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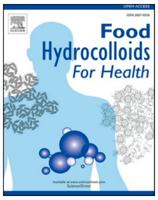

Hydrocolloid-assisted strategies for developing low-glycemic index rice: Mechanistic roles of starch modification, bioactive fortification, and processing innovations

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ABSTRACT

Rice, a staple for over half the global population, is associated with a high glycemic index (GI), contributing to diabetes, obesity, and related metabolic disorders. This review explores hydrocolloid-assisted strategies for developing low-GI rice, focusing on their mechanistic role in reducing starch digestibility. Hydrocolloids such as pectin, guar gum, xanthan gum, and β-glucan influence starch retrogradation, enzyme accessibility, and amylose-lipid complex formation, which slow glucose release. Processing techniques like retrogradation, germination, fermentation, and extrusion modify starch–protein–lipid interactions, enhancing GI reduction. Additionally, fortification with rice-derived bioactives, including polyphenols, flavonoids, γ-aminobutyric acid, dietary fibers, and local herbs (e.g., turmeric, garlic, green tea, mulberry leaves, pandan leaves, and butterfly pea flowers) reduces digestibility and promotes antioxidant and gut health benefits. These strategies are integrated into the mechanistic integration, highlighting how molecular, structural, and processing modifications collectively reduce GI. The review also addresses limitations and challenges, including variability in GI testing methods, sensory acceptability issues, nutrient loss during processing, and scalability for industry adoption. A summary table of human clinical trials evaluating the glycemic response to low-GI rice is provided to enhance practical relevance. Future research directions include multi-omics approaches for rice starch modification, intelligent processing technologies, and targeted nutrition interventions for at-risk populations, such as diabetics and the elderly, to optimize structure–function relationships and facilitate the adoption of low-GI rice in mainstream food systems.

1. Introduction

Rice is a global staple food, particularly in Asia, where it provides the primary source of calories for more than 3.5 billion people. More than 90 % of the world's rice is produced and consumed in Asia, with China and India being the largest producers (Hashim et al., 2024). While rice is a

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critical source of carbohydrates and cultural identity, its nutritional quality varies by type and processing. Polished white rice, the most widely consumed form, has a high glycemic index (GI) due to its easily digestible amylopectin starch and the removal of bran and germ during milling, which eliminates fiber and resistant starch. This results in rapid digestion and sharp postprandial glucose spikes. Habitual consumption of high-GI rice has been linked to insulin resistance, obesity, and Type 2 diabetes, particularly in populations where rice is consumed daily in large quantities (Du, Fu, Zhao & Xu, 2025).

The GI reflects how quickly carbohydrate-rich foods elevate blood glucose, with high-GI foods contributing to metabolic stress and increased risk of chronic diseases such as Type 2 diabetes and cardiovascular disorders (Du et al., 2025). However, the GI of rice is not fixed; it is influenced by amylose content, starch structure, and processing methods. High-amylose rice varieties generally exhibit lower GI values due to slower digestion, while cooking, cooling, parboiling, and extrusion can alter starch digestibility and glycemic response (Farooq & Yu, 2025). Pigmented and whole-grain rice varieties also offer health benefits by retaining fiber, phenolics, and bioactive compounds that moderate glycemic impact and improve metabolic outcomes (Du et al., 2025; Kusumawardani & Luangsakul, 2024).

Given the global burden of non-communicable diseases (NCDs), particularly obesity, type 2 diabetes, and cardiovascular diseases, the development of low-glycemic index (GI) rice offers a promising dietary strategy to improve glycemic control and reduce disease risk. Various approaches are being explored, including the incorporation of hydrocolloids, genetic and breeding methods to increase amylose content, fortification with fibers, polyphenols, and plant/herb extracts, as well as innovative food processing techniques such as parboiling, soaking, germination, and extrusion.

A key strategy for modulating the GI of rice is the use of hydrocolloids like pectin, guar gum, xanthan gum, and β-glucan. These substances influence starch retrogradation, enzyme accessibility, and amylose-lipid complex formation, all of which contribute to a slower glucose release. By forming gels, altering starch crystalline structures, and preventing rapid enzymatic breakdown, hydrocolloids help to reduce postprandial glucose spikes (Lu et al., 2025).

In addition to these techniques, there is an increasing focus on utilizing the whole rice product. Traditionally viewed as by-products, rice fractions such as bran, husk, and germ are now being valorized for their rich content of bioactive compounds, offering an opportunity for functional fortification. This not only enhances the nutritional profile of rice but also contributes to sustainable food production, in line with circular bioeconomy principles, by reducing waste.

This review synthesizes recent advances in the development of low-GI rice, with a focus on (i) structural modification techniques, (ii) emerging food processing technologies, (iii) functional and metabolic properties, (iv) clinical evidence from human trials, and (v) the potential for market commercialization and consumer acceptance. We also discuss the challenges associated with these approaches, including variability in GI testing methods, sensory acceptability issues, nutrient loss during processing, and the scalability of these innovations for industry adoption. Looking ahead, future research will likely explore multi-omics approaches for rice starch modification, intelligent processing technologies, and targeted nutrition interventions for populations with specific needs, such as diabetics and the elderly.

2. Glycemic index and health benefits of low-GI foods

The glycemic index (GI) is a numerical scale that ranks carbohydrate-rich foods based on how quickly they increase blood glucose levels after consumption. The scale ranges from 0 to 100, with pure glucose assigned a value of 100. Low-GI foods ($GI \leq 55$) are digested more slowly and result in a gradual increase in blood glucose, while high-GI foods ($GI > 70$) lead to rapid spikes in blood sugar (Dona, Pages, Gilbert & Kuchel, 2010). The GI of a food depends on factors such as its starch composition, fiber content, and the food's processing method. Rice, particularly white rice, is known to have a high GI, meaning it can cause significant fluctuations in blood sugar levels (Du et al., 2025).

Numerous studies have shown that consuming low-GI foods has a beneficial impact on health, particularly for individuals with Type 2 diabetes, obesity, and those at risk of cardiovascular diseases (Du et al., 2025). Low-GI foods help improve insulin sensitivity, manage blood glucose levels, and promote satiety, thus contributing to better weight management. In addition to their metabolic benefits, low-GI foods may reduce the risk of developing heart disease by lowering blood cholesterol levels and improving overall cardiovascular health (Jenkins et al., 2002). As a result, there is growing interest in promoting low-GI diets as a preventive strategy for these chronic diseases.

3. Rice and its impact on glycemic response: the need for low-GI alternatives

Rice, particularly white rice, is a major contributor to high-GI diets. The rapid digestion of white rice is due to its high starch content and the absence of fiber, which slows digestion (Du et al., 2025; Kusumawardani & Luangsakul, 2024). Rice's GI varies depending on the variety, amylose:amylopectin ratio, and preparation method (Ritudomphol & Luangsakul, 2019). Carbohydrates in rice consist of amylose (AM) and amylopectin (AP), with amylose being less digestible and therefore linked to lower GI. Rice with a soft texture typically contains more amylopectin and exhibits a higher GI. Conversely, harder-textured, high-amylose rice digests more slowly and has a lower GI (Nounmusig et al., 2018). For example, basmati rice tends to have a lower GI than other rice varieties (Pereira et al., 2023), while parboiled rice generally has a lower GI than traditional white rice (Alkandari et al., 2025). The glycemic index (GI) of white rice generally falls in the range of approximately 70 to 90, classifying it as a high-GI food and indicating it can quickly raise blood sugar levels (Farooq & Yu, 2025). Despite these variations, the widespread consumption of high-GI rice remains a concern, particularly in Asia where rice consumption is highest. Given rice's central role in many cultures and diets, finding ways to lower its GI could have significant public health benefits.

The glycemic index (GI) of rice is determined by the rate and extent of starch digestion and glucose absorption. Traditional polished white rice, with high amylopectin content and low fiber, generally exhibits a high GI, contributing to rapid postprandial glucose spikes (Ritudomphol & Luangsakul, 2019). Lowering the GI of rice is essential to addressing public health challenges related to diet. With rising global rates of NCDs especially obesity, Type 2 diabetes, and metabolic syndrome, improving the nutritional profile of staple foods like rice is an urgent priority. Low-GI rice could help mitigate the health risks associated with high-GI rice, particularly for populations with high rice consumption. By reducing the GI of rice through breeding, fortification, and processing innovations, we can provide consumers with a healthier alternative that supports better metabolic health.

5. Innovative approaches to developing low-GI rice and structural modification

To mitigate the associated health risks, researchers have explored various strategies to develop low-GI rice, broadly categorized into genetic and breeding techniques, processing and structural modifications, fortification with functional ingredients, and emerging food technologies. Each method focuses on reducing the rate at which starch is digested, enhancing the content of resistant starch (RS), and integrating bioactive compounds to improve glycemic response as illustrated in Table 1.

5.1. Genetic and breeding approaches

To develop low-glycemic index (GI) rice, breeding strategies focus on

Table 1
Strategies for lowering the glycemic index (GI) of rice.

