Systematic Review

A systematic review of the influence of rice characteristics and processing methods on postprandial glycaemic and insulinaemic responses

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Abstract

Rice is an important staple food for more than half of the world’s population. Especially in Asian countries, rice is a major contributor to dietary glycaemic load (GL). Sustained consumption of higher-GL diets has been implicated in the development of chronic diseases such as type 2 diabetes mellitus. Given that a reduction in postprandial glycaemic and insulinaemic responses is generally seen as a beneficial dietary change, it is useful to determine the variation in the range of postprandial glucose (PPG) and insulin (PPI) responses to rice and the primary intrinsic and processing factors known to affect such responses. Therefore, we identified relevant original research articles on glycaemic response to rice through a systematic search of the literature in Scopus, Medline and SciFinder databases up to July 2014. Based on a glucose reference value of 100, the observed glycaemic index values for rice varieties ranged from 48 to 93, while the insulinaemic index ranged from 39 to 95. There are three main factors that appear to explain most of the variation in glycaemic and insulinaemic responses to rice: (1) inherent starch characteristics (amylose:amylopectin ratio and rice cultivar); (2) post-harvest processing (particularly parboiling); (3) consumer processing (cooking, storage and reheating). The milling process shows a clear effect when compared at identical cooking times, with brown rice always producing a lower PPG and PPI response than white rice. However, at longer cooking times normally used for the preparation of brown rice, smaller and inconsistent differences are observed between brown and white rice.

Key words: Rice; Blood glucose; Insulin; Glycaemic index; Starch; Processing

Rice is a daily dietary staple food for more than half of the world’s population, and the major single food source of carbohydrate and energy in China and many other Asian countries[1]. In South India, for example, nearly half of daily energy intake comes from refined grains, and white polished rice constitutes >75% of refined grain intake[2]. In China, brown rice is rarely consumed[3]. As a result, in Asian populations, white rice makes large contributions to dietary glycaemic load, an index reflecting the acute blood glucose-raising potential of foods or diets[4]. Higher levels of postprandial glycaemic exposure have been implicated in the development of chronic metabolic diseases, particularly type 2 diabetes mellitus and CVD[5]. A recent systematic review and meta-analysis has shown a clear relationship between white rice intake and the risk of type 2 diabetes mellitus, with higher levels of rice intake being more strongly associated with the risk in Asian than in Western populations[6,7].

There are many varieties of rice grain in the world, which vary considerably in the postprandial blood glucose (PPG) response they produce[8]. The results of glycaemic index (GI) studies around the world[9] report values ranging from 64 to 93. Moreover, the post-harvest treatment of rice and the method of consumer preparation can also play a significant role in this variation. Starch comprises two glucose polymers: amylose and amylopectin. Amylose is a linear and relatively short polymer of glucose units linked by \((1\rightarrow4)\) bonds. Amylopectin is a branched and longer polymer where glucose units are arranged linearly through \((1\rightarrow4)\), with branches emerging via \((1\rightarrow6)\) bonds occurring every twenty-four to thirty glucose units[10]. It is well known that starches with a higher amount of amylose are more resistant to digestion[11]. In addition to the variation in amylose content, cooking (and cooling) processes can influence starch digestibility via

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Abbreviations: G1, glycaemic index; iAUC, incremental AUC; II, insulinaemic index; PPG, postprandial glucose response; PPI, postprandial insulin response; RS, resistant starch.
the degree of gelatinisation and retrogradation of rice starch. Gelatinisation is the collapse (disruption) of molecular order (breaking of H bonds) within the starch granule, manifested in irreversible changes such as granular swelling, native crystallite melting, loss of birefringence and starch solubilisation during hydrothermal treatment\(^{(12)}\). This leads to the dissociation of crystalline regions in starch with associated hydration and swelling of starch granules, leading to higher starch availability to human digestive enzymes\(^{(13)}\). Retrogradation is the recrystallisation of amorphous phases created by gelatinisation\(^{(14)}\) and, in the case of amylose, results in the formation of type 3 resistant starch (RS3)\(^{(15)}\). RS3 is resistant to digestion, because it is heat stable and melts above 120°C\(^{(16)}\). In contrast, retrograded amylopectin is thought to melt upon reheating (cooking) due to the low melting point (46–65°C) of these crystallites, and therefore it is digestible upon cooking.

