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FACTORS AFFECTING STARCH DIGESTIBILITY AND GLYCEMIC INDEX OF RICE: A COMPREHENSIVE REVIEW

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ABSTRACT

Rice, as a staple food for a significant portion of the global population, plays a crucial role in determining dietary patterns and health outcomes, particularly concerning glycemic response. The digestibility of starch and the glycemic index (GI) of rice are crucial factors affecting its nutritional and health benefits. The rice starch composition, amylose and amylopectin ratios, determines the starch digestibility kinetics and subsequent glucose release profiles. Intrinsic factors such as rice genotype, grain structure and starch granule contributes to variations in starch accessibility and GI. The impact of extrinsic factors, including processing methods (*e.g.*, milling, parboiling), cooking techniques and enzymatic activities during digestion, affects starch hydrolysis and GI. Environmental factors such as soil conditions and climatic variations are also discussed for their potential influence on rice starch composition and metabolic responses. The factors are particularly important for managing diet-related health issues such as diabetes and obesity, as they affect blood glucose levels. This review synthesizes the current knowledge on the multifaceted determinants of starch digestibility and GI in rice. These findings, provides insights into how these variables interact and influence the nutritional profile of rice. Understanding these factors is essential for developing rice-based dietary strategies that promote better health outcomes.

Key words : Glycemic index, Starch digestibility, Rice, Amylose, Amylopectin.

Introduction

Rice (*Oryza sativa* L.), cultivated in diverse agro-ecosystems, is one of the most important staple foods worldwide, particularly in Asia, Latin America, and parts of Africa. Its significance extends beyond basic nutrition; it is ingrained in society's cultural, economic, and nutritional fabric. According to the Food and Agriculture Organization (FAO, 2013), rice is the most importance grain for human consumption, underscoring its vital role in global nutrition and food systems. Nearly 4 billion people globally depend on rice as a staple food, supplying 15% of their protein and 21% of their energy needs (Kaur *et al*., 2016). As a primary source of carbohydrates, rice delivers essential energy and vital nutrients, making it indispensable in combating hunger and malnutrition. Brown rice, for example is noted for its higher fiber content and richer nutritional profile compared to its white counterpart. Moreover, the versatility of rice allows it to be adapted into a multitude of dishes, enhancing its appeal and utility across various cuisines (Juliano, 1993). Economically, rice cultivation is a lifeline for millions of farmers, playing a pivotal role in rural economies and contributing to food security and poverty alleviation (Zhou *et al*., 2020). Given its centrality to the diet of nearly half the world's population, understanding the multifaceted importance of rice is crucial for addressing global food security challenges and ensuring sustainable agricultural practices (Fukagawa and Ziska, 2019; Lee *et al*., 2019).

Rice starch content ranges from 60–80%, depending on the variety (Van Thai *et al*., 2023). Typically, rice exhibits a medium to high glycemic index (GI) (Kaur *et al*., 2016). The nutritional profile of rice grains differs among varieties due to variations in both macro and microstructural characteristics, which in turn influence their GI values. Geographic location and antioxidant content are also critical factors that significantly affect the GI of rice and its derived products. Intrinsic factors such as starch composition, starch structure, macronutrient content and the presence of polyphenols and fiber contribute to the GI variability of rice products (Ngo *et al*., 2022; Kunyanee *et al*., 2022). Additionally, extrinsic factors like production and processing methods play a substantial role in modulating digestion behaviour. This behaviour is affected by several factors, including cooking techniques, preparation processes and the presence of other food components (Toutounji *et al*., 2019). The mechanisms by which these factors influence the GI of rice and rice products are complex and varied.

Starch digestibility and glycemic index are crucial factors in determining the heath impacts of rice- based diets. Starch digestibility refers to how quickly and efficiently the starch in rice is broken down into glucose, which subsequently enters the bloodstream. The glycemic index measures how rapidly a carbohydrates containing food raises blood glucose levels. Starch in rice exists in two main forms; amylose and amylopectin. Amylose has a linear structure and is less readily digestible, leading to a slower release of glucose. Amylopectin, with its branched structure, is more easily digested, resulting in a quicker spike in blood sugar levels. Consequently, rice varieties with higher amylose content tend to have a lower glycemic index (Fitzgerald *et al*., 2011). The glycemic index of rice can vary significantly depending on the variety and preparation methods. For instance, white rice generally has a higher GI compared to brown rice, which retains more fiber and nutrients. A lower GI is beneficial for maintaining stable blood glucose levels, and promoting satiety, which can aid in weight management (Hu *et al*., 2012). Incorporating rice varieties with lower GI and improving starch digestibility through breeding and processing techniques can thus play a significant role in enhancing the nutritional profile of rice-based diets (Atkinson *et al*., 2008). This review aims to elucidate the various factors influencing starch digestibility and glycemic index (GI) of rice. By systematically examining the biochemical, environmental determinants as well as the impact of processing and cooking methods, it aims to provide a holistic understanding of how these factors interact to affect the nutritional quality of rice.