Approach	Mechanism	Examples/Studies	Outcomes	References
Genetic & breeding	Modify starch composition (↑ amylose, ↑ RS, ↓ amylopectin), improve DF; gene editing (Wx, SBEIIb, GBSSI); pigmented varieties with polyphenols.	PK+4#20A09 line (GI 41.7, GL 21.3); CRISPR/Cas9-modified GBSSI & SBEIIb; QTL mapping for RS.	↓ GI, ↑ amylose & RS, slower starch digestion; improved insulin/glucose response; added agronomic traits.	Chaichoompu et al. (2024); Nounmusig et al. (2018) Liu et al. (2022); Badoni et al. (2024); Selvaraj et al. (2021) Kader et al. (2024); Fitzgerald et al. (2011)
Postharvest processing	Heat-moisture treatment (HMT), soaking, controlled drying, parboiling → promote retrogradation, ↑ RS, stabilize amylose.	HMT at 60–65 °C for 12–18 h; hot-air drying at 90 °C; parboiling.	↓ GI (as low as 39 with pressure-parboiling); ↑ RS, SDS; preserved firmness & moisture.	Alkandari et al. (2025); Donlao and Ogawa (2017); Donlao, Matsushita and Ogawa (2018); Rondanelli et al. (2023); Thuengtung et al. (2025); Thuengtung, Ketnawa, Ding, Cai and Ogawa (2023); Tian et al. (2018)
Germination	↑ GABA, phenolics, flavonoids, DF; starch mobilization alters digestibility.	Germinated parboiled rice (GI ∼41.7, GABA 78.6 mg/100 g).	↓ GI vs polished rice; ↑ bioactives; functional food for prediabetes.	Guzman et al. (2017); Kongkachuichai, Charoensiri, Meekhruerod and Kettawan (2020); M et al. (2025)
Cooking–cooling	Repeated cooking/cooling cycles → amylose retrogradation, RS formation, amylose–lipid complexes.	Cooling at 4 °C for 24 h + coconut oil; chapati/dalia.	↑ RS (+4.17 g/100 g), ↓ RDS; improved prebiotic effect; lower GI in rice & wheat.	Lian, Loo, Tan and Lye (2024); Kaur et al. (2023)
Enzymatic modification	Pullulanase, amylosucrase, β-amylase, etc. → chain elongation, crystallinity changes, resistant networks.	Pullulanase + heat; Amylosucrase; β-amylase/ transglucosidase/pullulanase; APU_Aquae enzyme.	↑ RS (up to 40.5 %); ↑ SDS; ↓ digestibility; scalable enzymatic tailoring.	Wijaya, Muhandri, Hasanah and Haryo Bimo Setiarto (2024); Geng et al. (2023) Song et al. (2023); Li et al. (2019); Peng et al. (2021)
Fermentation	LAB/yeast enzymes restructure starch, ↑ amylose/RS, ↑ phenolics/GABA, ↓ RDS.	Fermented rice germ extracts; co-fermentation for noodles; Monascus rice; L. plantarum fermentation.	↓ GI (e.g., from 82.9 → 74.5); ↑ RS, SDS, antioxidant activity; ↓ GLUT2/ SGLT1 expression; improved glucose metabolism.	Hyun, Kim, Jung and Kim (2021); Hyun, Park and Kim (2023); Jiang et al. (2024); Ren et al. (2025); Tang et al. (2023)
Fortification	-Addition of fibers, RS, proteins, lipids, and plant extracts → slow starch hydrolysis & enzyme inhibition. -Addition of hydrocolloids (pectin, guar gum, xanthan gum, β-glucan, alginate, κ-carrageenan, konjac glucomannan, CMC) increases digesta viscosity and matrix entrapment; hydrocolloid–starch hydrogen bonding and network formation reduce starch swelling and enzyme accessibility; inhibition of α-ylase/amyloglucosidase; promotion of amylose retrogradation and starch–fiber/lipid complexes, shifting RDS to SDS/RS.	FiberCreme, Cowpea flour, White bean and carob fruit; Tea catechins, herbal tea Mulberry leaf, Jicama and mulberry leaf extracts Chinese bayberry leaves Turmeric, garlic, pandan leaf + minerals; Protein/lipid enrichment Coconut oil Cooking fat Quecertin Pectin with tailored degree of methoxylation/amidation; guar gum alone or combined with dry heat, extrusion, or thermomechanical treatment; xanthan gum with dry heat or thermomechanical processing; oat/barley β-glucan enrichment (e.g., LoGICarb™ rice); alginate, κ-carrageenan, konjac glucomannan, CMC in rice, rice starch, rice flour, noodles, and rice analogues.	↓ GI (to ∼20 with pandan extract + cooling); ↑ RS, SDS, antioxidants; protein/lipid networks form resistant starch complexes. ↓ GI / pGI (in some systems to ∼20–40 when combined with cooling or optimized processing); ↓ RDS; ↑ SDS and RS; slower starch hydrolysis and glucose absorption; improved insulin response and satiety; effects dependent on hydrocolloid structure, molecular weight, concentration, and processing.	Apinanthanuwong et al. (2023); Arribas, Cabellos, Guillamón and Pedrosa (2020); Aumasa et al. (2024); Aumasa, Ogawa, Singh, Panpipat and Donlao (2023); Fibri and Marsono (2024); Guo (2020) Ho, Wong and Siewn (2021);Zheng et al. (2021); Tang, Gan and Mustapha (2024) Yulianto (2020); Yulianto, Sulistyani, and Swasono (2021); (Kongkachuichai et al., 2020; Krishnan et al. (2020); Poomsa-ad, Wiset, Suwannarong & Pakdeenarong, 2024); Yang, Qiu and Zhang (2025) He et al. (2020, 2021); Luo et al. (2017); Ma et al. (2024); Oh, Bae and Lee (2018); Zheng et al. (2020, 2021); Chen and Raymond (2008); Lee et al. (2020); Aoe et al. (2014); Fouda and Anderson (2016); Guo et al. (2025); Dartois et al. (2010); Cao and Li (2025); He, Zhang, Liao and Shen (2023)
Extrusion	High T/P disrupts granules → gelatinization + retrogradation, ↑ RS & SDS, co-extrusion with bioactives.	Extrusion + HMT; purple sweet potato; grape seed/bayberry polyphenols; millet/quinoa blends; fiber fortification.	↓ eGI (≤55); ↓ starch hydrolysis (86.6 → 70.9 %); ↑ RS, SDS; sustainable upcycling of broken rice; improved nutrition & texture.	Bodie, Micciche, Atungulu, Rothrock and Ricke (2019); Dalbhagat and Mishra (2019); Huang, Liu, Ma, Mai and Li (2022); Shaikh, Pathare, Chakraborty and Annapure (2025); Wang et al. (2021); Xia, Lin, Wang, Liu and Liu (2024); Yadav, Dalbhagat and Mishra (2021); Yang et al. (2020); Zheng et al. (2021)

modifying starch composition and dietary fiber (DF) content to slow carbohydrate digestion and reduce postprandial blood sugar spikes. Key approaches include conventional breeding, marker-assisted selection (MAS), and genome editing technologies such as CRISPR/Cas9, targeting starch properties like amylose content and resistant starch (RS) levels. High-amylose rice varieties are particularly effective in lowering GI, as amylose is less digestible than amylopectin (Nounmusig et al., 2018).

For instance, the rice line PK+4#20A09, developed through pseudo-backcrossing, incorporates low-amylose traits from Pathum Thani 1 (PTT1) and has shown a low GI (GI = 41.7) and glycemic load (GL = 21.3), significantly reducing postprandial blood glucose and insulin levels in clinical trials (Chaichoompu et al., 2024). This line also offers improved disease resistance and submergence tolerance, making it ideal for regions with high diabetes prevalence.

Molecular breeding has utilized key genes like Waxy (Wx) and SBEIIb, controlling starch synthesis and branching, to develop rice with low GI. Advanced QTL mapping has identified genes linked to resistant starch and intermediate GI traits, enabling efficient selection for low-GI rice (Liu et al., 2022). CRISPR/Cas9 has further enabled the precise modification of genes, such as GBSSI and SBEIIb, producing lines with higher amylose content and lower GI (Xingdan Liu et al., 2022).

Whole-grain and pigmented rice varieties, such as red, black, and purple, naturally have lower GI due to higher soluble dietary fiber (SDF) and phenolic compounds, which slow starch digestion and provide additional health benefits. New evidence also highlights the importance of pseudo-backcrossing, which led to the development of new rice lines, including PK+4#20A09, with GI values ranging from 48.1 % to 66.1 % (Chaichoompu et al., 2024). Clinical studies demonstrated that this variety significantly lowered blood glucose and insulin levels, while enhancing GLP-1 (insulin-promoting hormone) and reducing GIP (a hormone elevated in insulin resistance) (Chaichoompu et al., 2024).

Additionally, the grain morphology of low-GI rice, including larger starch granules and lower endosperm porosity, contributes to slower enzymatic hydrolysis and slower glucose absorption (Badoni et al., 2024; Selvaraj et al., 2021). Breeding efforts are increasingly focused on integrating nutritional traits with high yield, ensuring both health benefits and agronomic stability (Kader et al., 2024). Future breeding will likely incorporate haplotype-based selection, genomic prediction models, and synthetic biology to create rice varieties with both low GI and enhanced nutritional profiles (Badoni et al., 2024; Fitzgerald et al., 2011; Kader et al., 2024), offering promising solutions for diabetes prevention and food security in diabetes-prone populations worldwide.

5.2. *Postharvest processing techniques*

Postharvest processing techniques such as mild heat soaking, heat-moisture treatment (HMT), controlled drying, and parboiling have emerged as practical and scalable strategies to reduce the glycemic impact of rice while maintaining desirable sensory qualities as demonstrated in Table 1. Mild soaking of harvested rough rice at 65 °C has been shown to lower the equilibrium level of starch hydrolysis without significantly altering resistant starch (RS) content or texture, indicating modest glycemic modulation potential (Thuengtung et al., 2025). Similarly, HMT applied at temperatures of 60–65 °C for 12 to 18 h increases RS content and reduces *in vitro* starch digestibility, particularly when treatment duration and temperature are higher. Importantly, these treatments preserve cooked rice firmness and moisture, ensuring minimal adverse effects on eating quality (Thuengtung, Ketnawa, Ding, Cai & Ogawa, 2023). Postharvest drying methods also influence glycemic responses; hot-air drying at temperatures up to 90 °C consistently reduces the estimated glycemic index (GI) of cooked rice more effectively than sun drying (Donlao & Ogawa, 2017). Drying at 90 °C produces the lowest GI values without compromising cooking characteristics, likely through enhanced starch retrogradation and RS formation (Donlao, Matsushita & Ogawa, 2018).

Parboiling, a well-established postharvest technique involving soaking, steaming, and drying of paddy rice, further enhances rice's nutritional profile by increasing RS and preserving amylose content, thereby lowering GI. Hydrothermal treatment during parboiling causes starch gelatinization followed by retrogradation, increasing both resistant starch and slowly digestible starch fractions while reducing rapidly digestible starch (Alkandari et al., 2025). For example, an *in vitro* study demonstrated that equilibrium starch hydrolysis was significantly reduced in parboiled rice (76.95 %) compared to polished rice (86.55 %) and brown rice (80.59 %). X-ray diffraction analysis revealed that parboiled rice contains A-, B-, and V-type crystalline structures, which form physical barriers to enzymatic digestion (Tian et al., 2018). These structural changes translate into favorable metabolic outcomes in humans. Rondanelli et al. (2023) reported low GI values (∼48–54) across various parboiled rice varieties, confirming parboiling's capacity to lower glycemic response. Among individuals with type 2 diabetes, more intense parboiling methods further reduce GI values: non-parboiled (55), traditionally parboiled (46), and pressure-parboiled rice (39). Collectively, these findings underscore parboiling and related thermal treatments as effective postharvest approaches to produce rice with improved glycemic properties and enhanced nutritional benefits.

5.3. *Germination*

Germination is a powerful postharvest process that enhances the nutritional profile of rice by increasing γ-aminobutyric acid (GABA), phenolics, flavonoids, and dietary fiber—compounds linked to slower carbohydrate absorption and improved glucose metabolism (M et al., 2025). When combined with parboiling, germination has been shown to significantly reduce the GI of rice. For instance, in South Indian indica varieties, germinated parboiled rice achieved GI values as low as 41.7 (M et al., 2025). A recent study on Thai landrace varieties confirmed that germinated parboiled brown rice retained the highest levels of bioactives, especially GABA (78.57 mg/100 g), and had medium GI (60.58), much lower than polished rice (83.10) (Kongkachuichai, Charoensiri, Meekhruerod & Kettawan, 2020). This makes germinated parboiled brown rice a functional food option for pre-diabetic individuals. Furthermore, new research suggests that starch mobilization during seed germination mimics human digestion, offering a novel method for screening low-GI rice varieties. Differences in starch structure, resistant starch content, and gene expression related to starch metabolism can predict rice digestibility and inform precision breeding programs for healthier rice cultivars (Guzman et al., 2017).