Post-harvest processing includes milling, parboiling and quick-cooking. The rice milling process starts with the husking stage to remove the husk from paddy rice, followed by the whitening–polishing stage to transform brown rice into polished white rice, and finally the grading and blending stage to obtain head rice with predefined amounts of broken rice. However, while this may affect the overall nutritional value, the effects on digestibility and PPG are less clear\(^{(17)}\). Other post-harvest treatments such as parboiling can also play a role in digestibility. Parboiling is a hydrothermal treatment that includes soaking in water, heating, drying and milling of paddy rice. During the parboiling process, the crystalline structure of the starch present in rice is transformed into an amorphous form. Pressure parboiling is accomplished by soaking paddy rice in warm water (65–68°C) for 4–5 h followed by steaming under pressure and drying\(^{(18)}\). Other post-harvest processes are used to produce quick-cooking rice. The latter is a precooked rice where the starch has been partially gelatinised by soaking in water and heating\(^{(19)}\). For consumer consumption, additional processes include cooking, storage and reheating. There are different ways of rice cooking depending on the ratios between rice and water, equipment (pressure cooking and steaming), and consumer preference (sticky rice, aromatic basmati, etc.). Cooking of polished white rice strongly affects gelatinisation. Retrogradation is affected by cooling and storage conditions (see also Fig. 3).

Given that reductions in PPG responses are generally seen as a beneficial dietary change\(^{(5)}\), it is useful to objectively establish the variation in the range of PPG responses to rice and the primary intrinsic and processing factors known to affect such responses. Therefore, we performed a systematic search of the literature characterising the range of PPG and PPI responses to different rice types, and considered this alongside available data on rice grain and processing characteristics. The main emphasis is on in vivo studies conducted in human subjects, supplemented in places by the in vitro literature related to specific mechanisms that may be relevant (e.g. influence of microstructure on rice).

**Methods**

The literature database ‘Scopus’ was searched for the following combinations of keywords (without language or time restrictions): rice\(^*\) AND glycaem* or glycem* or digestib* or glucose* or insulin* or hyperglycaem* or hyperglycem* or hypoglycaem* or hypoglycem* or normoglycaem* or normoglycem* AND combined with the title from 1980 through July 2014, resulting in ninety-four records. In addition, the PubMed and SciFinder databases were also searched using the same search terms, resulting in one additional article. A further three ‘missed’ articles were identified from the cited references in the articles identified in the formal searches, resulting in ninety-eight articles. From manual inspection of the ninety-eight abstracts, we identified twenty-eight original articles describing the results of thirty-two randomised clinical trials with rice as the test food and a measure of PPG (and in some cases also PPI) as an outcome measure (for a detailed flow chart, see Fig. 1).

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**Fig. 1.** Flow chart of the systematic review article selection process. RCT, randomised controlled trial.
Results

Evidence base

Studies identified in the search and their key relevant results are presented in Table 1. In addition, specific comparisons of amylose content, parboiling and milling are presented in online Supplementary Tables S2, S3 and S4, respectively. The thirty-two randomised clinical trials on PPG responses to rice included different rice types (e.g. regional varieties) and different processes (milling, parboiling, ‘quick-cook’ and (pressure) cooking). Outcome measures for blood glucose included GI (twenty-seven studies) and/or the incremental area under the PPG response curve (AUC, nineteen studies), or peak glucose values (eight studies). The iAUC is the actual blood glucose response to a given serving of rice, whereas the GI and the corresponding insulinaemic index (II) use a fixed available carbohydrate load (usually 50 g) and represent responses as a comparison with a reference (assigned a value of 100). Except where noted, the GI and II studies compared rice with glucose as the reference. A subset of studies reported the II (seven studies) or insulin AUC (eight studies). Furthermore, two studies took breath hydrogen into account as an indicator of carbohydrate malabsorption

Characterisation of rice and processing

In most studies, rice was well characterised with respect to the percentage of amylose (nine studies), dietary fibre (four studies), RS (two studies) and available starch (sixteen studies). In some studies, gelatinisation or amylograph measurements of milled rice flour were taken into account, while in others, in vitro glucose release assays were included. A few studies reported grain size, rheology or retrogradation determined by differential scanning calorimetry (a thermo-analytical technique to identify phase transition). The processes explored in the studies involved post-harvest treatments such as parboiling and milling (Fig. 2). Variation observed in the glycaemic index and insulinaemic index and its causes

