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Black rice (*Oryza sativa* L.) and its anthocyanins: mechanisms, food applications, and clinical insights for postprandial glycemic and lipid regulation

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Abstract

Postprandial hyperglycemia and hyperlipidemia are key contributors to chronic metabolic disturbances, thereby promoting the onset and progression of cardiovascular diseases and diabetes. Current dietary interventions aim to effectively control postprandial glucose and lipid levels while ensuring adequate antioxidant intake. Black rice (*Oryza sativa* L.) cultivations have gained attention for their resistant starch content and phytochemical compositions. Notably, black rice is rich in anthocyanins, known for their anti-diabetic and antioxidant effects. This review demonstrates the potential of black rice in regulating postprandial glycemic and lipid responses, thus extending its applications to the development of functional food products. Based on in vitro studies, black rice anthocyanins exhibit a variety of mechanisms, including the inhibition of carbohydrate and fat digestive enzymes, binding to bile acids, interference with cholesterol micellization, and the inhibition of glucose and cholesterol uptake in enterocytes. Utilizing black rice flour and its anthocyanin-rich extracts in food products enhances health benefits by suppressing starch digestibility and increasing phytochemical content and antioxidant capacity. Clinical studies support the potential of black rice and its food derivatives to effectively manage postprandial glycemic and lipidemic responses while increasing plasma antioxidant capacity. However, comprehensive, long-term investigations are crucial to delineate the optimal dosage and duration of black rice consumption and further elucidate its positive effects on metabolic responses.

Keywords Black rice, Anthocyanins, Postprandial hyperglycemia, Postprandial hyperlipidemia

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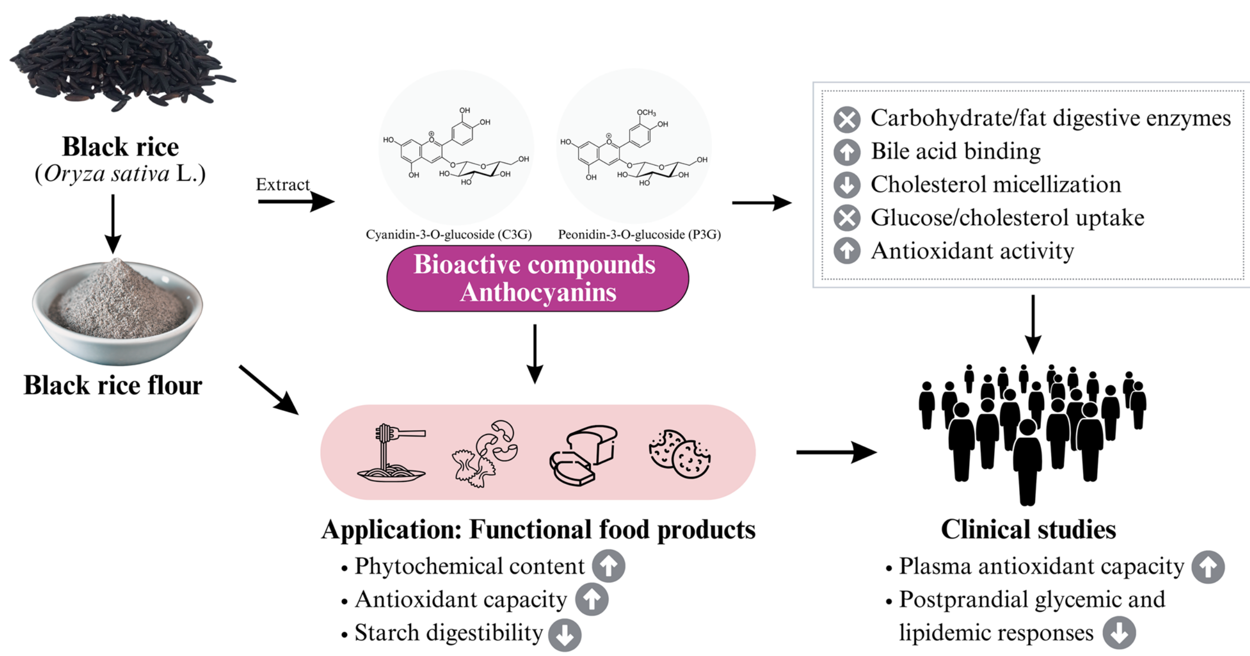
Graphical Abstract



Background

Emerging evidence underscores the significance of metabolic imbalances, particularly after consuming high-energy meals rich in fats and/or carbohydrates (Dimitriadis et al., 2021; Fewkes et al., 2022; Yoshinaga et al., 2021). These postprandial abnormalities are key contributors to the onset of chronic conditions such as cardiovascular diseases (CVDs) (Neumann & Egert, 2022) and diabetes (Henry et al., 2020). Researchers are investigating nutritional strategies that focus on modulating postprandial glycemic and lipid responses. These refined strategies, which involve inhibiting key processes in nutrient digestion and absorption, hold considerable promise as impactful tools in addressing postprandial dysmetabolism (Pasmans et al., 2022). Their potential to maintain optimal nutrient metabolism, thus preventing chronic diseases, signifies a significant advancement in nutritional science.