5.4. *Cooking–cooling cycles (Retrogradation)*

Cooking–cooling cycles significantly reduce the glycemic response of rice and wheat-based foods by promoting starch retrogradation, which increases resistant starch (RS) and reduces rapidly digestible starch (RDS). Cooling cooked rice at 4 °C for 24 h, especially when combined with coconut oil (which forms amylose-lipid complexes), enhances RS formation and slows glucose release. *In vitro* studies showed improved prebiotic effects and reduced digestibility, while a meta-analysis confirmed a mean RS increase of 4.17 g/100 g and RDS decrease of 7.09 g/100 g (Lian, Loo, Tan & Lye, 2024). Similar effects were observed in wheat products like chapati and dalia, where cold storage reduced GI (e.g., chapati GI: 43) and improved glucose control in human and rat models. These strategies are practical and effective in improving the metabolic profile of common staple foods (Kaur et al., 2023).

5.5. *Enzymatic modification*

Enzymatic modification of rice starch using debranching and transglycosylating enzymes has shown strong potential to reduce digestibility and glycemic index (GI) while enhancing resistant and slowly digestible starch (RS and SDS) (Wijaya, Muhandri, Hasanah & Haryo Bimo Setiarto, 2024). Pullulanase (PUL) treatment, especially when combined with controlled preheating (60–80 °C), modifies starch granule structure by releasing linear chains, transforming A-type to B-type crystallinity, and weakening gel networks—resulting in reduced digestibility and lower estimated GI (Geng et al., 2023). Amylosucrase (DgAS) application elongates amylopectin side chains and increases B-type crystallinity, significantly enhancing SDS content and attenuating glucose release *in vitro* (Jung et al., 2020; Song et al., 2023). Further, sequential treatments with β-amylase, transglucosidase, and pullulanase (BA/TG/PUL) increase crystallinity and thermal stability, producing starch with high enzyme resistance and low GI due to the formation of resistant structures with linear chains of DP 9–11 (H. Li et al., 2019). Additionally, the use of a thermostable bifunctional amylopullulanase (APU_Aquae) from *Aquifex aeolicus* allows a one-step enzymatic process at high temperature (100 °C), efficiently generating RS3 (up to 40.5 %) within 7 h by promoting the formation of medium-length B1 chains (DP 13–24) (Peng et al., 2021). Collectively, these enzymatic strategies offer scalable, efficient methods to tailor rice starch for functional, low-GI food applications.

5.6. Fermentation

Microbial fermentation significantly improves the nutritional profile of rice while reducing its glycemic impact through structural starch modifications and enhanced bioactive compound production (Lim et al., 2024). Fermented rice germ extracts, particularly those extracted with 30 % ethanol after *Lactobacillus plantarum* fermentation, demonstrated potent inhibition of glucose uptake by downregulating GLUT2 and SGLT1 expression and improving postprandial glycemic control in mice. Long-term feeding of fermented rice germ extracts in diabetic models also improved glucose tolerance, regulated hepatic glucose metabolism, and reduced oxidative stress, attributed to elevated ferulic acid and GABA content (Ye J. Hyun, Kim, Jung & Kim, 2021; Ye Ji Hyun, Park & Kim, 2023). During rice noodle fermentation, co-cultures of *Lactobacillus rhamnosus, Lactococcus cremoris*, and *Saccharomyces cerevisiae* increased α-amylase and debranching enzyme activity, promoting starch chain restructuring, increasing amylose and RS content while decreasing RDS (Ren et al., 2025). Moreover, fermentation time and starter concentration directly influenced starch multi-scale structural reassembly—boosting slowly digestible starch (SDS) through increased crystallinity, short-range order, and compactness (Ren et al., 2025). In high-RS rice varieties, Monascus-mediated fermentation enhanced RS, GABA, phenolics (especially ferulic acid), and antioxidant activity, creating value-added functional red mold rice (RMR) (Jiang et al., 2024). Similarly, fermentation of indica rice by L. *plantarum* led to a GI reduction from 82.88 to 74.53, alongside increases in RS, SDS, and starch structural stability due to increased short-chain amylopectin and crystallinity (Tang et al., 2023). Overall, fermentation emerges as a versatile tool to restructure rice starch, regulate glucose absorption, and enrich bioactives—positioning it as a promising strategy in the development of low-GI, functional rice-based foods.

5.7. Fortification

Fortification of food with functional ingredients like fibers, resistant starch, proteins, and bioactive compounds has been recognized for its potential to modulate starch digestion and improve glycemic response. Various bioactive compounds, including polyphenols from plants like turmeric, ginger, lemongrass, and tea, have been shown to inhibit key enzymes involved in starch digestion namely α-amylase and α-glucosidase thus slowing down the breakdown of carbohydrates and mitigating rapid blood glucose spikes (Farooq & Yu, 2025; Nithya, Dalbhagat & Mishra, 2021)

5.7.1. Hydrocolloids

Hydrocolloids are widely used as food additives to enhance the stability, texture, and sensory qualities of diverse food products (Li & Nie, 2016). Beyond these functional roles, they can interact with starch in multiple ways to slow its digestion, thereby reducing postprandial glucose spikes. Hydrocolloids can modify starch structure, delay gastric emptying, and limit enzyme accessibility, contributing to lower starch hydrolysis. In addition, many hydrocolloids act as fermentable fibers, promoting the growth of beneficial gut microbiota and potentially influencing metabolic health (Lu et al., 2025). Within food systems, these compounds play a critical role in modulating starch retrogradation and hydrolysis while supporting gut microbiota, collectively impacting both food quality and human health outcomes.

Among the most studied hydrocolloids for glycemic control are pectin, guar gum, alginate, and β-glucan. These compounds have attracted increasing attention for their ability to reduce starch digestibility and glycemic index (GI) through structural and molecular interactions during digestion. In the following sections, we provide an overview of these hydrocolloids, their sources, physicochemical properties, and recent research highlighting their effects on glycemic response.

Types and sources of hydrocolloids

Pectin. Pectin is a naturally occurring polysaccharide found in plant cell walls, particularly in fruits such as citrus and apples. It is highly soluble, viscous, and capable of forming gels, making it widely used as a gelling agent in food systems (He, Bian, Xie & Chen, 2021). The molecular chains of pectin contain hydroxyl, carboxyl, and amide groups that can form hydrogen bonds with starch molecules, promoting the formation of more ordered and dense starch structures. This interaction reduces enzyme accessibility, slows gelatinization, and enhances resistant starch (RS) and slowly digestible starch (SDS) content while lowering rapidly digestible starch (RDS) (He et al., 2021; Ma et al., 2024).

Recent research has highlighted that the structural characteristics of pectin including galacturonic acid content, degree of methoxylation, degree of amidation, and molecular weight significantly influence the pasting properties of rice starch (Luo et al., 2017). Pectin with varying structures were added to rice starch, resulting in notable differences in pasting behavior (He et al., 2021; J. Zheng, S. Huang, et al., 2021; Zheng, Wang, Huang, Kan & Zhang, 2021). These findings indicate that tailoring pectin's structural properties can modulate starch gelatinization and pasting behavior, providing insights for designing functional rice-based foods with controlled digestibility and reduced glycemic response.

Guar gum. Guar gum (GG), a galactomannan derived from the seeds of *Cyamopsis tetragonoloba*, is widely used as a thickening, emulsifying, and stabilizing agent in starch-based foods, including dairy, sauces, and bakery products. It is rich in soluble dietary fiber, which constitutes approximately 80 % of its total fiber content. In the gastrointestinal tract, guar gum forms a viscous gel that entangles food and absorbs water, slowing gastric emptying, reducing enzyme accessibility, and consequently moderating the rate of glucose absorption. These properties contribute to improved postprandial glycemic control, making it beneficial for diabetes management (He et al., 2020). Additionally, guar gum undergoes fermentation by gut microbiota in the large intestine, producing short-chain fatty acids that may further support metabolic health. However, excessive fermentation can lead to gas production, distension, and flatulence (Dartois, Singh, Kaur & Singh, 2010; Ma et al., 2024). Overall, guar gum's viscosity, fiber content, and fermentability make it an effective ingredient for modulating starch digestibility and glycemic response.

Recent studies have extensively investigated the effects of GG and other hydrocolloids on starch digestibility and glycemic response. *In vitro* studies on rice starch have shown that GG reduces the rate of starch hydrolysis, particularly during the early stages of intestinal digestion, by forming a viscous gel that limits enzyme access and slows starch solubilization (He et al., 2020). Rheological analyses indicate that GG increases the consistency and maintains higher viscosity of digesta, contributing to delayed glucose release.

Processing methods combined with GG, such as micro-extrusion, thermomechanical treatment, and dry heat treatment, further enhance its effects. For example, micro-extruded rice starch with GG exhibited reduced digestion rates and predicted glycemic index (pGI), along with increased structural ordering at granule, lamellar, crystalline, and molecular levels. Similarly, dry heat treatment of high-amylose rice starch with GG lowered rapidly digestible starch (RDS) and pGI, demonstrating that GG–starch complexation *via* heat or extrusion can improve resistant starch content and modulate glycemic response (Oh, Bae & Lee, 2018). These findings collectively indicate that combining GG with rice starch, often under controlled processing conditions, is an effective strategy to slow starch digestion and improve metabolic outcomes.

Xanthan gum. Xanthan gum (XG) is an anionic extracellular polysaccharide produced by *Xanthomonas campestris* and is widely used as a thickening and stabilizing agent in the food industry (J. Zheng, S. Huang, et al., 2021). XG solutions exhibit pseudoplastic behavior, with high viscosity at low shear and low viscosity at high shear, which allows it to mix easily with other viscous systems and form a protective layer on food surfaces, reducing enzyme accessibility (Zheng et al., 2021). When combined with starch, XG can alter the water solubility, rheological, and physicochemical properties of starch, influencing digestibility (Liu et al., 2022).

Recent studies have demonstrated that XG can both promote and inhibit starch digestibility depending on the system. For example, in dry fermented rice flour, XG promoted porous structures in starch granules, increasing enzyme accessibility and raising the estimated glycemic index (Srikaeo, Laothongsan & Lerdluksamee, 2018). Conversely, studies using rice starch and high-amylose rice starch modified with XG via dry heat or thermomechanical treatments showed that XG effectively slowed starch hydrolysis, increased resistant starch content, reduced rapidly digestible starch, and lowered predicted glycemic index (pGI) (Oh et al., 2018). These effects were associated with enhanced structural ordering, increased crystallinity, and modifications at multiple scales, including granule, lamellar, and molecular structures. Dry heat treatment for 2 h with XG was particularly effective in improving hydration, pasting, and gel properties while retarding starch digestibility (Oh et al., 2018).

Overall, XG modifies starch digestibility by altering its physical structure, rheology, and enzymatic accessibility, and its effects can be fine-tuned through processing techniques, making it a versatile ingredient for controlling glycemic response in starchy foods.

β-Glucan. β-Glucans are non-starch polysaccharides widely present in cereal grains, particularly oat and barley, and are also distributed throughout rice grain tissues, including the endosperm, bran, and husk. β-glucan is known for its ability to lower cholesterol and improve gut health. It increases the viscosity of digestive contents, slowing starch digestion and glucose absorption, thus improving insulin sensitivity and lowering the GI of foods (Chen & Raymond, 2008).

