ampatzoglou *et al.,* 2015).

The mixed meal or lente effect in moderating metabolic outcome is an important approach in improving diet quality. In addition to rice, pulses and legumes contribute about 8% of daily energy intake for Indians in Southern India (Radhika *et al.,* 2010). The addition of legumes to a brown rice diet significantly lowered the overall 24-h glycaemic and insulin responses compared to the brown or white rice only diets consumed by diabetes-free, overweight Indians (Mohan *et al.,* 2014). This echoes the findings of another Indian study whereby a traditional dietary pattern rich in pulses and rice was inversely associated with diabetes incidence (Daniel *et al.,* 2011). Similarly in Korea, eating rice with beans significantly lowered the risk for central obesity and abnormal fasting glucose in women compared to eating white rice alone (Ahn *et al.,* 2013). Reductions in fasting plasma glucose, insulin and lipid peroxidation markers (malondialdehyde, homocysteine) and improved β-cell function were reported in Korean patients with coronary artery disease after replacing breakfast with a whole-grain rice and legume (brown rice, barley, black beans) (Jang *et al.,* 2001). Further, Asian diabetic patients in Australia consuming a diet with 60% white rice and 40% of mixed legumes, nuts and seeds, achieved significantly lower postprandial blood glucose levels compared to consuming white rice alone (Zhang *et al.,* 2015).

Aside from brown rice, pre-germinated brown rice (PGBR) has generated interest in Japan as a health approach to disease prevention. PGBR, also called as "sprouted brown rice", is produced by repeatedly soaking brown rice at 35 to 40°C for 24 to 36 hours until a 0.5 to 1-mm long sprout is formed from the brown rice seed (Roohinejad *et al.,* 2010, 2011). Brown rice when subjected to germination will undergo enhancement of its nutritional and functional properties such as protein, gamma-amino butyric acid (GABA), phenolic acids, γ-oryzanol and total dietary fibre (Patil & Khan, 2011). By consuming PGBR in place of white rice, subjects with impaired glucose tolerance or T2D benefit with increased HDL-C but decreased serum triglycerides, LDL-C and glycaemic markers (Hsu *et al.,* 2008; Bui *et al.,* 2014). The hypocholesterolemic effects of PGBR may be attributed to its greater GABA (Roohinejad *et al.,* 2010), oryzanol and tocopherols (Esa *et al.,* 2011) content as well as up-regulation of the LDL and Apolipoprotein A1 receptor genes (Imam *et al.,* 2013), as demonstrated in animal models.

Overall, these results should be interpreted with caution as the lack of positive findings could be attributed to underpowered observation from small sampling size, administration of non-isocaloric intervention meals or negligible GI differences between the white and brown rice types.

CONCLUSIONS AND FUTURE DIRECTIONS

Rice in the human diet serves underprivileged populations in Asia as a means of nutritional replenishment for energy and protein as well serving as a vehicle for micronutrient fortification. But today, the prospect of rice in human nutrition has taken on the additional role of safeguarding against NCDs development. Malaysia has witnessed a tremendous economic advancement with national GDP per capita growing from ~500USD in 1961 to ~10000 USD in 2011. In line with this wealth growth is the high prevalence of NCDs. The threat is real enough for the scientific community to promote whole grain consumption in place of refined grains. However, the interpretation of whole grain consumption as a choice of brown over polished white rice is to be cautioned as clearly not all rice types could be classified as low GI. For now more research is warranted to elucidate if there is any safe, gender-specific tolerable level of daily rice consumption or would partial or total replacement of white rice with brown rice offer additional health benefits. Additionally, nutrition education

Table 3. Summary table of interventional studies examining substitution of alternative rice types for white rice on metabolic risk markers