The growing interest in black rice (*Oryza sativa* L.) stems from its potential health benefits attributed to its unique starch and phytochemical compositions (Thiranusornkij et al., 2019). The inherent pigments of black rice, distinguished for their abundance in phytochemicals, notably anthocyanins, manifest a spectrum of pharmacological activities such as anti-diabetic (Bhuyan et al., 2022; Feng et al., 2022) and antioxidant effects (Sumczynski et al., 2016). This comprehensive review investigates the current understanding of the mechanisms by which black rice and its phytochemical compounds inhibit key processes of nutrient digestion and absorption in small intestine. Additionally, it explores the application of black rice within the food industry and present the most recent research findings concerning its health benefits, particularly in regulating postprandial glycemic and lipid responses. Ultimately, this review aims to provide a thorough and insightful understanding of black rice's potential to enhance human health and overall well-being.

Methodology and data collection

A comprehensive literature search was conducted across PubMed, Scopus, ScienceDirect, and Google Scholar databases using EndNote™ Version 21 to identify relevant articles published between 2010 and 2023. The literature search included terms such as "carbohydrate digestion", "carbohydrate absorption", "fat digestion", "fat absorption", "lipid-lowering activity", "anti-hyperglycemic activity", "postprandial hyperglycemia", "postprandial hyperlipidemia", "food products", "black rice", "pigmented rice", and "black rice anthocyanin". The primary aim was to identify articles that elucidate the mechanisms of action, food applications, and recent clinical studies to provide new insights into the protective effects of black rice and its food products concerning postprandial glycemic and lipidemic responses. A total of 2,065 articles were retrieved using the specified keywords. Excluded from the selection were letters, comments, communications, reviews, theses, animal studies, articles published in non-English languages, and duplicate studies. Ultimately, 36 articles were selected for the review. Of these, 12 articles focused on the mechanism of action, 14 on food applications, and 12 on clinical evidence related to black rice. This review began by providing an overview of the postprandial dysmetabolic response to high-carbohydrate and/or high-fat meals. Following this, the nutritional profile and bioactive components, particularly anthocyanins, of black rice were explored. The mechanisms by which black rice consumption exerts anti-hyperglycemic and lipid-lowering effects were then elucidated. Subsequently, the utilization of black rice in various food formulations and its potential application in clinical trials for managing postprandial glycemia and lipidemia were addressed. Finally, the review concluded by comprehensively analyzing limitations, challenges, and future research perspectives in this field.

Managing postprandial glycemic and lipid responses through the modulation of nutrient digestion and absorption processes

Consuming high-caloric meals rich in fat and/or carbohydrates induces significant and atypical elevations in postprandial hyperglycemia and hypertriglyceridemia. These abnormal surges in blood glucose, triglyceride, and free fatty acid levels overwhelm the metabolic capabilities of the mitochondria, resulting in overproduction of reactive oxygen species (ROS), triggering a cascade of oxidative stress (Miglio et al., 2013; Sies et al., 2005). These excess levels of ROS can initiate an inflammatory response by activating nuclear factor-κB (NF-κB) pathways. The postprandial inflammatory state is evidenced by elevated expressions of tumor necrosis factor-α (TNF-α), interleukin-1β (IL-1β), and interleukin-6 (IL-6), subsequently stimulating hepatic production of C-reactive protein (Meessen et al., 2019). Additionally, saturated fatty acids, including lauric and palmitic acid, have been identified as mediators of inflammation through the activation of toll-like receptor (TLR) signaling pathways (Huang et al., 2012). The combined effects of oxidative stress and inflammation due to metabolic disruptions have the potential to damage endothelial cells and impair the production and bioavailability of nitric oxide, leading to endothelial dysfunction. This dysfunction manifests as impaired vasodilation, increased vascular tone, reduced blood flow, and an elevation in the prothrombotic state (Bell et al., 2008; O'Keefe & Bell, 2007). This association raises significant concerns about their potential contribution to the development of atherosclerosis, diabetes, and its vascular complications (Hanssen et al., 2020; Teno et al., 2000) (Fig. 1).