β-Glucans have also been shown to inhibit α-amylase and amyloglucosidase activity, either directly or by forming protective matrices around starch granules. Moreover, molecular weight plays a critical role, with low-molecular-weight oat β-glucans exhibiting stronger inhibition of starch digestion and substantially increasing resistant starch content (Guo et al., 2025). In addition to glycemic control, β-glucan enrichment of rice (LoGICarb™) either through blending with high β-glucan barley (Lin Lee, Chan, Chun, Bhaskaran, & Chen, 2020)or direct substitution (Aoe et al., 2014; Fouda & Anderson, 2016; Guo et al., 2025) has been associated with enhanced satiety and reduced subsequent energy intake. Collectively, these findings highlight β-glucans as effective functional ingredients for improving the metabolic quality of rice-based foods and support their application in the development of low-GI diets for the prevention and management of diabetes and related metabolic disorders.

Other hydrocolloids. A range of other hydrocolloids including alginate (Cao & Li, 2025), κ-carrageenan (He et al., 2021), Konjac glucomannan (He, Zhang, Liao & Shen, 2023), and carboxymethyl cellulose (CMC) (Oh et al., 2018) are widely used for their thickening and gelling properties. hese non-starch polysaccharides (NSPs) can influence starch digestibility by modifying starch gelatinization, pasting behavior, and retrogradation, as well as by increasing system viscosity and restricting enzyme diffusion.

More recently, NSP-encapsulated rice flour has emerged as a novel rice analogue aimed at improving nutritional functionality. Although this approach remains less extensively studied, available evidence suggests that hydrocolloid encapsulation can alter starch structure and starch–enzyme interactions, thereby slowing enzymatic hydrolysis and potentially reducing the glycemic index. Continued research is needed to better elucidate the mechanisms involved and to assess the applicability of these hydrocolloid-based systems in the development of low-GI rice products.

5.7.2. *Dietary fibers and resistant starch*

Dietary fibers, especially soluble fibers and resistant starch (RS), are crucial in modulating starch digestion and improving postprandial glycemic control. Soluble fibers, such as β-glucan and inulin, form viscous gels in the gastrointestinal tract, slowing starch digestion and glucose absorption by hindering digestive enzyme access to starch granules. This delay not only reduces postprandial glucose spikes but also enhances satiety due to delayed gastric emptying. Resistant starch (RS), which includes starch types like RS1, RS2, and RS3, escapes digestion in the small intestine and reaches the colon, where it is fermented by gut microbiota, producing beneficial short-chain fatty acids (SCFAs) like butyrate. These SCFAs have been linked to improved insulin sensitivity and reduced inflammation. Incorporating RS into staple foods, like rice, can lower the glycemic response and offer prebiotic benefits (Farooq & Yu, 2024; Zhang & Bao, 2023).

Various fortification strategies have been explored to enhance the nutritional profile of rice by increasing its fiber and resistant starch content. Studies on FiberCreme, a non-dairy creamer rich in dietary fiber, demonstrated that its addition to rice increases both fat content and fiber levels, significantly reducing the glycemic index (GI) of the rice (Fibri & Marsono, 2024). Similarly, fortifying rice with cowpea flour, which is rich in dietary fiber and protein, also improves the antioxidant properties, starch digestibility, and pasting properties of rice, while lowering its GI (Guo, 2020). The addition of carob fruit to gluten-free rice pasta has shown to boost fiber content and increase the resistant starch percentage, contributing to a better functional food profile (Arribas, Cabellos, Guillamón & Pedrosa, 2020).

Additionally, extrusion processing, as demonstrated in studies involving soybean dietary fiber, has been shown to enhance both soluble and insoluble dietary fiber content in rice analogs, further reducing the glycemic index and increasing resistant starch content. These findings underscore the importance of incorporating dietary fibers and resistant starch into rice and other staple foods to mitigate glycemic spikes and improve metabolic health (Liu et al., 2018)

By fortifying rice with fibers and resistant starch, such as through the addition of cowpea flour, FiberCreme, or by extrusion methods, rice can be transformed into a more functional food. This not only reduces its glycemic index but also promotes gut health and supports better management of chronic conditions such as diabetes and metabolic syndrome.

5.7.3. *Plant or herb extracts*

Fortification of rice with bioactive plant and herb extracts has emerged as a promising strategy to enhance metabolic health and manage chronic diseases like type 2 diabetes. These extracts are rich in polyphenols, flavonoids, and antioxidant vitamins (e.g., C and E), which have been shown to improve insulin sensitivity, reduce oxidative stress, and modulate inflammation. Incorporating such bioactive compounds into rice can also lower glycemic response and increase resistant starch (RS), making rice a functional food for diabetic and health-conscious consumers.

Recent studies on fortification with plant or herb extracts have highlighted their potential to modulate starch digestion and improve glycemic control. Tea catechins, particularly from green tea, have been shown to significantly inhibit starch digestion, lowering the estimated glycemic index (eGI) of rice, with green tea exhibiting the most potent effect (Apinanthanuwong et al., 2023; Aumasa, Ogawa, Singh, Panpipat & Donlao, 2023). Herbal teas like mulberry leaf, gymnema leaf, beal fruit, and chrysanthemum flower also demonstrate strong inhibitory effects on starch hydrolysis, with mulberry and gymnema leaf teas reducing eGI by up to 15 % (Aumasa et al., 2024). These effects are attributed to the antioxidant activity of phytochemicals, which interact with digestive enzymes, especially α-amylase, slowing starch breakdown and mitigating postprandial hyperglycemia. Further, the impact of mulberry leaf powder on starch digestibility is influenced by particle size, with smaller particles enhancing enzyme inhibition and reducing eGI (Aumasa et al., 2024). Jicama and mulberry leaf extracts also show promising hypoglycemic effects, with mulberry leaf exhibited greater effectiveness in reducing the release of reducing sugars during rice digestion. (P. L. Tang, Gan & Mustapha, 2024).

Recent studies have explored the role of polyphenol-rich herbs and spices, such as turmeric, garlic, and various herbs, in modulating starch digestibility and enhancing the functional properties of rice. The inclusion of turmeric (*Curcuma longa*) and garlic (*Allium sativum*) in rice fortification has also shown to be effective in reducing rice's glycemic impact. Ho, Wong and Siewn (2021) demonstrated that adding turmeric powder (3 % w/w) to cooked white rice reduced the rapidly digestible starch fraction, while increasing slowly digestible and resistant starch fractions. This not only enhanced the antioxidant content (92.02 mg GAE/100 g) but also lowered the glycemic index of rice, making it a functional food for health-conscious consumers. Similarly, garlic powder has been shown to inhibit α-amylase activity, slowing starch digestion and contributing to lower postprandial glucose levels.

Poomsa-ad, Wiset, Suwannarong and Pakdeenarong (2024) examined how cooking methods and the addition of Thai herbs, such as pandan leaf juice and butterfly pea flower, influence the resistant starch (RS) content in Thai jasmine rice KDML 105 rice. The study found that the use of extra virgin coconut oil and pressure cooking, especially when combined with citric acid soaking and Thai herbs, significantly increased RS levels. Among rice types, Sao Hai rice demonstrated the highest RS content (4.31 ± 0.30 %). Studies on fortifying rice with pandan leaf extract, combined with essential minerals like chromium (Cr) and magnesium (Mg), have shown significant improvements in both the nutritional and functional properties of rice (Yulianto & Swasono, 2021). When pandan leaf extract and minerals are added during the parboiling process, resistant starch (RS) content increases, and the glycemic index of rice decreases. For example, one study found that parboiled rice fortified with pandan leaf extract and soaked at 65 °C for 2.5 h, followed by cooling at 2 °C for 12 h, resulted in a rice with a low GI of 20.03 and the highest RS content of 23.99. This fortified rice was preferred by taste panelists, indicating that it is both a palatable and healthful option for diabetics. Another study on brown parboiled rice, which examined various methods of adding pandan leaf extract and fortificants during soaking and boiling, along with different cooling durations, found that cooling the rice for 36 h at 2 °C after soaking with pandan leaf extract and minerals resulted in a low GI of 40.39. This rice also exhibited improved cooking characteristics, such as a cooking time of 43 min, a water uptake ratio of 3.10 g/g, and an elongation of 1.21 mm/mm (Kongkachuichai et al., 2020).

Collectively, these findings support the efficacy of using natural plant extracts and optimized cooking techniques to improve the nutritional profile of rice by reducing digestibility and increasing its content of health-promoting resistant starch.

5.7.4. *Protein and lipid*

Rice, traditionally a high-glycemic food, contains relatively low protein (4.5–15.9 %) and lipid content, both of which can interact with starch and significantly influence its digestibility (Ngo, Kunyanee & Luangsakul, 2023). Studies show that rice protein, particularly from leguminous sources, slows starch hydrolysis by forming hydrogen bonds with starch molecules, reducing digestive enzyme accessibility. This interaction decreases the starch digestibility and, consequently, lowers the glycemic index (GI) of rice (Liu et al., 2018; Ngo et al., 2023). When rice protein is added, the digestion rate of rice starch is slowed, especially in varieties with higher amylose content, such as low-GI rice, where protein addition results in the formation of a more complex starch-protein network. This network creates a resistant starch structure, further decreasing the rate of starch digestion (Guo, 2020; Jan et al., 2025). Additionally, proteins control starch gelatinization and retrogradation, reducing its overall digestibility (Khatun, Waters & Liu, 2020) .

Lipids, especially those from endogenous rice sources like the embryo and aleuronic layer, also slow starch digestion by interacting with amylose to form amylose-lipid complexes. These complexes are more resistant to enzymatic breakdown, further reducing the GI of rice (Ngo et al., 2023). Long-chain saturated fatty acids, in particular, are more effective in forming stable starch-lipid complexes than shorter-chain fatty acids, enhancing starch resistance to hydrolysis (Krishnan et al., 2020). The synergy between proteins, lipids, and starch promotes the formation of resistant starch (RS), which not only decreases starch digestibility but also improves blood glucose regulation (Krishnan et al., 2020; Sun, Ranawana, Leow & Henry, 2014).

Incorporating plant-based proteins and healthy lipids into rice thus presents a promising strategy for improving its nutritional profile, lowering its glycemic response, and making it more suitable for individuals managing blood sugar levels. The combined effects of protein and lipid addition can reduce rice's glycemic index, enhance starch digestibility, and provide a healthier metabolic response.

5.8. *Extrusion technology*

Extrusion technology, which is used for the valorization of broken rice into functional products with a low glycemic index, is summarized

Table 2
Extrusion technology for valorization of broken rice into functional low-GI products.