The observed GI values ranged from 48 to 93, while the II values (0–120 min) ranged from 39 to 95 (Table 1). In the studies that specifically tested or varied the amylose content and its quantitative relationship with glycaemic and insulinaemic responses, the latter measures were significantly inversely associated with the amylose content (see also online Supplementary Table S2). However, some studies did not find this inverse relationship for all glycaemic parameters. Large differences in amylose content (2% v. approximately 30% amylose) were often associated with relatively large glycaemic and insulinaemic effects (approximately 300% decrease in PPG; approximately 55% decrease in PPI). However, there were also studies in which this effect was inconsistent or not observed

Rice that received post-harvest treatments such as parboiling and quick-cooking generally gave a lower GI compared with white rice not subjected to these post-harvest treatments (see also online Supplementary Table S3). Larsen et al. reported that an increased severity of parboiling conditions leads to significant decreases in PPG responses due to the formation of RS. In that study, mild traditional parboiling had no effect on the GI, whereas severe pressure parboiling reduced the GI by almost 30% compared with non-parboiled rice. However, one study did not show an effect of parboiling, and the reported GI of a thermally treated Indian basmati rice variety (thermal treatment not specified) was 55 (see online Supplementary Table S4). In those studies where cooking times were identical, brown rice always produced lower PPG and PPI responses. However, when realistic (longer) cooking times were applied to brown rice, the difference between brown and white rice was smaller and inconsistent.

Consumer processing can also make a large contribution to the formation of RS in rice. Chiu & Stewart quantified RS content in four white rice varieties (jasmine, long grain, medium grain and short grain) cooked in three different ways (oven-baked, conventional rice cooker and pressure cooker), and analysed the RS content immediately after preparation or after 3 d of refrigeration at 4°C. Refrigerated long-grain rice cooked in a conventional rice cooker had the highest RS content, while the refrigerated short-grain rice cooked in a pressure cooker had the lowest RS content. However, in this case, the GI values did not differ significantly between the higher-RS and lower-RS rice varieties. Consumer processing can also have a large effect on gelatinisation. Wolfe et al. showed that the GI generally increased with cooking time for rice, while Jung et al. observed a marked increase in gelatinisation upon cooking rice and a somewhat higher GI and II.

Discussion

The literature reveals considerable variation in the glycaemic or insulin response to rice. This is largely attributable to (1) starch characteristics, (2) post-harvest processing (particularly parboiling and to a much lesser extent dehulling and milling) and (3) consumer processing (cooking, storage and reheating). The relationships among rice characteristics and processing factors, and their physico-chemical effects and impact on glycaemic responses are qualitatively shown in Fig. 3.

Influence of the composition and processing of rice

The most consistently important source of variation in PPG responses to rice is amylose content. The amylose content of rice varies between 0% (waxy rice) and 30% (Doongara), with basmati having an intermediate value (20–25% amylose). One of the reasons for the lower PPG responses to high amylose varieties is incomplete gelatinisation of amylose...
Table 1. Human *in vivo* studies on the postprandial glycaemic and insulinaemic effects of rice*