Chemical composition of rice starch

The primary components of most cereals are the two types of starch molecules; amylose and amylopectin. Molecules of amylose have lower molecular weights and a few long chain branches, while molecules of molecules of amylopectin are highly branched glucose polymers with many short branches and high molecular weights. There are six basic levels to the starch structure found in cereal grains (Fig. 1); individual linear branches of starch molecules (level 1) consisting of anhydro glucose units linked together by R-1,4 glycosidic bonds; macromolecular branched structure (level 2) consisting of double helices of amylopectin branches joining together to form amylopectin and amylose (levels 1 and 2 are "molecular"; growth ring structure (level 4) consisting of several alternating crystalline and amorphous lamellae; granular structure (level 5) comprising of multiple growth rings; and whole grain structure (level 6), where starch granules interact with protein, lipid, non-starch polysaccharides, and other grains' constituents (Tran *et al*., 2011).

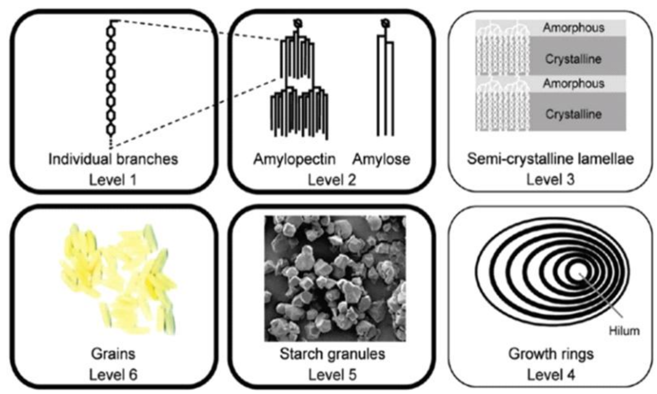

Fig. 1 : The structural level of starch. Adapted from Tran *et al.* (2011).

Amylose and amylopectin are both glucose polymers, but their structural differences lead to distinct functional properties. Amylose typically constitutes 15-30% of the total starch in rice, while amylopectin accounts for 70-85% (Juliano, 1992). Amylose tends to form a gel upon cooling after cooking, contributing to firmer rice texture. In contrast, amylopectin results in a more sticky and cohesive texture due to its branched structure (Wang *et al*., 2015). Rice varieties are broadly classified into indica and japonica subspecies, which differ significantly in amylose and amylopectin content. Indicavarieties generally have high higher amylose content, ranging from 20-30%, leading to a firmer and less sticky texture. Japonica varieties, on the other hand, have lower amylose content, typically between 10-20%, resulting in a softer and stickier texture (Fitzgerald, 2009). Starches with a higher amount of amylose are more resistant to digestion (Boers *et al*., 2015). Consequently, rice varieties with higher amylose content tend to have a lower glycemic index (Fitzgerald *et al*., 2011). High amylose rice varieties (*e.g.*, Basmati) generally have a lower GI than low amylose varieties (*e.g.*, Jasmine rice).

Pigmented rice varieties exhibit a wide range of amylose and amylopectin contents, influenced by both genetic and environmental factors. The amylose content in Black rice varies, but is generally found to be lower compared to non-pigmented rice, often ranging between 16-22% (Chen *et al*., 2017). The amylose content in red rice is quite variable, ranging from 14-28% (Sompong *et al.*, 2011). Specific genes such as Waxy (Wx) play a crucial role in determining different amylose levels among pigmented rice varieties (Wang *et al*., 2015).