Strategy/ Approach	Mechanism / Process	Key Outcomes	References
High T–P extrusion	Disrupts starch granules → gelatinization & retrogradation; ↑ RS & SDS, ↓ RDS	Lower digestibility; reduced eGI	Farooq and Yu (2025)
Extrusion + HMT	Enhances crystallinity, amylose–lipid complex formation	Significantly lower eGI	Yang et al. (2020)
Purple sweet potato incorporation	Alters crystalline structure (A → *A* + *V* type)	Reduced starch hydrolysis; improved nutrition & structure	Wang et al. (2021)
Upcycling broken rice	Restructures milling by-product (12–15 % waste) into functional foods	Low-GI, sustainable use of by-products	Bodie et al. (2019); Yang et al. (2020); Nithya, Dalbhagat and Mishra (2021)
Starch structural transformation	A-type → V/B-type crystalline forms	↓ Starch hydrolysis; ↓ GI	Huang et al. (2022); Yang et al. (2020)
Co-extrusion with bioactives Proanthocyanin	Inhibits enzymatic hydrolysis; alters crystallinity/pasting	Hydrolysis reduced (86.6 % → 70.9 %); improved antioxidant function	Zheng et al. (2021)
Cassava starch blending (≤30 %)	Enhances gelatinization; lowers retrogradation	Improved cooking properties	Xia et al. (2024)
Millets & quinoa blending	Diversifies starch profile	Instant rice with GI ≤ 55; improved cooking quality	Yadav et al. (2021)
Dietary fiber fortification (1:3 SDF:IDF)	Fiber–starch interactions during extrusion	↑ RS (12.4 % → 16.5 %); better texture; diabetic-friendly rice analogues	Shaikh et al. (2025)
Micronutrient fortification + AI modeling	Addition of Fe, folic acid, B12; ANN optimization	Nutrient-enriched products with precise quality control	Dalbhagat and Mishra (2019)

in Table 2. High-temperature, high-pressure extrusion effectively reduces rice digestibility by disrupting starch granules, promoting gelatinization and retrogradation, and increasing resistant starch (RS) and slowly digestible starch (SDS), while reducing rapidly digestible starch (RDS) (Farooq & Yu, 2025). When combined with heat-moisture treatment (HMT), extrusion further enhances starch crystallinity and forms amylose-lipid complexes, leading to a significantly lower estimated glycemic index (eGI) (Yang et al., 2020). Extruded rice with added purple sweet potato also showed reduced starch hydrolysis and altered crystalline structure (A-type to $A + V$-type), demonstrating both nutritional and structural improvements (Wang et al., 2021) . These methods are particularly valuable for transforming broken rice into functional, low-GI products.

Broken rice, a by-product generated during milling, represents a substantial portion of rice production waste (typically 12–15 %), particularly in rice-consuming countries. Traditionally underutilized or relegated to animal feed or industrial uses, broken rice holds considerable potential for upcycling into high-value, health-promoting foods (Bodie, Micciche, Atungulu, Rothrock & Ricke, 2019; Yang et al., 2020). Recent studies have shown that by employing emerging food processing technologies such as extrusion, broken rice can be restructured into nutritionally enhanced, low-glycemic index (GI) rice-based products (Dalbhagat & Mishra, 2019; Nithya et al., 2021; Yadav, Dalbhagat & Mishra, 2021). These processes not only modify starch digestibility but also provide a delivery matrix for functional bioactive compounds, improving both sustainability and health outcomes.

Extrusion modifies starch structures, transforming the native A-type crystalline pattern into less digestible V- or B-type forms, thereby reducing starch hydrolysis and lowering the glycemic index (GI) (Huang, Liu, Ma, Mai & Li, 2022; Yang et al., 2020). Co-extrusion with bioactive compounds such as grape seed (GSPA) and Chinese bayberry leaf proanthocyanidins (CBLPs) significantly decreases starch digestibility by inhibiting enzymatic hydrolysis and altering starch crystallinity and pasting behavior (hydrolysis reduced from 86.6 % to 70.9 %) (Zheng et al., 2021).

Incorporation of cassava starch into broken rice (up to 30 %) during extrusion enhances gelatinization, lowers retrogradation, and improves cooking properties (Xia, Lin, Wang, Liu & Liu, 2024). Similarly, blending with millets and quinoa enables the development of instant low-GI rice ($GI \leq 55$) with improved cooking time, water absorption, and reduced cooking losses (Yadav et al., 2021).

Dietary fiber fortification *via* extrusion (in a 1:3 soluble:insoluble ratio) has also been shown to significantly increase resistant starch (RS) content (from 12.4 % to 16.5 %), improve textural properties, and modify the starch matrix, supporting the development of diabetic-friendly rice analogues. Optimized processing parameters such as temperature, screw speed, and feed moisture play critical roles in nutrient retention and product quality (Shaikh, Pathare, Chakraborty & Annapure, 2025). Moreover, extrusion has enabled the fortification of broken rice with essential micronutrients (iron, folic acid, and vitamin B12), while AI-based modeling (e.g., ANN) enhances precision in product development (Dalbhagat & Mishra, 2019).

Together, these innovations exemplify the functional transformation of a low-value by-product into high-value, health-promoting rice-based products, addressing both nutritional deficiencies and food system waste. Table 3 summarizes the key research themes and outcomes related to the valorization of broken rice into functional food ingredients using extrusion technology. The table highlights how emerging processing strategies and targeted ingredient incorporation improve the nutritional and functional properties of restructured rice products.

Table 3
Key themes in the valorization of broken rice into functional food ingredients via extrusion.

Theme	Key outcome
Starch modification	Lower crystallinity, delayed digestibility, A- to V-type transition
Polyphenol fortification	Reduced hydrolysis rate and eGI via enzyme inhibition
Fiber enrichment	Increased RS, improved texture and matrix density
Multi-ingredient formulation	Instant low-GI rice with enhanced nutritional profile
Micronutrient fortification	Efficient retention through controlled extrusion parameters
Sustainability	Valorization of waste (broken rice) into functional food ingredients

6. Emerging food processing technologies enhance rice starch modification and bioactive delivery

Recent advances in food processing technologies offer promising strategies to modify starch digestibility and improve the delivery and stability of bioactive compounds in staple foods like rice. These novel techniques not only enhance the functional properties of food but also contribute to sustainability and improved health outcomes by lowering the glycemic index (GI) and increasing the content of resistant starch (RS). Key emerging technologies include high-pressure processing (HPP), ultrasound treatment, microwave cooking, and nano-encapsulation.

6.1. *High-pressure processing (HPP)*

High-pressure processing (HPP) is a non-thermal food processing technology that applies intense pressure (100–600 MPa) to modify the molecular structure of food without significant heat degradation. HPP has been shown to increase the formation of resistant starch (RS) in rice, which resists digestion and lowers the glycemic index (GI), making it a promising method for creating low-GI functional foods. HPP also preserves bioactive compounds like polyphenols and enzymes, enhancing their bioavailability (Farooq & Yu, 2024).

Studies demonstrate that HPP improves the functional properties of rice starch. For instance, a study on yellow glutinous rice starch (Y-GRS) complexed with Buddleja officinalis Maxim. extract (BOME) found that HPP at 500 MPa increased starch-BOME interactions, thermal stability, and crystallinity, while reducing rapidly digestible starch (RDS) and increasing RS (Yue et al., 2025). Similarly, HPP treatments at 200–600 MPa were found to alter rice starch's microstructure and digestibility, with lower pressures (200 MPa) enhancing RS formation more effectively than higher pressures (600 MPa), which caused structural disruption (Deng et al., 2014).

HPP also improved the digestibility and functionality of waxy rice starch by altering its morphology and gelatinization properties. At 600 MPa, complete starch gelatinization was induced, while lower pressures enhanced slowly digestible starch (SDS) formation (Zeng, Li, Gao, Liu & Yu, 2018). Additionally, high-pressure homogenization and branched chain amylase treatment produced rice-resistant starch with improved structure and glycemic modulation in type 2 diabetic mice (Wu et al., 2024).

In summary, HPP is an effective method for enhancing rice starch properties, increasing RS, and lowering GI. Combining HPP with other treatments, such as enzyme addition, can further improve starch digestibility and health benefits, making it a promising strategy for functional food development.

6.2. *Ultrasound treatment (UT)*

Ultrasound treatment (UT) is a promising method for modifying starch structure, enhancing functionality, and increasing resistant starch (RS), which helps reduce the glycemic index (GI) of starchy foods. UT uses high-frequency sound waves to induce cavitation and mechanical shear, disrupting starch granules and promoting retrogradation, which in turn increases RS formation. Additionally, ultrasound improves the bioavailability of bioactive compounds, such as polyphenols, by breaking down cell walls and enhancing solvent penetration (Vela, Villanueva & Ronda, 2024).

Studies have shown that UT enhances starch properties. For instance, ultrasound-modified broken rice starch with quercetin resulted in a more stable structure, increased amylose content, and a significant rise in RS (from 6.57 % to 20.23 %), while reducing digestibility by inhibiting starch-hydrolyzing enzymes (Yang, Qiu & Zhang, 2025). Similarly, ultrasound-treated black rice starch and gallic acid formed V-type complexes, increasing crystallinity and RS content up to 37.60 % (Yu Wang et al., 2024). Ultrasound also reduced the GI of Japonica and Indica rice by enhancing amylose chain formation and limiting enzyme access (Shah, Wang, Tao, Zhang & Cao, 2023).

Furthermore, ultrasound applied to waxy rice flour blended with high-amylose corn starch increased RS content and decreased the glycemic index, emphasizing ultrasound's potential for developing low-GI rice-based foods (Wang et al., 2025). As a protective parboiling method, ultrasound improved starch crystallinity and RS formation, making it suitable for diabetic and weight management diets (Shah et al., 2023).

In conclusion, ultrasound treatment effectively enhances starch properties, increases RS, and lowers the GI of rice-based foods, contributing to healthier, low-GI food products with better glucose control. The combination with bioactive compounds further boosts the functional benefits of starch, offering a viable strategy for improving the nutritional quality of starchy foods.

6.3. *Microwave cooking*

Microwave cooking, as an alternative to conventional steam cooking, has been shown to influence the morphological structure, starch fractions, and starch digestibility of Thai pigmented rice (Thuengtung, Matsushita & Ogawa, 2019). The impact of microwave cooking on starch properties varies with the rice cultivar and cooking method.

In a study comparing steam and microwave cooking, it was found that the crystalline structure of non-waxy rice cultivars remained Vh-type after cooking, while the waxy rice cultivar showed no crystalline peaks. The X-ray diffraction (XRD) pattern and crystallinity degree of steam-cooked rice underwent more significant changes after simulated small intestinal digestion compared to microwave-cooked rice. Specifically, microwave-cooked rice exhibited a significantly lower equilibrium starch hydrolysis rate, suggesting that microwave cooking may preserve starch structure better than steaming (Thuengtung et al., 2019).

The variation in starch digestibility between the two cooking methods underscores the role of microwave cooking in potentially reducing starch hydrolysis and lowering the glycemic index (GI). Additionally, microwave cooking has been linked to enhanced retention of bioactive compounds, such as phenolics and anthocyanins, contributing to improved antioxidant activity in pigmented rice varieties (Thuengtung & Ogawa, 2020; Thuengtung, Niwat, Tamura & Ogawa, 2018). This makes microwave cooking an efficient and health-promoting method for preparing rice, especially for individuals aiming to manage blood sugar levels. Therefore, microwave cooking may not only help lower GI but also maintain or improve the nutritional quality of rice.