| Publication et al.           | Expt Participants | Food                                                                 | Amylose (w/w%) | AUC (mU/ml) | GI | Peak | Insulin response |
|-----------------------------|-------------------|----------------------------------------------------------------------|----------------|--------------|----|------|------------------|
| Brand-Miller et al. (1992)  | Healthy volunteers n 8, age 19–36 years, BMI 18–25 kg/m² | Rice types grown in Australia min = minutes boiled | Amylose | 28 | 64 | 40 | v. bread |
|                             |                   | Doongara (white), 14 min                                             |                |              |    |      |                  |
|                             |                   | Doongara (brown), 30 min                                             |                |              | 30 |      |                  |
|                             |                   | Pelide (brown), 30 min                                               |                |              | 30 |      |                  |
|                             |                   | Sunbrown (quick), 16 min                                             |                |              | 30 |      |                  |
|                             |                   | Calrose (white), 14 min                                              |                |              | 30 |      |                  |
|                             |                   | Calrose (brown), 35 min                                              |                |              | 30 |      |                  |
|                             |                   | Pelide (parboiled), 14 min                                           |                |              | 30 |      |                  |
|                             |                   | Waxy rice, 14 min                                                    |                |              | 30 |      |                  |
|                             |                   | Pelide white, 14 min                                                 |                |              | 30 |      |                  |
| Ranawana et al. (2009)      | Healthy subjects n 14, age 18–65 years, BMI < 30 kg/m²              | min = minutes boiled | Amylose | 28 | 64 | 40 | v. bread |
|                             |                   | Guilin rice noodles, 8 min                                           |                |              |    |      |                  |
|                             |                   | Jiangxi rice noodles, 8 min                                          |                |              | 76 |      |                  |
|                             |                   | Easy-cook long grain rice, 15 min                                    |                |              | 76 |      |                  |
|                             |                   | Long-grain (Indica type), 15 min                                     |                |              | 76 |      |                  |
|                             |                   | White basmati rice, 10 min                                           |                |              | 76 |      |                  |
|                             |                   | White (60%) and brown (40%)                                          |                |              | 76 |      |                  |
|                             |                   | basmati rice, 25 min                                                 |                |              | 76 |      |                  |
|                             |                   | Basmati + wild rice, 20 min                                          |                |              | 76 |      |                  |
|                             |                   | White basmati rice, 25 min                                           |                |              | 76 |      |                  |
|                             |                   | Thai red rice, 25 min                                                |                |              | 76 |      |                  |
|                             |                   | Easy-cook basmati rice, 15 min                                       |                |              | 76 |      |                  |
|                             |                   | Thai glutinous rice, 10 min                                          |                |              | 76 |      |                  |
| Li et al. (2010)            | Healthy subjects n 16, (n 9 male/n 7 female), age 23–26 years, BMI 18–24 kg/m² | RS-enriched (RS 20 %) (high amylose) Indica type (Oryza sativa L. cultivar Te-Qing) | Amylose | 28 | 64 | 40 | v. bread |
|                             |                   | Indica type (Oryza sativa L. cultivar Te-Qing)                       |                |              | 48 |      |                  |
|                             |                   | RS-enriched (RS 20 %, high amylose), produced with an antisense inhibition starch-branching enzyme | Amylose | 28 | 64 | 40 | v. bread |
|                             |                   | Wild type (RS 2 %)                                                   |                |              | 48 |      |                  |
| Casiraghi et al. (1993)     | Healthy subjects n 9, mean age 26 years, BMI 22 kg/m² | Italian Fino rice, processed as: | Amylose | 28 | 64 | 40 | v. bread |
|                             |                   | Parboiled (15 min boiling time)                                      |                |              | 70 |      |                  |
|                             |                   | Quick-cooking parboiled (8 min)                                      |                |              | 70 |      |                  |
|                             |                   | Conventionally polished (20 min)                                     |                |              | 70 |      |                  |
| Al-Mssallem et al. (2011)   | Healthy subjects n 13, (n 6 male/n 7 female), 25–42 years, BMI 25–6 (SEM 1) kg/m² | Long-grain rice variety ‘UBR’ and traditional Saudi Arabian rice ‘HR’ | Amylose | 28 | 64 | 40 | v. bread |
|                             |                   | UBR                                                                  |                |              | 70 |      |                  |
|                             |                   | HR                                                                   |                |              | 70 |      |                  |
|                             |                   | Conventional polished (20 min)                                       |                |              | 70 |      |                  |
| Juliano & Goddard (1986)    | n 16 Rice cooked: same degree of doneness (AUC 0–180 min) | Labelle                                                             | Amylose | 28 | 64 | 40 | v. bread |
|                             |                   | Newrex                                                               |                |              | 48 |      |                  |
|                             |                   | Mochi Gome                                                           |                |              | 48 |      |                  |
|                             |                   | Labelle                                                              |                |              | 48 |      |                  |
|                             |                   | Pecos                                                                |                |              | 48 |      |                  |
| Juliano & Goddard (1986)    | n 33 Rice cooked: same degree of doneness (AUC 0–180 min) | Mochi Gome                                                           | Amylose | 28 | 64 | 40 | v. bread |
|                             |                   | Labelle                                                              |                |              | 48 |      |                  |
|                             |                   | Pecos                                                                |                |              | 48 |      |                  |
|                             |                   | Long-grain non-waxy (RD21 and RD23) and wasy rice                    |                |              | 48 |      |                  |
|                             |                   | Non-waxy rice                                                        |                |              | 48 |      |                  |
|                             |                   | Waxy rice                                                            |                |              | 48 |      |                  |
| Panlasigui et al. (1991)    | Healthy subjects n 11, (n 4 male/n 7 female), age 23–44 years, 90–110% | Long-grain, non-waxy rice: IR62, IR36 and ideal body weight          | Amylose | 28 | 64 | 40 | v. bread |
|                             |                   | IR42; white rice: boiled for 22 min                                  |                |              | 70 |      |                  |
|                             |                   | IR62                                                                  |                |              | 70 |      |                  |
|                             |                   | IR36                                                                  |                |              | 70 |      |                  |