Amylose is more resistant to digestion than amylopectin due to its linear structure, which forms tight, crystalline regions that less accessible to digestive enzymes (Englyst *et al*., 1992). High amylose rice varieties are valued for their health benefits, including lower glycemic index and slower digestion rates, making them beneficial for individuals with diabetes (Frei *et al*., 2003). Examples include certain traditional varieties like basmati and Jasmine rice. Low amylose rice varieties are preferred for their sticky and soft texture in Asian cuisines. Amylopectin, due to its highly branched structure, is more easily digested, leading to quicker glucose absorption and higher GI. Rice varieties with high amylopectin content are digested rapidly, resulting in rapid spikes in blood glucose levels (Goddard *et al*., 1984).

Physical properties of rice starch

Rice starch granules exhibit a diverse range of sizes and morphologies, which play a crucial role in determining their functional properties. The size distribution of rice starch granules varies widely, with diameters typically ranging from 2 to 20 microns (Jane *et al*., 1994). The granules can be classified into three categories based on size: A-type granules (2-5 microns), and B-type granules (5-10 microns) and C-type granules (10-20 microns) (Juliano, 1992). The proportion of these granules' types vary among rice varieties. The morphology of rice starch granules is characterized by their shape and surface features. Under scanning electron microscopy (SEM), rice starch granules typically appear smooth and round, with occasional irregularities in shape (Bao *et al*., 2004). Different rice varieties have distinct starch granule characteristics. For example, glutinous rice varieties tend to have smaller and more spherical granules compared to non-glutinous varieties (Boa *et al*., 2006). Environmental condition such as high temperature during grain filling can lead to smaller granule sizes (Jane *et al*., 1994). Processing techniques such as milling can break down granules, leading to a more heterogeneous size distribution (Juliano, 1992).

Crystallinity in rice starch refers to the degree of organization of starch molecules within the granules. Starch granules contain both the crystalline and amorphous regions. The crystalline regions are formed by the alignment of linear chains of amylose and amylopectin molecules, while the amorphous regions are less organized. The degree of crystallinity can affect the functional properties of rice starch, such as its gelatinization behavior and digestibility. Rice starches with higher amylose content tend to have a higher degree of crystallinity and require more energy to gelatinize (Jane *et al*., 1999). Gelatinization of the rice starch is the process by which starch granules absorb water and swell when heated in the presence of water. This process involves the disruption of the semi-crystalline structure of starch granules, leading to the release of amylose and amylopectin molecules into the surrounding water (Zhu *et al*., 2016). Typically, rice starch gelatinizes between 60°C and 80°C (Hoover *et al*., 2002). The degree of crystallinity and the extent of gelatinization play a crucial role in determining the starch digestibility. High crystallinity and low gelatinization starches are less digestible due to the inaccessibility of the crystalline regions to enzymatic action (Zhang *et al*., 2013). Low crystallinity and high gelatinization starches are more digestible because gelatinization disrupts crystalline regions, enhancing enzyme access (Zhang *et al*., 2013). When starch is gelatinized, the amorphous regions become more prominent, allowing enzymes to hydrolyze the starch more easily into glucose, which is then absorbed in the small intestine (Copeland *et al*., 2009). Processing methods such as milling, heat-moisture treatment, and extrusion can affect the crystallinity and gelatinization properties of rice starch (Jane *et al*., 1999). Prolong storage under high humidity can lead to retrogradation, where amylose molecules reassociate and form a more ordered structure, increasing the starch's crystallinity (Bhattacharya and Hanna, 1988).

Effects of rice processing methods

Different cooking methods significantly impact the digestibility of starch by altering its structure and gelatinization properties. Boiling involves cooking in water at high temperatures, which leads to the gelatinization of starches this process increases starch digestibility due to extensive gelatinization (Singh *et al*., 2010). Steaming cook moderately increase in digestibility as it causes sufficient gelatinization but less than boiling (Dutta *et al*., 2011). Heat moisture treatment (HMT) involves treating starch with limited moisture at high temperature for a specific period. This process induces structural changes in starch granules that significantly impact their digestibility. HMT-treated starch retained more of its crystal structure and helics following thermal processing leading to slower digestibility, which may be beneficial in food processing and obtaining gelatinized starch-foods with nutritional functions (Xie *et al*., 2020). HMT decreases the proportion of rapidly digestible starch, resulting a slower release of glucose into the bloodstream (Chung *et al*., 2009). Parboiling methods which involve soaking, steaming, and dried before final cooking partially gelatinizes the starch which leads to changes in the crystalline structure and makes the starch more digestible upon final cooking (Bhattacharya *et al*., 2013). Both parboiled brown and parboiled milled rice have greatly decreased glycaemic index after parboiling and resistance starch has increased correspondingly. Thus, parboiling rice as a method reducing starch digestibility and increase the bioavailability of nutrients, which is beneficial for diabetes (Kumar *et al*., 2022).