6.4. *Nano-encapsulation*

Nano-encapsulation is an innovative technique that encapsulates bioactive compounds, such as polyphenols and antioxidants, within nanocarriers to enhance their stability, bioavailability, and controlled release. This process protects sensitive ingredients from degradation during cooking and storage, improving their functional properties (T, Akhavan-Mahdavi, Abdullahi, Navina & Periakaruppan, 2025). For example, encapsulating phenolic compounds from black rice bran in nanoemulsions stabilized their antioxidant activity and improved their resistance to thermal degradation, while also controlling the release of bioactive compounds during digestion (Saleh, Salam & Capanoglu, 2024). In another application, Joshi, Rao and Shakeb (2025) studied nano-encapsulated curcumin was incorporated into quick-cooking rice and millet extrudates to improve curcumin bioavailability. The formulations exhibited high curcumin retention and bioaccessibility, showing the highest curcumin release. Despite some degradation during extrusion, substantial curcumin content remained, indicating the potential of nano-encapsulation to enhance bioactive retention in processed foods.

These examples demonstrate that nano-encapsulation effectively stabilizes bioactive compounds, improves their bioavailability, and offers controlled release, making it a valuable tool for developing functional foods with health benefits, such as improved glucose regulation and enhanced antioxidant activity.

7. Mechanistic integration and conceptual framework for glycemic index (GI) reduction in rice

Although the strategies reviewed in this work span postharvest processing, cooking practices, enzymatic modification, fermentation, fortification, extrusion, and emerging technologies, their effects on glycemic index (GI) are mediated through a common mechanistic core. A mechanistic integration framework for glycemic index (GI) reduction in rice is presented in Table 4.

7.1. *Physicochemical changes as the central mechanistic driver*

Rice starch is composed of amylose and amylopectin arranged in semicrystalline granules, and its digestibility is governed by amylose content, chain-length distribution, crystallinity, and multiscale structural organization. Low-GI rice systems consistently exhibit higher proportions of resistant starch (RS) and slowly digestible starch (SDS), which resist rapid enzymatic hydrolysis in the small intestine and slow glucose release (Farooq & Yu, 2024).

At the molecular and supramolecular levels, many processing interventions act by restructuring starch architecture. Thermal and hydrothermal treatments including parboiling, heat–moisture treatment, cooking–cooling cycles, extrusion, microwave processing, and high-pressure processing (HPP) which induce starch gelatinization followed by controlled retrogradation. This promotes the formation of RS3 and increases SDS content (Farooq & Yu, 2024). Enzymatic modifications (e.g., pullulanase, amylosucrase, and β-amylase/transglucosidase systems) further refine starch chain-length distribution by releasing or elongating linear chains, facilitating the transformation of native A-type crystallinity into more digestion-resistant B- and V-type polymorphs (Wu et al., 2024). Ultrasound and HPP amplify these effects by disrupting native granule organization and enabling controlled molecular reassembly. These crystalline polymorphs, together with amylose–lipid complexes, function as energetic and physical barriers that reduce susceptibility to α-amylase and α-glucosidase, thereby lowering starch digestibility (Shah et al., 2023; Zeng et al., 2018).

7.2. *Micro- and macro-structural modulation of starch digestion*

At the meso- and microstructural levels, fortification with hydrocolloids, dietary fibers, proteins, and lipids alters starch packing density, porosity, and matrix continuity. Hydrocolloids such as guar gum, pectin, xanthan gum, and β-glucan increase system viscosity, restrict enzyme diffusion, and promote starch–polymer interactions (Ma et al., 2024). Proteins and lipids form starch–protein networks and amylose–lipid complexes that physically shield glycosidic bonds from enzymatic attack (Liu et al., 2018; Ngo et al., 2023). These effects are further reinforced when combined with thermomechanical treatments (e.g., extrusion or dry heat processing), which stabilize multiscale structural ordering.

Table 4
Mechanistic integration framework for glycemic index (GI) reduction in rice.

Mechanistic level	Intervention / Strategy	Key physicochemical or Biochemical change	Effect on starch digestion	Functional / Metabolic outcome	References
Molecular & supramolecular structure	Parboiling, heat–moisture treatment, cooking–cooling, extrusion, microwave, HPP	Gelatinization–retrogradation; ↑ RS3 and SDS; transformation from A-type to B-/V-type crystallinity	↓ α-amylase accessibility; slower starch hydrolysis	↓ postprandial glycemia; ↓ insulin demand; improved insulin sensitivity	(Farooq & Yu, 2024; Shah et al., 2023)
Enzymatic starch modification	Pullulanase, amylosucrase, β-amylase/ transglucosidase	Altered chain-length distribution; increased linear amylose	Formation of digestion-resistant crystalline polymorphs	Sustained glucose release; lower GI	(Wu et al., 2024; Zeng et al., 2018)
Granular disruption & reassembly	Ultrasound, HPP	Disruption of native granules followed by controlled molecular reorganization	Enhanced RS formation; enzyme diffusion barriers	Reduced starch digestibility	(Shah et al., 2023)
Micro- and mesostructural modulation	Hydrocolloids (guar gum, β-glucan, pectin, xanthan)	↑ viscosity; starch–polymer interactions	Restricted enzyme diffusion; delayed hydrolysis	↓ postprandial glucose; ↑ satiety	(Ma et al., 2024)
Macromolecular complexation	Protein and lipid fortification	Starch–protein networks; amylose–lipid complexes	Physical shielding of glycosidic bonds	Attenuated glycemic response	(Liu et al., 2018; Ngo et al., 2023)
Biochemical inhibition (small intestine)	Polyphenols, herbal extracts, fermented metabolites	Inhibition of α-amylase and α-glucosidase	Slower starch-to-glucose conversion	Reduced glycemic excursions	(Apinanthanuwong et al., 2023; Aumasa et al., 2023)
Fermentation-driven modification	Germination and microbial fermentation	Starch restructuring; ↑ GABA, phenolics, ferulic acid	Combined structural and enzymatic digestion delay	Improved glycemic control; antioxidant benefits	(Hyun et al., 2021; Hyun et al., 2023)
Colonic fermentation	Increased RS and dietary fiber	SCFA production (acetate, propionate, butyrate)	Improved insulin signaling and gut–metabolic axis	↓ inflammation; ↑ insulin sensitivity	(Li et al., 2025)
Emerging technologies	Nano-encapsulation, ultrasound, HPP	Stabilization and controlled release of bioactives	Preservation of structure–function during digestion	Enhanced metabolic efficacy	(Joshi et al., 2025)
Integrated outcome	Multi-strategy approaches	Synergistic structural + biochemical modulation	Sustained glucose release across GI tract	Lower GI with maintained satiety and metabolic health	(Farooq & Yu, 2025; Zhang & Bao, 2023)

7.3. *Biochemical modulation during digestion*

Beyond structural effects, several strategies exert biochemical control over starch digestion. Polyphenol-rich plant and herb extracts, fermentation-derived metabolites, and selected dietary fibers directly inhibit α-amylase and α-glucosidase, slowing the conversion of starch into absorbable sugars (Apinanthanuwong et al., 2023; Aumasa et al., 2023). Fermentation additionally modifies starch through microbial enzymatic activity while enriching bioactive compounds such as γ-aminobutyric acid (GABA), ferulic acid, and phenolics, further enhancing glycemic modulation (Hyun et al., 2021; Hyun et al., 2023)

7.4. *Translation to functional and metabolic outcomes*

The physicochemical and biochemical mechanisms described above directly underpin the functional and metabolic benefits of low-GI rice. Increased RS and SDS slow glucose release, attenuate postprandial glycemic excursions, and improve insulin sensitivity which effects particularly relevant for individuals with type 2 diabetes (Farooq & Yu, 2024; Zhang & Bao, 2023). Simultaneously, increased digesta viscosity and delayed gastric emptying enhance satiety and support weight management.

In the colon, fermentation of RS and dietary fibers promotes the production of short-chain fatty acids (SCFAs), which play key roles in regulating glucose metabolism, reducing inflammation, and improving insulin sensitivity (Li et al., 2025). Polyphenols and antioxidants further contribute to metabolic health by mitigating oxidative stress and low-grade inflammation associated with metabolic disorders (Farooq & Yu, 2025; Nithya et al., 2021).

Emerging technologies such as nano-encapsulation, ultrasound, and HPP strengthen this structure–function relationship by preserving bioactive stability and enabling controlled release during digestion (Joshi et al., 2025). These approaches ensure that physicochemical starch modifications and bioactive functionality are retained throughout processing and gastrointestinal transit. Nevertheless, optimizing sensory quality alongside metabolic benefits remains a critical challenge for future rice fortification and processing strategies.

8. Human clinical evidence linking low-GI rice to glycemic control

While *in vitro* digestion models and animal studies provide mechanistic insight into starch digestibility, human clinical trials are essential to confirm the physiological relevance of low-GI rice interventions. Recent human clinical studies consistently demonstrate that replacing high–glycemic index (GI) rice with low- or medium-GI rice improves postprandial glycemia and longer-term metabolic outcomes across diverse populations, including women with gestational diabetes mellitus (GDM), individuals with type 2 diabetes mellitus (T2DM), adults with obesity, and healthy subjects. Importantly, benefits are most robust when rice interventions explicitly modify starch physicochemical properties such as amylose content, resistant starch (RS) formation, crystallinity, and matrix structure rather than relying on whole-grain status alone. A summary of human clinical evidence on low–glycemic index (GI) rice is presented in Table 5.

8.1. *Acute postprandial glycemic and insulinemic responses*

Most human studies assessing low-GI rice employ randomized crossover designs to quantify postprandial glucose and insulin responses following single-meal consumption. Across these studies, parboiled rice consistently exhibits lower GI values than polished white rice, typically in the range of ~48–55 versus ~70–85 for conventional white rice (Kumar et al., 2022). More intensive hydrothermal processing further amplifies this effect; for example, pressure-parboiled rice has been shown to reduce GI to ~39–46, with marked reductions in incremental area under the glucose curve (iAUC), particularly in individuals with impaired glucose tolerance or T2DM (Dutta & Mahanta, 2012).

Rice subjected to cooking–cooling cycles also demonstrates clinically meaningful reductions in postprandial glucose and insulin excursions.

Table 5
Summary of human clinical evidence on low–glycemic index (GI) rice.