*Abbreviations: AUC, area under the curve; GI, glycemic index; glucose; IR, index of response; Glu, glucose; Peak, peak response; RR, resistance ratio.*
| Publication + Expt | Participants | Food | Amylose (w/w%) | Glycaemic response |
|-------------------|--------------|------|---------------|-------------------|
| Panlasigue et al. (1991) Expt 2(25) | Healthy subjects n 11 (n 3 male/n 8 female), age 23–50 years, 90–110% ideal body weight | Long-grain, non-waxy rice: IR62, IR36 and IR42; white rice: 50 g Expt 2: boiled for minimum cooking | IR42, boiled for 14 min 26.7 | mmol × min/l 26.7 |
| | | | IR62, boiled for 20 min 27 | GI 81 |
| | | | IR36, boiled for 19 min 26.7 | Peak 75 |
| | | | | Insulin response 78 |
| Panlasigui & Thompson (2006) Expt 1(26) | Healthy subjects n 10 (n 3 male/n 7 female), age 24–50 years, 90–110% ideal body weight | IR42 rice, brown rice | 26.7 | mmol × min/l 107 |
| | | | IR42 rice, white rice | GI v. bread 83 |
| Panlasigui & Thompson (2006) Expt 2(26) | T2DM patients n 9 (n 5 male/n 4 female), age 45–64 years | IR42 rice, brown rice | 26.7 | mmol × min/l 406 |
| | | | IR42 rice, white rice | GI v. bread 56 |
| Kim et al. (2004)(27) | T2DM patients n 10 (n 4 male/n 6 female), mean age 57 years, BMI 24 kg/m² | Korean rice products: Garaeduk: 16 mm stick of steamed, extruded rice flour | 730 | mmol/l per 4 h 406 |
| | | | Cooked rice: gelatinised grains, boiled polished rice | 914 |
| | | | Bageolsi (rice cake): large block of steamed rice flour | 1070 |
| Larsen et al. (2000)(28) | T2DM patients n 9, age 60 years, BMI 26.6 kg/m² | Indica rice variety BR16, high amylose, long grain | 27 | IAU European/Chinese 102 |
| | | | Pressure parboiled rice 27 | GI European/Chinese 102 |
| | | | Traditional mild parboiled rice 27 | 109/179 |
| | | | Non-parboiled rice 27 | 55/67 |
| Kataoka et al. (2012)(29) | Healthy Chinese n 32, age 33 years, BMI 22.9 kg/m² and Healthy European subjects n 31, age 34 years, BMI 25.8 kg/m² | Rice types: jasmine rice; basmati; brown rice; Doongara; parboiled rice (Uncle Ben’s) | 30(29) | IAU European/Chinese 109/179 |
| | | | Donongara | 109/179 |
| | | | Parboiled | 112/194 |
| | | | Basmati | 116/184 |
| | | | Brown | 129/210 |
| | | | Jasmine | 140/225 |
| | | | Low(30) | 66/80 |
| Trinidad et al. (2013)(31) | Healthy volunteers n 9–10, age 27–55 years | Cooked milled and brown rice | 27 | mmol × min/l 102 |
| | | | Milled rice | 27 |
| | | | PSB rc10 | 188 |
| | | | IR64 | 22.9 |
| | | | PSB Rc18 | 221 |
| | | | IMS2 | 233 |
| | | | PSB Rc12 | 236 |
| | | | NSIC RC180 | 280 |
| | | | Sinandomeng | 12.1 |
| | | | Brown rice | 189 |
| Zarrati et al. (2008)(32) | Healthy subjects n 30 (n 13 male/n 17 female), age 35 years, BMI 23.9 kg/m² | One Iranian rice type: Kazemi and imported rice | 32 | Maximum changes |
| | | | Soma pearl | 52 |
| | | | Basmati | 61 |
| | | | Kazemi | 68 | II 1.2 |
| | | | Maximum changes | 47 |
| | | | Maximum changes | 52 |
| | | | Maximum changes | 17 |
| | | | Maximum changes | 62 |
| Publication et al. | Expt | Participants | Food | Glycaemic response |
|-------------------|------|--------------|------|--------------------|
|                  |      |              | Amylose | AUC | GI | Peak | Insulin response |
| Larsen et al. (1996) | 32 | T2DM patients (7 male/5 female), mean age 58 years, BMI 30 kg/m² | Dehulled, milled rices: | iAUC (mmol/l per 3 h) | Gl v. bread | mmol/l | iAUC (mmol/l per 3 h) |
|                   |      |              | BR2 = low amylose variety | 27 | 361 | 47 | 14.5 | 12964 |
|                   |      |              | BR4 = low gelatinisation temperature and gel consistency v. BG16 | 28 | 391 | 50 | 14.7 | 12821 |
|                   |      |              | BR16-PB | 28 | 411 | 53 | 14.8 | 11087 |
|                   |      |              | BR16-NP | 12 | 566 | 73 | 15.9 | 16215 |
|                   |      |              | BR2-PB | 756 | 100 | 17.3 | 20183 |
| Goddard et al. (1984) | 33 | n 33 (16 male/17 female), age 27–81 years, within 20% desirable body weight | Long-grain rice: Labelle | 23–25 | 19 | 41 | 6.3 | 100 µU/ml |
|                   |      |              | Medium-grain rice: Pecos | 14–17 | 20 | 02 | 6.6 | 105 |