Given these concerns, exploring and adopting effective nutritional strategies become crucial as a proactive approach to mitigate the risks associated with a rise in postprandial hyperglycemia and hypertriglyceridemia (Brynes et al., 2005; Dimitriadis et al., 2021). For instance, recommending a low glycemic index (GI) diet (Vlachos et al., 2020), incorporating a high proportion of resistant starch (RS) in foods (Harris, 2019), and combining fiber-rich foods into the diet (Weickert & Pfeiffer, 2018) can all lower postprandial glucose and insulin responses. Additionally, consuming whole grains and vegetables containing insoluble fibers contributes to cholesterol excretion by binding to bile acids (Cetiner et al., 2022). Meanwhile, soluble fibers slow stomach emptying and induce a feeling of fullness, facilitating a gradual nutrient release (Salleh et al., 2019). This effect not only manages postprandial metabolic responses but also enhances cardiovascular health (Nie & Luo, 2021).

Scientists are currently refining postprandial nutritional approaches by targeting key steps of digestion and absorption in the small intestine to refine postprandial nutritional approaches. For instance, there is significant evidence supporting the inhibition of carbohydrate digestive enzymes, including pancreatic α-amylase, and intestinal α-glucosidase, and glucose uptake in the small intestine to reduce postprandial glucose levels (Pasmans et al., 2022). Similarly, lipid digestion strategies target mechanisms such as inhibiting pancreatic lipase activity (Rajan et al., 2020; Sun & Miao, 2020), interfering with the formation of cholesterol micelles (Micallef & Garg, 2009), increasing bile acid binding (Naumann et al., 2020), and inhibiting the cholesterol transporter Niemann-Pick C1-Like 1 (NPC1L1) (Lamb, 2020). This collaborative inhibition of triglyceride breakdown, disruption of cholesterol micelle assembly, and blocking cholesterol uptake collectively contributes to delaying lipid absorption, thereby holding promise in potentially controlling postprandial hyperlipidemia. Ongoing researches are actively seeking inhibitors, especially from natural ingredients and phytochemical compounds that can act on these pathways (Anuyahong et al., 2022; Chusak et al., 2018; Naumann et al., 2020; Proença et al., 2022; Sun & Miao, 2020; Thilavech et al., 2021).

Black rice and its nutritional and phytochemical composition

For centuries, rice varieties with black, red, and purple hulls (pericarp) have been cultivated throughout Asia. These vibrant colors result from mutations, both natural and chemically induced, in genes that control