Country	Study design	Participants' characteristics Study duration	Follow-up/	Intervention arms	Outcomes	Results Arm 1 *vs* Arm 2 (Between-group *P*-value‡)	References
South Korea	Open-labelled, parallel, randomized	• n=76 • Male only • Patients with coronary artery disease	16 weeks	1. White rice (cooked, 150 g.day^{-1}) 2. WG (barley and brown rice) and legume coarse powder (70 g.day^{-1}) – *taken during breakfast only*	ΔTC (mmol/L) ΔTG (mmol/L) ΔLDL-C (mmol/L) ΔHDL-C (mmol/L) ΔFBG (mmol/L) ΔInsulin (pmol/L) *75-g OGTT* ΔHOMA-β (%)[a]	-0.02 *vs* -0.09 (NS) -0.08 *vs* -0.21 (NS) -0.04 *vs* -0.15 (NS) -0.01 *vs* +0.16* (0.001) +0.19 *vs* -1.50* (<0.001) 0.0 *vs* -10.8* (NS) [1] -31.8 *vs* +196.1* (0.003) [2] -63.6 *vs* +76.8* (NS)	Jang *et al.* (2001)
South Korea	Open-labelled, crossover, randomized	• n=21 (11 normal weight; 10 overweight)	Two 4-week rotations with a 6-week washout period	1. White rice 2. White rice and Goami No. 2 rice (1:1 ratio) 3. meals/day ≈ 228g raw rice/day	*Normal weight* ΔWeight (kg) ΔBMI (kg/m^2) ΔTC (mg/dL) ΔTG (mg/dL) ΔLDL-C (mg/dL) ΔHDL-C (mg/dL) ΔHOMA-IR *Overweight* ΔWeight (kg) ΔBMI (kg/m^2) ΔTC (mg/dL) ΔTG (mg/dL) ΔLDL-C (mg/dL) ΔHDL-C (mg/dL) ΔHOMA-IR	 +0.1 vs -0.9* (0.041) +0.1 vs -0.2* (0.047) -11.2 vs +8.4 (0.041) -15.6 vs -7.1 (NS) -3.8 vs +9.1 (NS) -4.3 vs +0.7 (0.041) +0.12 vs +0.25 (NS) -0.4 *vs* -2.0* (NS) -0.2 *vs* -0.7* (0.037) -13.4 *vs* -24.5* (NS) +6.0 *vs* -44.2* (NS) -4.5 *vs* -14.3* (NS) -2.6 *vs* -1.0 (NS) +0.55 *vs* +0.46 (NS)	Lee *et al.* (2006)
Japan-Taiwan	Open-labelled, crossover, randomized	• n=11 • age, 51.5±16.2y (range: 27-72y) • type 2 diabetics (91% on OHAs)	Two 6-week rotations with a 2-week washout period	1. White rice 2. Pre-germinated brown rice 3. packs/day ≈ 540g/day	ΔFBG (mg/dL) ΔTC (mg/dL) ΔTG (mg/dL) ΔHDL-C (mg/dL) ΔInsulin (μU/mL)	+3.0 *vs* -19.0* (<0.01) +5.8 *vs* -22.8* (<0.05) +1.7 *vs* -47.4* (<0.05) -1.8 *vs* +8.5* (<0.05) -0.3 *vs* +0.65 (NS)	Hsu *et al.* (2008)
South Korea	Open-labelled, parallel, randomized	• n=40 • age range: 20-35y • overweight or moderately obese, healthy premenopausal women	6 weeks	Very-low calorie diet (~800 kcal/day) was prescribed to both groups. 3 meals were replaced with a low-energy meal replacement shake made of: 1. White rice 2. Mixed rice (brown and black rice)	Weight (kg) ΔBMI (kg/m^2) ΔTC (mg/dL) ΔTG (mg/dL) ΔHDL-C (mg/dL) ΔTBARS (nmol/L) ΔGPx (U/g Hb)	-5.4* *vs* -6.8* (<0.05) -2.0* *vs* -2.6* (<0.05) -27.5* *vs* -30.3* (NS) -44.9* *vs* -47.0* (NS) +3.0 *vs* +5.0* (NS) +1.8* *vs* -2.0* (<0.05) +3.5 *vs* +15.4 (<0.05)	Kim *et al.* (2008)