|                   |      |              | Sweet rice: Mochi Gome | <2 | 19 | 41 | 6.8 | 110 |
| Hettiarachchi et al. (2001) | 24 | Healthy subjects n 22, age 25–50 years | Shri Lankan rice varieties (red v. white and parboiled v. raw rice) | 182 | 55 | 76 |
| Srinivasa et al. (2013) | 83 | Healthy volunteers (64 male/19 female), age 18–37 years, body weight 44–74 kg | Thermally treated Indian basmati rice | mmol x min/l | mg/l |
| Henry et al. (2009) | 8 | n 8, mean age 37 years, BMI 23 kg/m² | Basmati rice, Indian, boiled 8 min | 13 | 84 | 51 | 39 |
|                   |      |              | Basmati rice, Indian, easy-cook, boiled 9 min | 15 | 130 | 79 | 63 |
|                   |      |              | Basmati rice, boiled 12 min | 18 | 141 | 86 | 68 |
| Karupaiah et al. (2011) | 9 | Healthy subjects n 9 (6 male/4 female), age <30 years, BMI 23 kg/m² | Transgressive brown rice, cross between wild rice O. rufipogon Griff. and O. sativa L. subsp. indica cultivar MR219, polished version and white rice (Cap Rambutan) | mmol x min/l | II |
| Chiu & Stewart (2013) | 21 | Healthy subjects n 21 (12 male/9 female), age 18–65 years, BMI 18.6–30.1 kg/m² | Refrigerated long-grain rice prepared with rice cooker (2.55 g RS/100 g as consumed) high RS | 211 | 84 |
|                   |      |              | Refrigerated short-grain rice prepared with pressure cooker (0.20 g RS/100 g) low RS | 211 | 84 |
|                   |      |              | High-RS rice | 211 | 84 |
|                   |      |              | Low-RS rice | 181 | 78 |
| Publication & Expt | Participants | Food | Amylose (w/w%) | AUC | GI | Peak | Insulin response |
|--------------------|--------------|------|----------------|-----|----|------|------------------|
| Wolever et al. (1986) Expt 1 | NIDDM n 13 (n 6 female/n 7 male), age 67 years, 124% ideal body weight and IDDM n 5 (n 4 female/n 1 male), age 54 years, 104% ideal weight | White bread | 23 | 951/1220 | 100/100 | 22/7.9 | 7.7/9.7 |
| | NIDDM/IDDM (mmol £ min/l) | (GI v. bread) (mmol/l) | | | | | |
| Wolever et al. (1986) Expt 2 | NIDDM n 13 (n 6 female/n 7 male), age 67 years, 124% ideal body weight and IDDM n 5 (n 4 female/n 1 male), age 54 years, 104% ideal weight | White bread + tomato | 23 | 1003/1208 | 107/95 | 8.2/9.6 |
| | NIDDM/IDDM (GI v. bread) | | | | | | |
| Jung et al. (2009) | Healthy females n 12, mean age 22 years, BMI 21 kg/m² | Korean (Pungtak region) rice, processed as: | II | 103 | 50 | 74 | 74 |
| | | Uncooked rice powder | | | | | |
| | | Freeze-dried uncooked rice powder | | | | | |
| | | Cooked rice (boiled 15 min) | | | | | |
| Parastouei et al. (2011) | Healthy young adults n 10, mean age 20 years, BMI 20 kg/m² | ‘Irani’ white rice (no further details on type): Fluffy (soaked 35 min → boiled 10 min → drained and simmered 20–30 min) Steamed (boiled 5–8 min → simmered 30 min) | 55 | 66 | 50 | 74 | 74 |
| | | Four brands of Jasmine rice: Delia (USA) Jazmen (USA) Reindeer (Thailand) Mahatma (Thailand) | | | | | |
| | | Low | Low | Low | Low | | |
| Truong et al. (2014) | Healthy volunteers n 12 (n 9 female/n 3 male), age 18–65 years, BMI 23 kg/m² | Rice was cooked in two different ways: Boiled in salt water Baked for 10 min at 160°C after boiling | 61 | 2536 | 96 | 68 | 68 |
| | | Low | Low | Low | Low | | |
| | | 60 min AUC (U/ml) 43 | 2676 | | | | |
| Gatti et al. (1987) | Healthy subjects n 14 (n 9 male/n 5 female), age 21–32 years, body weight 88–115 kg | Indian rice varieties (Sona Masuri, Ponni and Surti Kolam) | 48 | 2536 | 115 | 116 | |
| | | Sona Masuri | 61 | 2536 | | | |
| | | Ponni | 175 | 70 | | | |
| | | Surti Kolam | 172 | 72 | | | |
| | | Mahatma | 185 | 77 | | | |
| | | Gatti et al. (1987) | Healthy adults n 8 (n 3 male/n 5 female), mean age 25 years, BMI 20 kg/m² | Short-grain Koshikari rice | 3 h GI and II v. glucose reference | 48 | II = 65 | |
| | | | | | | | |
| | | | | | | | |
| Shobana et al. (2012) | Healthy volunteers n 23, mean age 18–45 years, BMI 20 kg/m² | | mmol × min¹ | | | | |
| | | | Ponni and Surti Kolam | 70 | 175 | 172 | 185 | |
| | | | Sona Masuri | 70 | 175 | 172 | 185 | |
| | | | Surti Kolam | 70 | 175 | 172 | 185 | |