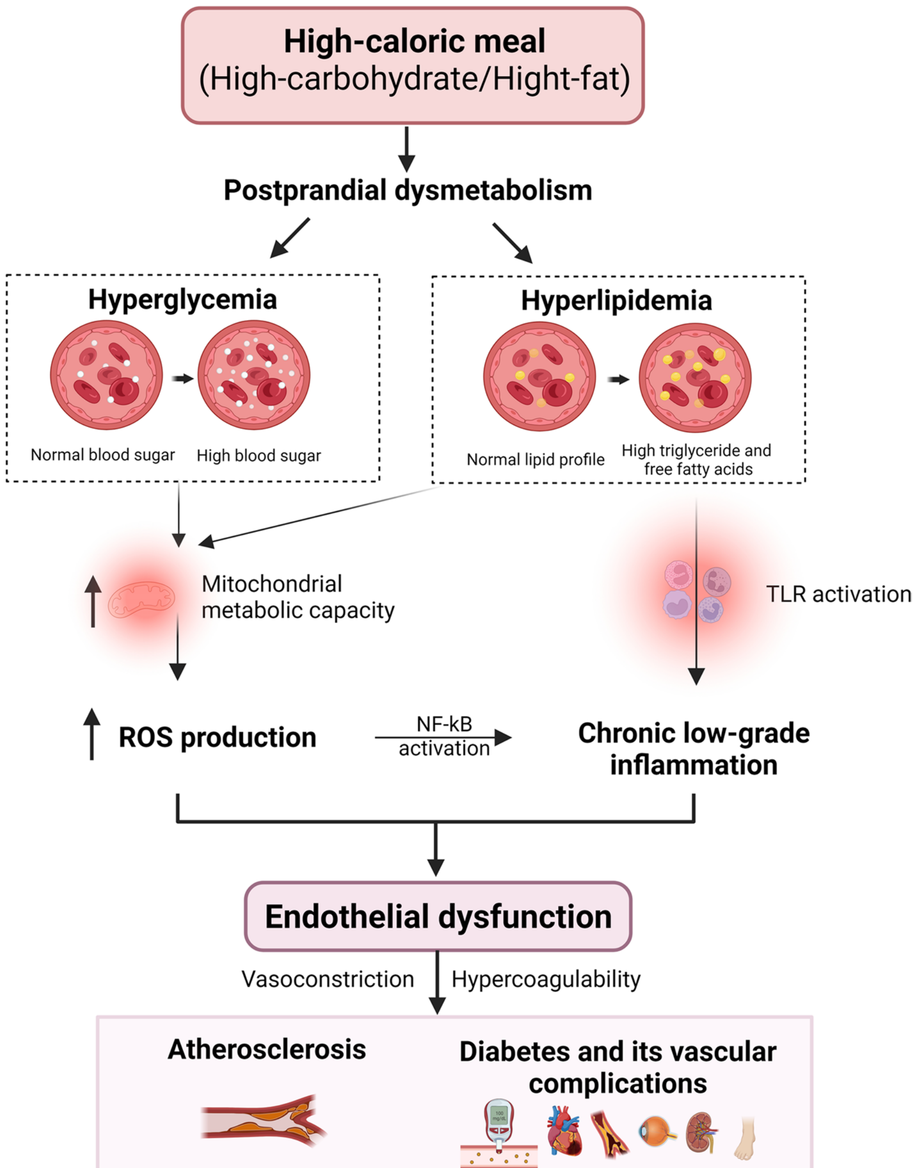


Fig. 1 Postprandial dysmetabolism and its relation to atherosclerosis, diabetes, and associated vascular complications. Consuming high-caloric meals rich in fat and/or carbohydrates induces elevations in postprandial hyperglycemia and lipidemia. These metabolic disruptions trigger a cascade of oxidative stress and initiate an inflammatory response, potentially damaging endothelial cells. This association raises concerns about their contribution to the development of cardiovascular diseases and diabetic complications. ROS: Reactive oxygen species, TLR: Toll-like receptors, NF-κB: Nuclear factor-κB

pigment production in rice grains. Modern breeding programs for these pigmented varieties often involve crossing two different rice cultivars and meticulously selecting offspring with the most desirable physical characteristics (phenotypes) (Ito & Lacerda, 2019). Black rice cultivation has expanded to numerous regions, including Africa, America, Australia, and southern Europe, with Asia remaining a predominant area of production and cultivation. A diverse array of over 200 black rice varieties has gained widespread recognition owing to their rich nutrient content and potent phytochemical compounds, which confer significant biological and health advantages (Pratiwi & Purwestri, 2017). Black rice serves as a plant-based protein source with a relatively low lipid content. The primary lipid composition in black rice consists of triglycerides, where glycerol is esterified with three fatty acids, primarily oleic, linoleic, and palmitic acids on a total lipid basis (Frei & Becker, 2005). Furthermore, starch takes on the role of the primary carbohydrate in black rice, consisting of two key α-glucans: amylose and amylopectin. Interestingly, black rice contains dietary fibers, of which approximately 75% are insoluble fibers (Marlett et al., 2002). In a study by An et al., increasing the substitution of black rice flour for wheat flour within the range of 10% to 40% led to a marked reduction in glucose release during simulated digestion (An et al., 2016). This substitution prompted an elevated proportion of RS, subsequently resulting in a consistent decrease in the predicted glycemic index (pGI) (An et al., 2016). Comparing the starch digestion process between black rice flour and white rice flour reveals a significant difference. Black rice flour demonstrates a slower release of maltose and glucose during the phase of starch digestion. This distinctive behavior subsequently leads to an augmentation in the proportion of RS (Farooq et al., 2021; Thiranusornkij et al., 2019). This phenomenon can be attributed to the intact outer layer of black rice, which reduces the susceptibility of carbohydrate-hydrolyzing enzymes. The elevated RS content in foods has been linked to benefits such as maintaining stable postprandial glucose levels and enhancing feelings of satiety (Guo et al., 2023; Magallanes-Cruz et al., 2017; Raben et al., 1994). This is achieved through the delayed absorption of glucose and lipids into the bloodstream, as well as the regulation of gut satiety hormones (Guo et al., 2023; Magallanes-Cruz et al., 2017; Raben et al., 1994). Therefore, the starch components present in black rice flour indicate its significant potential as a beneficial ingredient option for developing food products aimed at managing postprandial glucose levels, particularly for individuals with prediabetic and diabetic conditions.

In addition to nutritional content, black rice flour emerges as a noteworthy constituent due to discernible levels of phytochemicals, particularly anthocyanins. These phytochemical compounds, known as natural pigments, manifest a captivating spectrum of colors ranging from reddish hues to deep purples (Kim et al., 2008). Research has substantiated that black rice flour demonstrates elevated content of total polyphenols, anthocyanins, and potent antioxidant activity compared to white rice and wheat flour (Aalim et al., 2021; Bae et al., 2017; Shahidi et al., 2022; Xie et al., 2020). Remarkably, the primary anthocyanin found in black rice is cyanidin-3-glucoside (C3G), accounting for a substantial 88% of the total anthocyanin content (Hou et al., 2013). Additionally, minor anthocyanins like peonidin-3-glucoside (P3G), cyanidin-3-rutinoside (C3R), and malvidin-3-glucoside (M3G) are also present (Ito & Lacerda, 2019). The biosynthesis of anthocyanins depends on various environmental factors during cultivation, including the light quality and duration, altitude, temperature, moisture content, water conditions, and nutrient availability in the soil (Keosonthi et al., 2022).