Studies have shown that milling and polishing of rice significantly affect starch digestibility. Whiteness and stickiness of rice grain increase with increasing milling degree but decrease the content of protein and lipids. This is because degree of milling removes the bran layer of rice leading to leaching of more amylopectin during cooking (Li *et al*., 2021). Different milling methods such as wet, dry, semi-dry and jet milling can lead to variations in damaged starch content, gelatinization temperature and crystalline structure. Semi-dry and wet milling methods tend to produce rice with lower damaged starch content and higher gelatinization temperatures, which can lead to lower glycaemic index compared to dry and jet milling methods (Tian *et al*., 2023). Zheng *et al.* (2020) found that rice grains with autoclaving for 60.96 mins and refrigeration time for 17.11hr have reduced estimated glycaemic index from 78.35 to 66.08 and a higher resistant starch content. The duration of autoclaving and refrigeration both affects the resistant starch content. Increasing in the resistant starch may influence in the lower estimated glycaemic index.

Rice varieties and their glycemic response

The diversity in the glycemic index (GI) among different rice cultivars is primarily driven by their varying amylose and amylopectin content. Ranawana *et al*. (2009) found that Basmati rice, which has high amylose content, had a low GI of 58, while Jasmine rice, with lower amylose content, had a high GI of 109. Similarly, Fitzgerald *et al*. (2011) analyzed 235 rice varieties, observing a GI range from 48 to 92 and noted that varieties with higher amylose and resistant starch levels generally had lower GIs. Kaur *et al*. (2016) found that traditional Indian rice varieties such as Swarna had a lower GI (55) compared to modern varieties like IR64 (74), highlighting the impact of breeding and selection on GI values. Hu *et al*. (2004) reported that Japonica rice, which typically has lower amylose content, showed higher GI values compared to Indica rice, with GI values ranging from 48 to 93. Additionally, Juliano and Goddard (1989) established that high-amylose rice varieties (25-30% amylose) had lower GIs (50-60) compared to low-amylose varieties (10-20% amylose), which had GIs above 70.

Although, rice is generally considered a high GI food, the genetic background of different varieties results in significant diversity (Fitzgerald *et al*., 2011). Enzymes involved in amylose synthesis during grain development influence the GI (Fitzgerald *et al*., 2011). Additionally, the inherent characteristics of each variety impact glycemic response (Thiranusornkij *et al*., 2019). The ratio of amylose to amylopectin in starch, along with other molecular structural characteristics, determines its ultimate digestibility (Kong *et al*., 2015), with higher amylose content starches exhibiting greater resistance to digestion (Hu *et al*., 2004). The starch biosynthetic pathway can influence the distribution of branch (chain) lengths in both amylose and amylopectin, consequently affecting the GI (Kong *et al*., 2015). Genome studies focusing on starch biosynthesis have been employed in rice to alter soluble starch synthase isoforms, enhancing amylose content up to 63% and increasing resistant starch (Jameel *et al*., 2022). Besides starch composition, additional macronutrients found in rice, such as protein, fiber, and lipid content, can impact starch digestibility (Khatun *et al*., 2022).

Variations in glycemic response are also influenced by multiple factors, including the type and amount of carbohydrate consumed the presence of dietary fiber, food processing and preparation methods, and individual physiological differences. The type of carbohydrate, particularly the GI of foods, plays a crucial role; foods with high GI values cause rapid increases in blood glucose levels, while low GI foods result in slower, more sustained glucose release. Dietary fiber, especially soluble fiber, can significantly modulate glycemic response by slowing gastric emptying and glucose absorption (Jenkins *et al*., 2002). Processing and preparation methods, such as grinding, cooking, and cooling, also affect the glycemic response by altering the physical structure of food and the availability of starch for digestion. For instance, cooling cooked starches can increase resistant starch content, thereby reducing glycemic response (Wang *et al*., 2015). Moreover, individual physiological factors, including age, insulin sensitivity, and gut microbiota composition, contribute to inter-individual differences in glycemic response. Insulin sensitivity, which varies among individuals, significantly affects postprandial glucose levels (Goff *et al*., 2013). Additionally, the gut microbiota influences glycemic response through its impact on fermentation processes and the production of short-chain fatty acids (SCFAs), which affect glucose metabolism (Kovatcheva-Datchary *et al*., 2015).