GI, glycaemic index; II, insulinaemic index; NR, not reported; RS, resistant starch; UBR, Uncle Ben’s rice; HR, Hassawi rice; iAUC, total AUC; T2DM, type 2 diabetes mellitus; IAUC, incremental AUC; PB, parboiled; NP, not parboiled; Bg, Bathalagaoda; Bw, Bombuwala; NIDDM, non-insulin-dependent diabetes mellitus; IDDM, insulin-dependent diabetes mellitus.

* For the GI and II values, 50 g of available carbohydrates were used, with glucose as the reference (except where noted) being assigned the value of 100.

† The AUC was not calculated by the trapezoidal method but by the following formula: (time 1)/4 + (time 2)/2 + 3/4 time 3 + time 4 + time 5.
under normal cooking conditions, while amylopectin is fully gelatinised under these conditions\(^{(42)}\). Gelatinisation temperature is known to be positively correlated with amylose content\(^{(43)}\), implying that rice with a higher amylose content requires a higher gelatinisation temperature due to restrained swelling by amylose, resulting in a longer required cooking time\(^{(44)}\). The formation of complexes between amylose and lipids upon heating further contributes to reduced access to starch by gut enzymes\(^{(33)}\). These complexes with lipids are only found in association with amylose; therefore, rice with the highest amylose content would have more lipid–amylose complexes\(^{(33)}\). In addition, a higher amylose content (after cooking and cooling) leads to a greater degree of retrogradation\(^{(18)}\). A recent study found the major gene associated with the variation in the GI was the waxy gene\(^{(44)}\), which codes for different structures of amylose within the grain and leads to different retrogradation rates\(^{(45)}\).

The \textit{in vitro} literature showed that the rice cultivar, clustered as Indica, Japonica and Hybrid rice type, plays a pivotal role in the rate and degree of starch digestion: low-amylose Indica showed a faster and higher degree of digestion than low-amylose Japonica, while a high-amylose Japonica was faster and more completely digested (reflected by a higher content of rapidly digestible starch and a lower content of slowly digestible starch and RS) than high-amylose Indica\(^{(11)}\). In addition, Benmoussa \textit{et al.}\(^{(46)}\) showed that amylopectin fine structure in rice cultivars affects starch digestion properties \textit{in vitro}: cultivars with the highest amount of slowly digestible starch contained mainly long-chain amylopectin.