Beyond anthocyanins, black rice contains a diverse range of phenolic acids, classified as either free or bound compounds. These include cinnamic acid and its derivatives such as protocatechuic acid, chlorogenic acid, and gallic acid (Alves et al., 2016; Goufo & Trindade, 2014). Additionally, tocotrienols, tocopherols, and γ-oryzanol have been reported as bioactive compounds present in high concentrations in black rice bran, followed by the whole grain, endosperm, and husk, respectively (Goufo & Trindade, 2014). The natural phytochemical compounds found in black rice have long been recognized for their natural antioxidant properties, effectively scavenging free radicals within the human body (Aalim et al., 2021; Goufo & Trindade, 2014; Tai et al., 2021).

The key question lies in comparing whole grain black rice and its rice bran components to determine their relative impact on starch digestion and antioxidant activity. This evaluation serves to identify them as potential recommended ingredients. Rice bran is the richest source of phenolic compounds and anthocyanins, which accumulate in the pericarp of the rice grain. This accumulation contributes to the stronger antioxidant properties of rice bran compared to whole grains (Goufo & Trindade, 2014; Hui Zhang et al., 2020a, 2020b). Additionally, rice bran has been shown to effectively reduce rice flour digestibility and lower its pGI by decreasing the rapidly digestible starch (RDS) and increasing RS. Considering these findings, black rice bran emerges as a promising ingredient, surpassing whole grains due to its abundance in phenolic-enriched antioxidants and its ability to manage glycemic responses. Therefore, black rice bran has the potential to become an alternative ingredient, enhancing the nutritional and health advantages of food products.

Mechanisms underlying the postprandial glycemic response to black rice and its anthocyanins

One potential mechanism by which black rice slows carbohydrate digestion and reduces postprandial glucose levels involves the inhibition of α-glucosidase and pancreatic α-amylase enzymes (Proença et al., 2022). As shown in Table 1, numerous studies support this mechanism, demonstrating that phenolic-rich black rice extract can inhibit carbohydrate-hydrolyzing enzymes, including both intestinal α-glucosidase and pancreatic α-amylase (Aalim et al., 2021; Gong et al., 2020; Poosri et al., 2019; Wu et al., 2018; Zhang et al., 2022a, 2022b). Among the major phytochemical components, C3G shows promise in inhibiting pancreatic α-amylase (Akkarachiyasit et al.,

Table 1 Effect of phenolic-rich black rice extract and anthocyanins on the inhibition of carbohydrate digestion and absorption in vitro

Compounds	Findings	References
Phenolic-rich black rice extract	Inhibition of intestinal α-glucosidase Inhibition of pancreatic α-amylase	Aalim et al., 2021, Gong et al., 2020, Poosri et al., 2019, Zhang et al., 2022a, 2022b, Wu et al., 2018
C3G, P3G, C3R and M3G	Inhibition of pancreatic α-amylase	Akkarachiyasit et al., 2010, Sui et al., 2016a, Akkarachiyasit et al., 2011
C3G and C3R	Inhibition of maltase and sucrase	Akkarachiyasit et al., 2010, Adisakwattana et al., 2011
C3G	Suppression of glucose uptake in Caco-2 cells	Barik et al., 2020, H. Zhang et al., 2020a, 2020b

C3G Cyanidin-3-glucoside, *P3G* Peonidin-3-glucoside, *C3R* Cyanidin-3-rutinoside, *M3G* Malvidin-3-glucoside

2010), exhibiting a stronger effect compared to P3G (Sui et al., 2016a). Molecular docking analysis suggests that hydrogen bonding interactions of anthocyanins and the active site of pancreatic α-amylase, particularly involving the GLU233 residue, are crucial for inhibition (Sui et al., 2016a; W. Zhang et al., 2023a, 2023b).