The selection of rice varieties has significant potential health implications, particularly concerning their impact on glycemic response and the risk of chronic diseases. Different rice varieties exhibit varying glycemic indices (GIs), which influence postprandial blood glucose levels. For instance, selecting low-GI rice varieties such as black or brown rice over high-GI white rice can help in better managing blood glucose levels and reducing the risk of type 2 diabetes (Mohan *et al*., 2014). Moreover, whole grain rice varieties, which retain the bran and germ layers, provide higher fiber content, essential fatty acids, vitamins, and minerals compared to polished white rice. This higher nutrient content contributes to improved metabolic health and reduced cardiovascular risk (Sun *et al*., 2010). Furthermore, pigmented rice varieties, such as red and black rice are rich in anthocyanins and other antioxidants that possess anti-inflammatory and anti-carcinogenic properties (Chen *et al*., 2012). Therefore, the careful selection of rice varieties based on their nutritional profiles can significantly contribute to the prevention and management of various health conditions.

Role of food matrix and preparations

The glycemic index (GI) of rice-based dishes and mixed meals can significantly vary depending on the preparation methods and the inclusion of other ingredients. The combining rice with protein, fiber, and fat can lower the overall GI of the meal. For instance, adding beans, vegetables, or lean meat to rice can slow down carbohydrate absorption, leading to a more gradual increase in blood glucose levels (Augustin *et al*., 2015). Moreover, the cooking method of rice, such as boiling versus steaming and the degree of processing, such as brown versus white rice, also impact its GI. Research by Sugiyama *et al*. (2003) demonstrated that mixed meals containing high-fiber foods significantly reduced postprandial glucose levels compared to meals with low-fiber foods. Furthermore, the presence of resistant starch, which is higher in cooled and reheated rice, can also contribute to a lower GI (Englyst *et al*., 2003).

Ingredients such as fats, proteins, and dietary fibers to starchy foods can significantly influence starch digestion and subsequent glycemic response. Fats and proteins have been shown to slow gastric emptying and reduce the rate of carbohydrate absorption, which can lower the glycemic index (GI) of the meal. The presence of fats can create a physical barrier that slows down the enzymatic access to starch, while proteins stimulate insulin secretion and delay glucose absorption (Raben *et al*., 2003). Additionally, dietary fibers, especially soluble fibers, form a gel-like substance in the digestive tract, which can further slow the breakdown and absorption of starches. This is evident in studies where meals high in fiber resulted in reduced postprandial blood glucose levels compared to low-fiber meals (Jenkins *et al*., 2000). Moreover, the inclusion of viscous fibers like beta-glucans in mixed meals has been associated with a significant decrease in postprandial glucose and insulin responses (Jenkins *et al*., 2002).

The particle size of rice and its cooking time can significantly impact the glycemic response of individuals consuming it. Smaller particle sizes and longer cooking times generally increase the digestibility of starch, leading to a higher glycemic index (GI). Smaller particles have a greater surface area for enzymatic action, which speeds up starch digestion and glucose absorption. Ranawana *et al*. (2013) demonstrated that finely milled rice particles result in a higher postprandial blood glucose response compared to coarser particles. Similarly, prolonged cooking times gelatinize starch granules more thoroughly, making them more accessible to digestive enzymes. A study by Venn *et al*. (2010) found that rice cooked for longer periods had a higher GI compared to rice cooked for shorter durations. This is because extended cooking disrupts the crystalline structure of starch, enhancing its digestibility.

Genetic and environmental factors

Genetic determinants play a crucial role in influencing rice starch composition and digestibility, impacting its nutritional and functional properties.

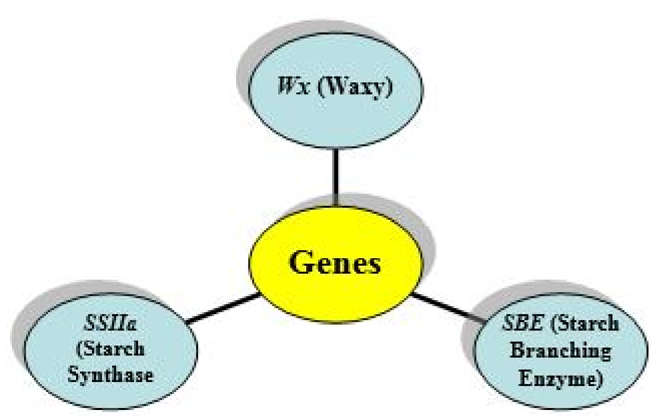

Fig. 2 : Key Genetic regulators of amylase and amylopectin content in rice.