Post-harvest treatments such as parboiling\(^{(21,29,34)}\) and quick-cooking\(^{(18,21)}\) also have a large influence on the GI (see online Supplementary Table S3). Gelatinisation and recrystallisation are the major changes that occur in rice starch during parboiling\(^{(47)}\). The parboiling process increases the gelatinisation temperature of rice that is proportional to the severity of the heat treatment\(^{(48)}\). This is probably the reason why pressure parboiling lowers the GI to such a large extent, especially of high-amylose starches\(^{(49)}\). The pressure parboiling process increases gelatinisation temperature due to the formation of retrograded amylose and amylopectin.

Wet heating and subsequent drying during these processes result in the gelatinisation of starch, followed by retrogradation of amylose and amylopectin\(^{(18)}\) leading to higher levels of RS. It is possible that amylopectin crystallites (part of RS) retain some of the associating forces during reheating, and are partly responsible for the low glucose response observed...
during pressure parboiling. The amylose–lipid complexes have a melting temperature above 100°C and are not melted during the cooking process, resulting in higher levels of RS\textsuperscript{(28)}

Another way of achieving a high RS content is to apply multiple heating/cooling cycles\textsuperscript{(50)}. After three heating/cooling cycles, the RS content of legumes, cereals and tubers increased from 4-18, 1-86 and 1-51% to 8-16, 3-25 and 2-51%, respectively, on a DM basis. However, a ten times greater RS content in rice varieties had no effect on the GI\textsuperscript{(58)}. It is possible that the tested range of difference in RS content in that study was not sufficient to observe a change in the GI\textsuperscript{(58)}, which is confirmed by the fact that only large differences in amylose content (leading to high RS content after cooking and cooling) lead to relatively large effects on the GI\textsuperscript{(59)}.

Another final process shown to have a major influence on the PPG response is the gelatinisation process during cooking, which needs moisture and a high temperature (above gelatinisation temperature) for a particular period of time. Using different rice types with the same high amylose content, Panlasigui et al\textsuperscript{(25)} reported that PPG responses differed between rice types when a fixed cooking time was used; however, these differences disappeared when the minimum cooking time for each particular rice type was used. This is likely attributed to other physico-chemical properties of rice types. Physico-chemical parameters that predict lower blood glucose responses are high gelatinisation temperature, high minimum cooking time, lower viscosity measured by amylograph consistency (amylograph is an instrument for measuring gelatinisation temperature and viscosity of flour and starch pastes), and low volume expansion upon cooking, all parameters relating to lower gelatinisation\textsuperscript{(29)}. Steaming also gave a larger PPG response than boiling and simmering\textsuperscript{(51)}, which may reflect greater gelatinisation by steaming.

A factor that has a relatively less impact on PPG responses is physical size and form of the whole kernel rice, probably due to the fact that size is minimised by chewing\textsuperscript{(52)}. Particle size may also increase the apparent magnitude of differences between rice types and characteristics.

While rice as a total category may be a major global contributor to dietary glycaemic load, there is a wide variation in glycaemic and insulinaemic responses to rice as consumed. This can be largely attributed to the inherent starch characteristics of specific cultivars; however, within a given rice type, the mode of post-harvesting processing and ‘at-home’ preparation can also have a large influence. A reduced glycaemic impact is mediated mainly by the relative content of amylose (\(v\). amylopectin), reduction in gelatinisation, or the facilitation of retrogradation. Perhaps, surprisingly, milling and polishing (thus white \(v\). brown rice) has been found to have inconsistent impacts on acute glycaemic responses when compared at realistic cooking times that are longer for brown rice. The glycaemic response to rice can be further influenced by
individual characteristics of the consumer, such as chewing habit and ethnicity. In order to interpret and compare the reported PPG responses between different studies in rice, the rice cultivar, amylose:amylopectin ratio, post-harvest processing parameters and cooking conditions should be considered. In addition, a lower PPG response to rice can be achieved by choosing right conditions, for example high amylose content, minimised cooking times (or pressure parboiled) and cooled before consumption. The opposite effect (a higher PPG response) can be achieved by selecting for low-amylose (waxy) white rice, with a long cooking time, and consuming directly after cooking.

Supplementary material
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