Shifting focus to α-glucosidase activity, C3G specifically inhibits sucrase, rather than maltase (Akkarachiyasit et al., 2010). The molecular interaction between C3G and microbial α-glucosidase involves specific amino acid residues, forming seven hydrogen bonds and four hydrophobic interactions (Xue et al., 2021). These interactions may induce changes in enzyme conformation, potentially explaining the observed decrease in α-glucosidase activity. Research findings have revealed that C3G has the capability to bind within the active sites of α-glucosidase, engaging specifically with residues like Leu 313, Ser 157, Tyr 158, Phe 314, Arg 315, and two Asp 307 (Xue et al., 2021). Within this interaction profile, a hydrogen bond at Tyr 158 appears to be critical binding region for C3G (Xue et al., 2021). However, a knowledge gap exists regarding the molecular docking interactions between C3G and intestinal maltase and sucrase. Future research in this area would undoubtedly enhance our understanding of C3G's interactions with mammalian α-glucosidases. Minor anthocyanins present in black rice also possess the ability to inhibit carbohydrate-hydrolyzing enzymes. For instance, C3R acts as an inhibitor of α-glucosidase and pancreatic α-amylase (Adisakwattana et al., 2004, 2011; Akkarachiyasit et al., 2011). Similarly, M3G demonstrates strong inhibition against pancreatic α-amylase (Kaeswurm et al., 2019).

The inhibitory effects of black rice on intestinal glucose absorption were studied using Caco-2 cells, an in vitro model of the intestinal epithelium and glucose transport (Poosri et al., 2019). Interestingly, black rice extract itself did not inhibit glucose uptake in this model. However, C3G, a major anthocyanin in black rice, exhibited some inhibitory effect on Caco-2 cell glucose uptake (Barik et al., 2020; H. Zhang et al., 2020a, 2020b). The lack of inhibition by black rice extract might be due to its lower C3G content. Molecular docking simulations suggest that C3G interacts with two key hexose transporters in enterocytes: sodium-dependent glucose transporter 1 (SGLT1) and glucose transporter 2 (GLUT2), which are crucial for glucose absorption across the intestinal barrier (Barik et al., 2020). C3G's structure, including the glucoside residue, likely introduces steric hindrance, potentially impeding glucose binding to the active sites of SGLT1 and GLUT2 transporters. (Barik et al., 2020). This interference could subsequently block the efficient transport of glucose through these pathways.

Based on existing scientific studies, black rice appears to inhibit carbohydrate-digesting enzymes and reduce intestinal glucose absorption, likely due to the presence of anthocyanins. However, it is important to note that other bioactive compounds in black rice, such as phenolic acids, might also contribute (Adisakwattana et al., 2009; Bhuyan et al., 2022; Wang et al., 2022). These phenolic compounds could potentially act synergistically or additively to further suppress postprandial glycemic response.

Other components found in black rice, such as dietary fiber, might also regulate carbohydrate-hydrolyzing enzymes. However, a study by An et al. found that the dietary fiber extracted from black rice did not inhibit α-glucosidase and pancreatic α-amylase, while a phenolic compound-rich extract from black rice did exhibit inhibitory effects (An et al., 2016). These findings suggest that phenolic compounds play a more significant role in inhibiting these enzymes and consequently, slowing down the in vitro starch digestibility of black rice-based foods. Additionally, anthocyanins may interact with starch molecules, creating steric hindrance and hindering enzyme binding. This effect could subsequently reduce the digestibility of starch (Zhang et al., 2023a, 2023b). Research by Zhang et al. demonstrated that anthocyanin extract from rice bran interacted with the internal cavities of amylose in rice starch, and significantly changed the crystalline structure through hydrogen bonding. This interaction formed a semi-crystalline (type II) intrahelical V-type complex, potentially explaining how rice bran anthocyanin extract suppresses rice starch digestibility. This effect is associated with a decrease in RDS and a notable increase in RS content (W. Zhang et al., 2023a, 2023b).

Black rice and its phytochemical compounds show promising effects in in vitro models for regulating postprandial glycemic response, such as stimulating glucose uptake in muscle cells (Feng et al., 2022) and enhancing insulin secretion from β-cells (Jayaprakasam et al., 2005; Kongthitilerd et al., 2022). However, the bioavailability of these phytochemicals, especially anthocyanins, is often limited, with less than 1% of the ingested dose being absorbed. Human studies show that anthocyanins and their metabolites reach peak concentrations of about 100 nM in the bloodstream within 1.5 h of consumption, but then decline rapidly within 6 h post-consumption (Krga & Milenkovic, 2019). Achieving plasma concentrations that reflect the cellular effects observed in vitro such as stimulating glucose uptake or promoting insulin secretion, remains a challenge.

Nevertheless, within the intestinal lumen, the phenolic compound-rich extract derived from black rice appears to directly influence dietary carbohydrates by inhibiting α-glucosidase and pancreatic α-amylase activities, independent of their limited bioavailability. This action in the gut lumen emerges as critical mechanism by which black rice extract and its anthocyanins regulate postprandial glucose dynamics (as illustrated in Fig. 2).