China	Open-labelled, parallel, randomized	• n=202 • mean age, 49y • type 2 diabetics or at high risk for diabetes	16 weeks	1. White rice 2. Brown rice 2 packs/day ≈ 450g/day	ΔHbA1c (%) ΔTC (mmol/L) ΔLDL-C (mmol/L) ΔHDL-C (mmol/L) ΔTC:HDL ΔHOMA-IR	+0.20* *vs* +0.13* (NS) -0.40* *vs* -0.10 (0.05) -0.33* *vs* -0.03 (0.02) -0.12** *vs* -0.03 (0.09) +0.09* *vs* -0.02 (NS) +0.07 *vs* +0.03 (NS)	Zhang *et al.* (2011)
Vietnam	Open-labelled, parallel, randomized	• n=60 • age, 56.9±5.8 (PGBR group); 56.6±5.0 (WR group) • Subjects with impaired glucose tolerance	16 weeks	1. White rice 2. Pre-germinated brown rice WR was gradually replaced by PGBR within a month.	ΔFBG (mg/dL)[b] ΔHbA1c (%) ΔTC (mmol/L) ΔLDL-C (mmol/L) ΔHDL-C (mmol/L) ΔTG (mmol/L)	+0.16 *vs* -0.74** +0.16 *vs* -0.72* +0.61** *vs* -0.27 +0.08 *vs* -0.39* +0.28** *vs* +0.41** -0.60 *vs* -1.27*	Bui *et al.* (2014)
Iran	Open-labelled, crossover, randomized	• n=35 • age, 32.6±6y • Free-living, non-diabetic overweight women	Two 6-week rotations with a 2-week washout period	1. White rice 2. Brown rice To consume 150g cooked rice/day	ΔFBG (mg/dL) ΔTC (mg/dL) ΔLDL-C (mg/dL) ΔHDL-C (mg/dL) ΔTG (mg/dL) ΔhsCRP (mg/L)	-7 *vs* -1 (NS) -2 *vs* -6 (NS) +0.5 *vs* +1.0 (NS) -0.5 *vs* -3.5 (NS) +1.0 *vs* +1.0 (NS) +1.2 *vs* -0.7 (0.01)	Kazemzadeh *et al.* (2014)
India	Open-labelled, crossover, randomized	• n=15 • Age, 25-45y • Free-living, non-diabetic overweight adults	2 test meals (breakfast and lunch) provided for 5 consecutive days with 9-day washout period	1. White rice 2. Brown rice (≥200g replaced) 3. Brown rice + legumes (50g/day)	Δ% iAUCglu Δ% fasting insulin	BR *vs* WR -19.8%* -57.0%**	Mohan *et al.* (2014)

y, years; BR, brown rice; FBG, fasting blood glucose; HbA1c, glycosylated haemoglobin; HDL-C, high-density lipoprotein cholesterol; HOMA-IR, homeostatic model assessment – insulin resistance; hsCRP, high-sensitivity C-reactive protein; LDL-C, low-density lipoprotein cholesterol; NS, not significant; OHA, oral hypoglycaemic agents; TC, total cholesterol; TG, triglyceride; WR, white rice

Significant within-group differences, **P*<0.05, ***P*<0.001

[a] Analyses were stratified according to non-diabetic (1) and diabetic (2) CAD patients.

[b] Significance of between-group changes were not indicated.

programs should focus on disseminating health-promoting traits of brown rice to consumers as a strategy in promoting whole grain consumption. In the meantime, rice breeding and improvement programs need to take into account traits that will improve rice quality in terms of GI as well as micronutrient capacity.

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LIST OF ABBREVIATIONS

aOR: adjusted odd ratio; BC: Before Christ; CI: confidence interval; BR: brown rice; CPM: chews per mouthful; CVD: cardiovascular disease; FAO: Food and Agriculture Organization; g: grams; GABA: gamma-amino butyric acid; GDP: gross domestic product; GI: glycaemic index; GL: glycaemic load; HDL-C: high-density lipoprotein cholesterol; IP6: inositol hexophosphate; IRRI: International Rice Research Institute; LDL-C: low-density lipoprotein cholesterol; MetS: metabolic syndrome; mins: minutes; mg: milligrams; NCD: non-communicable diseases; NGT: normal glucose tolerance; NSP: non-starch polysaccharides; PGBR: pre-germinated brown rice; PPG: postprandial glucose; RAG: rapidly available glucose; RDS: rapidly digestible starch; RR: relative risk; RS: resistant starch; SDI: starch digestible index; SDS, slowly digestible starch; T2D: type 2 diabetes; TDF: total dietary fibre; USD: United States dollar.

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