Genes involved in starch biosynthesis, such as *Wx* (Waxy), *SSIIa* (Starch Synthase IIa) and *SBE* (Starch Branching Enzyme) are key regulators of amylose and amylopectin content in rice grains. Variations in these genes can alter the proportion of amylose and amylopectin, thereby affecting starch digestibility. For instance, the *Wx* gene, which encodes granule-bound starch synthase, is primarily responsible for amylose synthesis. Mutations in the *Wx* gene lead to a reduction in amylose content, resulting in higher glycemic index rice (Hirose and Terao, 2004). Similarly, the *SSIIa* gene affects the structure of amylopectin, with different alleles influencing the degree of branching and, consequently, the gelatinization and digestibility of starch (Nakamura *et al*., 2005). Additionally, the *SBE* gene family contributes to the branching pattern of amylopectin, impacting the texture and digestibility of rice starch (Yamanaka *et al*., 2004).

Environmental factors play a significant role in influencing starch synthesis and metabolism in rice plants. High temperature, in particular, has a profound impact on the biosynthesis of starch and the quality of rice grains. The synthesis of starch in rice grains involves complex biochemical pathways that are regulated by various genes, and environmental conditions can alter these pathways, affecting the overall quality and yield of the rice. High temperatures during the grain-filling stage can lead to a reduction in amylose content (AC) and an alteration in the structure of amylopectin, which are crucial components of starch in rice grains. These changes can result in rice with poor cooking and eating qualities. Research has shown that elevated temperatures affect the expression of key genes involved in starch biosynthesis, such as those encoding granule-bound starch synthase (GBSS) and starch branching enzymes (SBEs). These enzymes are critical for the formation of amylose and the branching of amylopectin, respectively (Zhang *et al*., 2021). Drought and nutrient availability also influence starch synthesis in rice. Drought stress can disrupt the availability of carbohydrates necessary for starch production, while nutrient deficiencies can affect the activity of enzymes involved in starch metabolism. For instance, nitrogen deficiency has been shown to reduce the activity of ADP-glucose pyrophosphorylase (AGPase), a key enzyme in starch biosynthesis, leading to lower starch accumulation in rice grains (Fu and Xue, 2010). The unfolded protein response (UPR) is another critical mechanism that influences starch accumulation in rice grains under stress conditions. The UPR helps in maintaining protein homeostasis in the endoplasmic reticulum (ER) and is activated under environmental stresses such as heat. This response can modulate the synthesis of storage proteins and enzymes involved in starch biosynthesis, thereby impacting the starch content and quality of rice grains (He *et al*., 2021).

Breeding programs can leverage this knowledge to develop rice varieties that are more resilient to adverse environmental conditions such as high temperatures and drought. For instance, the identification of genes and alleles associated with heat tolerance and efficient starch biosynthesis can guide the selection of parental lines in breeding programs (Zhang *et al*., 2021). This can lead to the creation of rice cultivars that maintain high grain quality and yield under stress conditions. Additionally, cultivation practices can be optimized based on insights into environmental impacts on starch metabolism. For example, adjusting planting dates to avoid high temperature periods during the grain-filling stage can help in mitigating heat stress effects on rice quality. Implementing proper irrigation strategies can also alleviate drought stress, thereby ensuring sufficient carbohydrate availability for starch synthesis (Fu *et al*., 2010). Moreover, ensuring adequate nutrient supply, particularly nitrogen, can enhance the activity of enzymes critical for starch biosynthesis, thereby improving grain quality (He *et al*., 2021).

Conclusion

In conclusion, the starch digestibility and glycemic index of rice are influenced by a multitude of factors, including the intrinsic properties of the rice variety, the amylose to amylopectin ratio, and external factors such as processing and cooking methods. This review highlights the complexity of these interactions and their significant implications for dietary planning and health management. By understanding how these factors affect starch digestibility and GI, researchers and food technologists can develop rice varieties and processing techniques that optimize health benefits. Future research should focus on elucidating the molecular mechanisms underlying these effects and exploring innovative methods to produce rice with lower GI to cater to health-conscious consumers.

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