Mechanisms underlying the postprandial lipidemic response to black rice and its anthocyanins

Postprandial hyperlipidemia, characterized by an abnormal elevation in circulating lipid levels like cholesterol and triglycerides after meal, is a risk factor for CVDs such as atherosclerosis, stroke, and heart attacks (Alloubani et al., 2021). Black rice may offer benefits in managing this condition by influencing fat digestion and absorption. Several studies suggest that phenolic-rich black rice extract can inhibit pancreatic lipase activity (Poosri et al., 2019; Yao et al., 2013). Pancreatic lipase is a key enzyme responsible for breaking down dietary triglycerides into free fatty acids. Inhibiting this enzyme could potentially reduce the postprandial triglyceride response, thereby contributing to managing hyperlipidemia.

The inhibitory effect of black rice extracts on pancreatic lipase appears to be primarily due to anthocyanins, particularly C3G and P3G (as shown in Table 2). These anthocyanins are thought to interact with the hydrophobic pocket of pancreatic lipase, hindering substrate binding (Yao et al., 2013). Molecular docking studies suggest that hydroxyl and carboxyl groups in anthocyanins interact with the enzyme's active site. The inhibitory activity of anthocyanins against pancreatic lipase is influenced by several factors, including the degree of polymerization at the C-ring's 3-hydroxyl group, the number and position of phenolic hydroxyl groups, and the polyphenolic structure of the B-ring, which affects the molecule's hydrophobicity and affinity for the enzyme (Khoo et al., 2017; Wu et al., 2017). However, the presence of glycosides can increase anthocyanin hydrophilicity, reducing inhibitory potency against pancreatic lipase (Vijayaraj et al., 2019). This is evident in the higher IC_{50} value for C3G compared to cyanidin aglycone (Vijayaraj et al., 2019). Therefore, anthocyanins in their aglycone form, produced through hydrolysis in the intestine, may exert stronger pancreatic lipase inhibitory activity. Interestingly, anthocyanins act as noncompetitive inhibitors and can be combined with orlistat, a strong competitive inhibitor for synergistic effect (Vijayaraj et al., 2019). This combination could potentially minimize the unpleasant gastrointestinal side effects associated with orlistat. It is important to note that inhibiting pancreatic lipase activity to reduce fat absorption could lead to deficiencies in fat-soluble vitamins. Long-term clinical studies are crucial to monitor these potential side effects and ensure safety and nutritional adequacy.

Black rice extract also disrupts cholesterol absorption by interfering with micelle formation. Micelles are tiny particles that facilitate cholesterol transport in the bloodstream. Research suggests that black rice extracts reduce both the size and number of micelles formed (Poosri et al., 2019; Yao et al., 2013). This effect is likely caused by anthocyanins, particularly C3G and P3G, which may interact with cholesterol within micellar solutions, leading to its precipitation (Yao et al., 2013).

Another potential mechanism by which black rice extract lowers cholesterol absorption involves its interaction with bile acids. Studies suggest that black rice extract can effectively bind to both primary bile acids, like taurocholic acid, and secondary bile acids, such as glycodeoxycholic acid and taurodeoxycholic acid (Poosri et al., 2019). Primary bile acids, synthesized directly from cholesterol in the liver, are a crucial for fat digestion and absorption. They emulsify dietary fats, increasing the surface area for pancreatic lipase activity and facilitating micelle formation for intestinal uptake. (Chiang & Ferrell, 2018).

When black rice extract binds to primary bile acids, it diminishes the pool of available bile acids for the