Processing / Rice type	Study design & population	GI (approx.)	Key physicochemical features	Main glycemic / metabolic outcomes	References
Low–medium GI rice (RD43)	Triple-blind RCT; women with GDM ($n = 96$)	~56.9 vs ~80 (control)	Higher amylose, slower digestibility	↓ insulin initiation (6.3 % vs 22.9 %); delayed pharmacological escalation	(Sanpawithayakul et al., 2023)
Low-GI rice (RNR 15048)	3-month intervention; T2DM ($n = 80$)	~51.7	Higher amylose, RS enrichment	↓ fasting glucose, ↓ HbA1c; ↑ HDL; no weight change	(Sobhana et al., 2019)
Parboiled germinated brown rice (PGBR)	Double-blind pilot; T2DM (4 months)	~42–45	RS increase, germination bioactives (GABA, phenolics)	Greater ↓ glucose, BP, BMI; ↑ wellbeing vs PBR	(Tarawalie et al., 2025)
Parboiled rice (PBR)	Randomized crossover pilot; healthy + T2DM ($n = 20$)	~48–55	RS formation, mixed A/B/V crystallinity	↓ postprandial glucose; ↑ insulin sensitivity (MI, DI); minimal GLP-1 effect	(Alkandari et al., 2025)
Pressure-parboiled rice	Acute crossover; healthy & IGT/T2DM	~39–46	Enhanced RS, dense crystalline structure	↓ glucose iAUC; ↓ insulin response	(Dutta & Mahanta, 2012)
Cooking–cooling rice	Acute crossover; healthy adults	↓ by 10–20 units	RS3 via retrogradation	↓ postprandial glucose & insulin	(Strozyk et al., 2022)
Cooking–cooling + lipid	Acute feeding trials; healthy adults	Further ↓ GI	Amylose–lipid complexes (V-type)	Greater attenuation of glycemia	(Luangsakul & Ritudomphol, 2018)
Riceberry rice	Acute crossover; healthy adults	Low–medium	High fiber, polyphenols	↓ postprandial glucose via slower gastric emptying; ↓ GIP	(Muangchan et al., 2022)
High-fiber white rice (HFWR)	RCT; healthy adults	~61 vs ~79	↑ fiber, ↑ amylose, ↑ RS	~23 % GI reduction without sensory penalty	(Mohan et al., 2016)
Fiber / β-glucan–enriched rice	Randomized crossover; healthy & at-risk adults	↓ GI	Increased viscosity, delayed digestion	↓ postprandial glucose; ↑ satiety	(Chiu & Stewart, 2013)
Brown rice (conventional)	Meta-analysis (7 trials; prediabetes & T2DM)	Variable	Whole grain, modest RS	No significant ↓ HbA1c or FBG; ↓ weight; ↑ HDL	(Abdul Rahim et al., 2021)
Low-GI dietary education	RCT; adults with obesity	—	Behavioral GI reduction	↓ dietary glycemic load (12 weeks)	(Leung et al., 2024)

Cooling cooked rice for 12–24 h increases RS content via starch retrogradation and lowers glycemic responses in healthy adults (Strozyk et al., 2022). When combined with lipid sources (e.g., coconut oil), additional attenuation of glycemia has been reported, consistent with enhanced amylose–lipid complex (V-type) formation (Luangsakul & Ritudomphol, 2018).

8.2. Effects in individuals with type 2 diabetes and prediabetes

Clinical trials in populations with T2DM or prediabetes provide particularly strong support for the metabolic relevance of low-GI rice. Substitution of conventional white rice with parboiled, germinated, or fiber-fortified rice consistently results in lower postprandial glucose and insulin responses, reduced peak glucose concentrations, and improved glycemic variability (Alkandari et al., 2025). Germinated parboiled brown rice has achieved GI values as low as ~42, while simultaneously increasing dietary fiber, γ-aminobutyric acid (GABA), and phenolic intake (Imam et al., 2012).

Short- to medium-term interventions (2–12 weeks) further show that habitual consumption of low-GI rice improves fasting blood glucose, HbA1c, and insulin sensitivity indices, even when total carbohydrate intake is maintained (Abdul Rahim, Norhayati & Zainudin, 2021). These improvements are closely linked to increased RS intake, delayed carbohydrate absorption, and reduced postprandial insulin demand.

8.3. Gestational diabetes mellitus (GDM)

Compelling clinical evidence comes from a triple-blind, randomized controlled trial in women with GDM, in which substitution of high-GI Thai Hom Mali rice (GI ≈ 80.1) with a low-to-medium GI rice (RD43; GI ≈ 56.9) significantly reduced the need for insulin therapy. Only 6.3 % of women in the RD43 group required insulin compared with 22.9 % in the high-GI control group (Sanpawithayakul et al., 2023). Notably, many participants who initially met criteria for insulin initiation were able to avoid pharmacological escalation through dietary substitution alone, highlighting the clinical relevance of modifying starch digestibility during pregnancy.

8.4. Mechanistic insight from postprandial and gastrointestinal responses

Mechanistic evidence from acute crossover studies in healthy adults shows that fiber- and polyphenol-rich rice, such as Riceberry rice, significantly attenuates postprandial plasma glucose compared with white rice. This effect is mediated primarily by slower gastric emptying, rather than altered insulin or GLP-1 secretion, while glucose-dependent insulinotropic polypeptide (GIP) responses are markedly reduced (Muangchan et al., 2022). These findings directly link rice physicochemical structure to digestion kinetics and glycemic response in humans.

Consistent with this, a randomized crossover pilot study comparing parboiled rice (PBR) with white rice demonstrated that PBR reduced postprandial glucose responses and improved insulin sensitivity and β-cell function (increased Matsuda and Disposition Indices), particularly in healthy individuals (Alkandari et al., 2025). In T2DM, GLP-1 responses were blunted regardless of rice type, suggesting that the primary metabolic benefit of parboiling arises from reduced starch digestibility and improved insulin action, rather than incretin-mediated effects Fig. 1.

8.5. Satiety, appetite regulation, and metabolic co-benefits

Beyond glycemic control, several human studies report that low-GI rice enhances subjective satiety, delays hunger onset, and reduces subsequent energy intake. Rice enriched with dietary fiber or RS increases fullness ratings compared with standard white rice (Chiu & Stewart, 2013). These effects are attributed to increased digesta viscosity, delayed gastric emptying, and short-chain fatty acid (SCFA)–mediated appetite regulation, supporting the potential role of low-GI rice in weight management and obesity prevention (Ma et al., 2024; Park, Mok, Chung, Park & Kim, 2024).

Emerging clinical evidence also suggests favorable effects on gut health and metabolic biomarkers, with increased RS intake promoting SCFA production—particularly butyrate—associated with improved insulin sensitivity and reduced systemic inflammation (Park et al., 2024).

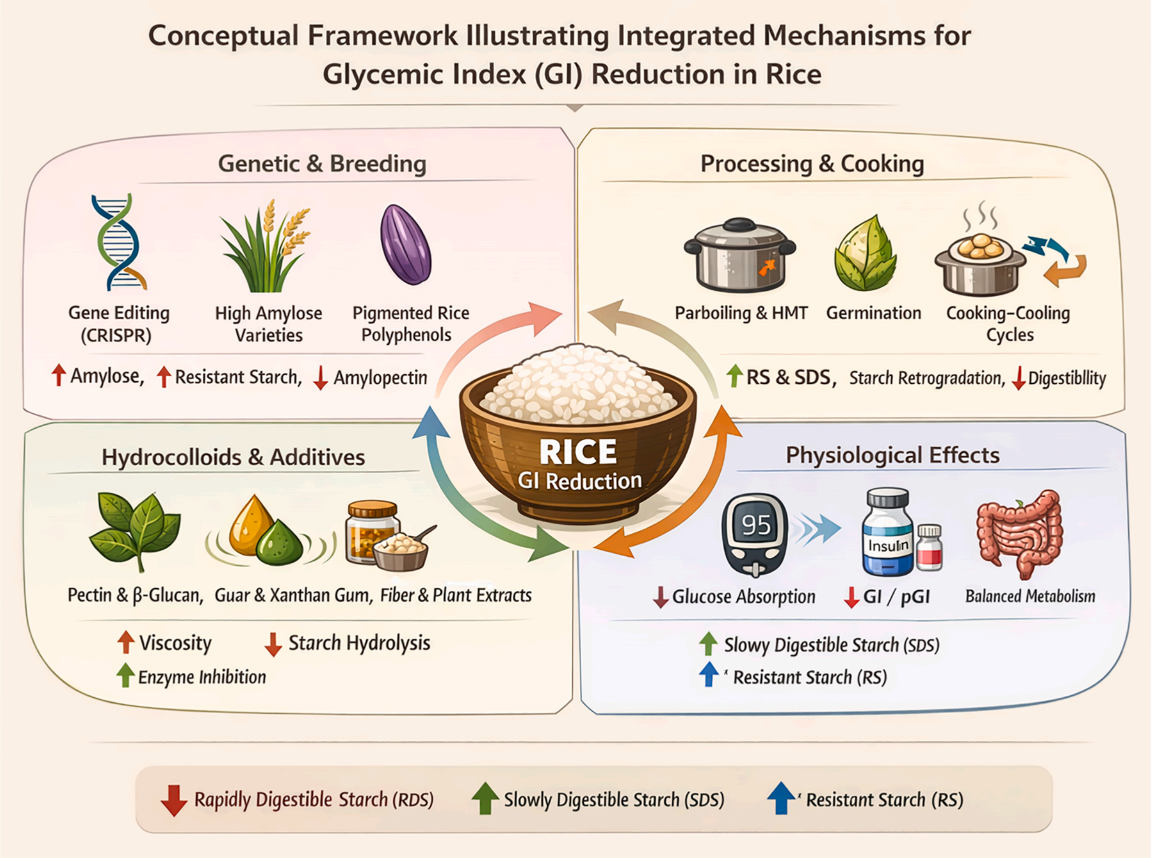

Fig. 1. Conceptual framework illustrating integrated mechanisms for glycemic index (GI) reduction in rice.

8.6. *Whole-grain rice: evidence from meta-analysis*

In contrast, a systematic review and meta-analysis of randomized and controlled clinical trials reported that substituting white rice with brown rice alone did not significantly improve HbA1c or fasting blood glucose in individuals with prediabetes or T2DM, although modest reductions in body weight and increases in HDL cholesterol were observed (Abdul Rahim et al., 2021). These findings indicate that whole-grain status per se is insufficient to guarantee glycemic benefit and reinforce the importance of targeted physicochemical modification of starch such as RS enrichment and altered crystallinity rather than fiber content alone.

8.7. *Dietary education and real-world feasibility*

Beyond product-based strategies, a randomized controlled trial in Chinese adults with obesity demonstrated that a culturally tailored low-GI dietary educational intervention significantly reduced dietary glycemic load over 12 weeks (Leung et al., 2024). Although cardiometabolic markers were unchanged over the short intervention period, the study highlights the feasibility and acceptability of low-GI strategies in real-world settings.

Collectively, human clinical evidence demonstrates that physicochemically modified and fortified rice varieties which achieved through parboiling, germination, cooking–cooling, fiber enrichment, or their combinations consistently elicit lower postprandial glycemic and insulinemic responses and improve metabolic outcomes across healthy, prediabetic, and diabetic populations. These findings align closely with mechanistic insights, confirming that starch structural restructuring is the dominant driver of clinical glycemic benefit, rather than grain refinement or whole-grain designation alone.

9. Market potential and consumer acceptance of low-GI rice

The global demand for functional foods, particularly low-GI rice, has surged due to rising awareness of the link between diet and health, especially concerning diabetes, obesity, and metabolic diseases. Low-GI rice, often fortified with bioactive compounds like fibers, polyphenols, and proteins, offers not only nutritional benefits but also therapeutic advantages, such as improved blood sugar control. As the prevalence of diabetes rises worldwide, the market for diabetic-friendly foods, including low-GI rice, is expanding rapidly (Tiozon et al., 2025). The growing preference for convenience has fueled the demand for quick-cooking and ready-to-eat low-GI rice products in developed markets, with the global functional food market expected to reach USD 275.77 billion by 2025 (Fortune Business Insights, 2025).

However, the commercialization of low-GI rice faces challenges related to consumer acceptance, especially regarding sensory characteristics like taste, texture, and aroma. Fortifying rice with bioactive compounds or modifying its structure through techniques like extrusion can lead to firmer, stickier, or chewier textures, which may conflict with the softer, fluffier texture traditionally preferred by consumers (Bonto, Camacho & Sreenivasulu, 2024; Liu et al., 2018). Additionally, bioactive compounds like polyphenols can introduce bitterness or earthy flavors, while herbal additives (e.g., turmeric) may alter aroma (Ho et al., 2021).

Despite these sensory challenges, low-GI rice can appeal to health-conscious consumers, especially those managing diabetes and seeking functional foods. Educating consumers on the health benefits of low-GI rice such as its role in weight management and metabolic health will be crucial to increasing its acceptance. Moreover, while low-GI rice often comes at a higher price, targeting health-focused consumers and making it more affordable will be key to its widespread commercialization. As consumer awareness and demand for functional foods grow, low-GI rice has the potential to carve out a significant niche in the global market

(Custodio et al., 2025).

10. Sustainability

10.1. Environmental considerations of low-GI rice production

The production of low-GI rice fortified with bioactive compounds must balance health benefits with environmental sustainability. Rice cultivation is resource-intensive and a major source of methane emissions, so sustainable farming practices such as alternate wetting and drying (AWD) to reduce water use, organic farming, and breeding climate-resilient varieties are essential to minimize environmental impact (Ishfaq et al., 2020). Future research should evaluate how fortification processes fit within these sustainable methods.

10.2. Integration with sustainable food systems and circular economy

Integrating low-GI rice into sustainable food systems also involves adopting circular economy principles by repurposing rice by-products. Whole-of-product utilization including bran, husk, germ, and broken rice reduces waste while enhancing nutritional and functional properties. Broken rice can be incorporated into fortified products, rice bran and husks can serve as biomass energy sources or nutrient-rich ingredients for functional foods, and germ can provide bioactive compounds for health promotion (Nithya et al., 2021). Promoting local production and consumption further lowers carbon footprints and strengthens food sovereignty. Aligning low-GI rice production with resource efficiency, climate adaptation, and full-product utilization will be key to achieving long-term sustainability and reinforcing its role in circular food systems.

11. Limitations and future research needs

Despite consistent acute and short-term benefits, most clinical trials remain small-scale, short in duration, and heterogeneous in rice variety and processing methods. Long-term randomized controlled trials evaluating diabetes incidence, cardiovascular risk markers, and gut microbiome modulation are still limited. Despite promising results, several limitations persist in the current clinical literature. Many studies involve small sample sizes, short intervention durations, and heterogeneous rice varieties and processing conditions, complicating cross-study comparisons. Additionally, long-term randomized controlled trials assessing hard metabolic endpoints (e.g., diabetes incidence, long-term glycemic control, cardiovascular risk markers) remain scarce.

11.1. Variability in glycemic index (GI) testing methods

One of the key limitations in glycemic index research is the variability in testing methods. Different studies use varying protocols for measuring the glycemic response, including differences in the type of subject (healthy individuals vs. diabetics), sample size, food portion size, and timing of blood glucose measurements. Such inconsistencies can result in inconsistent GI values, making it difficult to directly compare findings across studies. The future research should discuss this issue and recommend ways to standardize GI testing methods in future research to improve reliability and reproducibility.

11.2. Sensory acceptability issues

While modifying rice to reduce its GI may improve health outcomes, there are often sensory acceptability concerns associated with such modifications. Changes in the texture, taste, or appearance of rice (e.g., due to hydrocolloid addition, cooling, or autoclaving) may not be well-received by consumers. The future research should address the consumer acceptance of low-GI rice and its processed variants, including potential sensory challenges, and discuss possible strategies for improving acceptability without compromising the nutritional benefits.

11.3. Nutrient loss during processing

Many methods used to reduce the glycemic index of rice, such as autoclaving, cooling, or adding hydrocolloids, can lead to nutrient loss. For example, some vitamins and minerals may be degraded during the cooking or processing process, which could reduce the overall nutritional value of the rice. The future research should discuss the potential trade-offs between improving the GI and preserving the nutritional content, and highlight the need for research that optimizes processing methods to minimize nutrient loss while achieving a low-GI outcome.

11.4. Scalability and industry adoption challenges

Another critical limitation is the scalability of low-GI rice production for widespread industry adoption. While laboratory-scale experiments may show promising results, the practical challenges of producing low-GI rice on an industrial scale, maintaining quality control, and meeting consumer demand need to be addressed. Scaling up the use of specific hydrocolloids, or adopting processing methods like autoclaving, could be cost-prohibitive or logistically challenging. The future work should critically discuss these scalability issues and explore whether these strategies are feasible for large-scale food production.

11.5. Lack of long-term human studies

While animal and *in vitro* studies offer valuable insights, there is a lack of long-term human studies assessing the health outcomes of consuming low-GI rice over extended periods. The future work should discuss the need for long-term clinical trials to fully understand the long-term effects of low-GI rice on human health, particularly in relation to chronic conditions like type 2 diabetes and cardiovascular diseases. Without long-term data, it is difficult to determine the sustained benefits of consuming low-GI rice as part of a regular diet.

11.6. Economic and cultural considerations

The introduction of low-GI rice into various populations needs to consider economic and cultural factors. In many regions, rice is a staple food and part of traditional diets. Modifying rice for improved GI may be met with resistance due to cultural preferences or economic constraints (Cabral, Moura, Fonseca, Oliveira & Cunha, 2024). The future work should explore the economic feasibility of producing low-GI rice in different regions, as well as how cultural norms influence the acceptance and adoption of these modified products.

11.7. Multi-omics approaches for rice starch modification

One promising direction for future research is the application of multi-omics approaches (e.g., genomics, proteomics, metabolomics) to better understand the genetic, biochemical, and molecular mechanisms involved in rice starch modification (Anacleto et al., 2019). These integrated approaches could provide deeper insights into how starch structure and digestibility are influenced by various factors, such as processing methods, hydrocolloid addition, and genetic variation in rice cultivars (Suklaew et al., 2022). A multi-omics approach could help identify key biomarkers and genetic loci associated with the production of resistant starch or low-GI rice, ultimately facilitating the development of bioengineered rice varieties that are optimized for glycemic control (Badoni et al., 2024).

11.8. Intelligent processing technologies

The future of rice processing lies in the use of intelligent technologies that optimize processing methods for reducing the GI of rice without compromising other nutritional qualities. For example, smart cooking methods, which use real-time data to control factors such as temperature, pressure, and cooking time, could be developed to maximize the formation of resistant starch while minimizing nutrient loss. Additionally, sensor-based technologies could be used to monitor the physical and chemical properties of rice during processing, enabling more precise control over starch gelatinization, retrogradation, and digestibility. Research on these intelligent processing technologies could help scale up low-GI rice production for commercial and industrial applications.

11.9. Exploring the role of gut microbiota

The growing body of research on the gut microbiome offers an exciting avenue for future studies on low-GI rice. The composition of the gut microbiota plays a significant role in starch digestion and glycemic control. Future research could explore how low-GI rice and its modifications (such as fermentation or the addition of prebiotics) affect gut microbiota composition and activity (Lu et al., 2025). Investigating the microbiome's role in the digestibility of starch and the postprandial glucose response could reveal novel mechanisms through which low-GI rice provides health benefits, especially in individuals with metabolic diseases.

11.10. Targeted nutrition applications for diabetics and elderly populations

Another critical area for future research is the targeted application of low-GI rice in specific populations, such as individuals with type 2 diabetes, pre-diabetics, and the elderly. These groups often have distinct dietary needs and metabolic responses, which means that tailored interventions are necessary. Future studies could focus on developing personalized nutrition strategies that incorporate low-GI rice as part of a broader dietary plan to manage blood glucose levels, improve insulin sensitivity, and prevent or manage chronic conditions. Investigating the long-term effects of incorporating low-GI rice into the diet of these populations, as well as examining potential synergistic effects with other dietary interventions (e.g., high fiber, low-sugar diets), will be crucial for optimizing their health outcomes.

12. Conclusion

This review synthesizes current evidence demonstrating that the development of low–glycemic index (GI) rice is most effectively achieved through integrated starch-modifying strategies that operate across molecular, structural, and processing scales. Hydrocolloid-assisted approaches using pectin, guar gum, xanthan gum, and β-glucan which emerge as particularly powerful tools, as they directly modulate starch retrogradation, enzyme accessibility, and amylose–lipid complex formation, thereby slowing glucose release during digestion. When combined with processing techniques such as retrogradation, extrusion, germination, fermentation, and enzymatic treatment, these interventions consistently increase resistant starch and slowly digestible starch fractions, providing a robust mechanistic basis for GI reduction.

Beyond starch restructuring, fortification with rice-derived bioactives including dietary fibers, polyphenols, flavonoids, and γ-aminobutyric acid as well as locally available herbal ingredients (e.g., turmeric, garlic, green tea, mulberry leaves, pandan leaves, and butterfly pea flowers) further enhances the functional profile of low-GI rice. These bioactives contribute antioxidant, anti-inflammatory, and gut-modulatory effects, reinforcing glycemic control through both physicochemical and biochemical pathways. Importantly, the integration of hydrocolloids and bioactives aligns with consumer demand for clean-label, culturally familiar, and functionally enhanced staple foods.

From a sustainability and systems perspective, future low-GI rice development should adopt a whole-of-product utilization framework that valorizes rice fractions such as bran, germ, and husk. This approach not only reduces processing waste but also enables the recovery of high-value functional compounds, strengthening alignment with circular bioeconomy principles. However, despite promising mechanistic and short-term clinical evidence, broader validation through well-designed human intervention trials remains necessary particularly to substantiate long-term effects on glycemic control, satiety regulation, body weight management, and gut microbiota modulation.

Looking ahead, the successful translation of low-GI rice into mainstream food systems will depend on scalable and cost-effective processing technologies, standardized GI assessment protocols, and the preservation of sensory quality and nutritional integrity. Advances in multi-omics tools, intelligent processing, and targeted nutrition strategies offer new opportunities to optimize structure–function relationships and tailor low-GI rice products for vulnerable populations, including individuals with diabetes, obesity, and the elderly.

In the context of escalating global burdens of metabolic disease especially in rice-dependent regions across Asia and beyond, low-GI rice represents a compelling convergence of public health nutrition, functional food innovation, and sustainable food system design. With continued scientific, technological, and policy support, low-GI rice has the potential to serve as a flagship example of how staple foods can be re-engineered to deliver meaningful health benefits while maintaining cultural relevance and environmental responsibility.

Ethical statement (Studies in humans and animals)

This article is a review of previously published studies and does not involve any new studies with human participants or animals conducted by the authors. All data discussed herein were obtained from published literature, which adhered to recognized ethical standards at the time of the original research.

CRediT authorship contribution statement

Sunantha Ketnawa: Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Jinhu Tian:** Writing – review & editing, Conceptualization. **Yukiharu Ogawa:** Writing – review & editing, Validation. **Jaspreet Singh:** Writing – review & editing. **Lovedeep Kaur:** Writing – review & editing. **Suphat Phongthai:** Writing – review & editing. **Yardfon Tanongkankit:** Writing – review & editing. **Utthapon Issara:** Writing – review & editing. **Chanthima Phungamngoen:** Writing – review & editing. **Natthawuddhi Donlao:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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