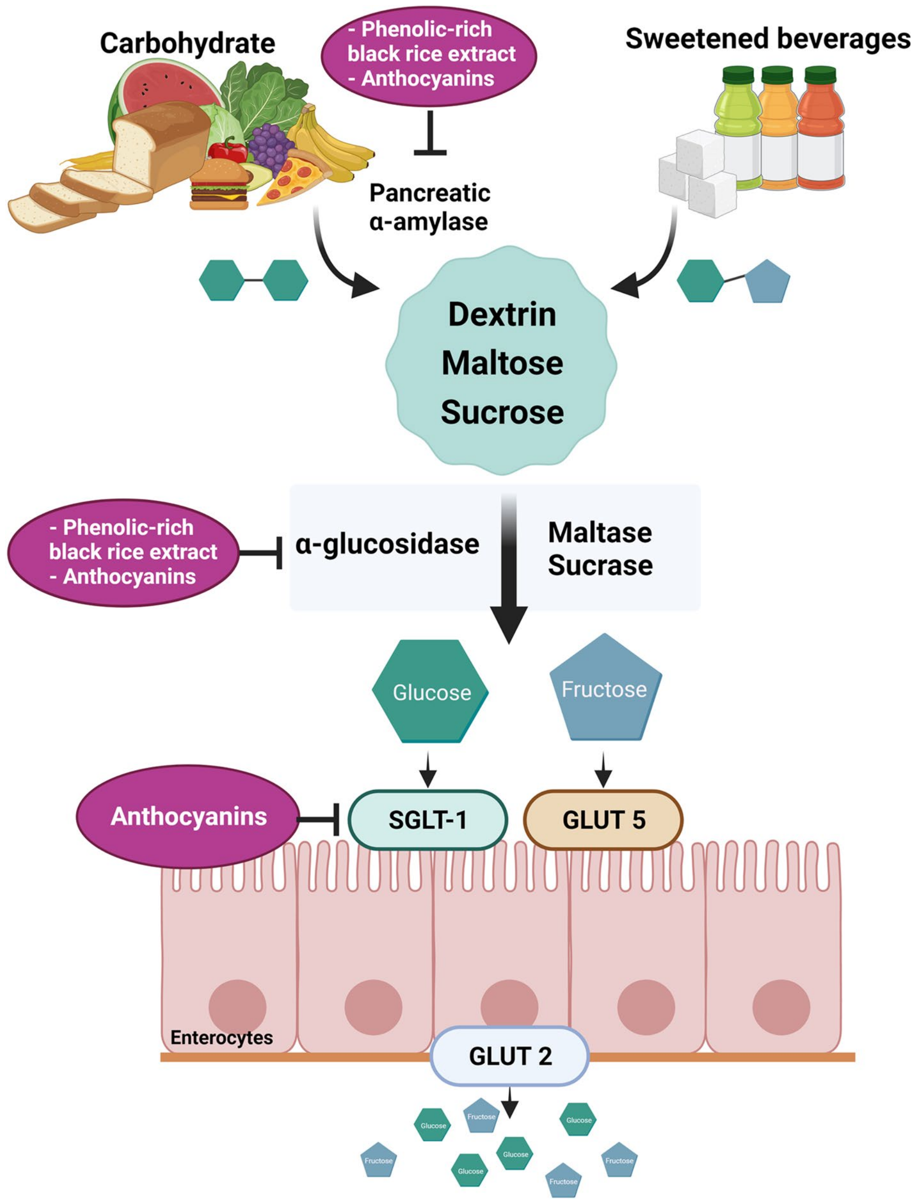


Fig. 2 The role of black rice extract and its anthocyanins in controlling postprandial glycemic response involves inhibiting carbohydrate digestive enzymes, specifically pancreatic α-amylase and intestinal α-glucosidase. This action slows down carbohydrate digestion into absorbable monosaccharides and suppresses glucose uptake in enterocytes. SGLT1: Sodium-dependent glucose transporter 1, GLUT2: glucose transporter 2, GLUT5: glucose transporter 5

emulsification of dietary fats, leading to a reduction in micelle formation and consequently lowering the absorption of triglyceride and cholesterol into the bloodstream. Most secondary bile acids, formed by gut bacteria from bile acids in the large intestine, are efficiently reabsorbed (around 95%) and cycled back to the liver (Chiang & Ferrell, 2018). Black rice extract may disrupt this cycle by hindering the reabsorption of some secondary bile acids, potentially leading to increased excretion in feces. Studies using apolipoprotein E-deficient mice have shown that C3G, a key anthocyanin in black rice, can enhance fecal bile acid excretion, leading to lower blood cholesterol levels (Wang et al., 2012). This effect might be due to C3G's ability to deplete the bile acid pool. In response, the liver upregulates cholesterol 7α-hydroxylase (CYP7A1), the rate-limiting enzyme for bile acid synthesis, promoting de novo synthesis of bile acids from cholesterol

Table 2 Effects of phenolic-rich black rice extract and anthocyanins on the inhibition of lipid digestion and absorption

Compounds	Findings	References
Phenolic-rich black rice extract, C3G and P3G	Inhibition of pancreatic lipase	Poosri et al., 2019, Yao et al., 2013
Phenolic-rich black rice extract, C3G and P3G	Inhibition of cholesterol micelle formation	
Phenolic-rich black rice extract	Increasing bile acid biding	
Phenolic-rich black rice extract, C3G and P3G	Inhibition of cholesterol uptake	Poosri et al., 2019, Yao et al., 2013

C3G Cyanidin-3-glucoside, *P3G* Peonidin-3-glucoside

(Wang et al., 2012). This increased bile acid production helps maintain overall bile acid levels while simultaneously reducing cholesterol stores within liver cells.

In addition to the previously mentioned mechanisms, black rice extract has also been found to inhibit cholesterol uptake in Caco-2 cells (Poosri et al., 2019; Yao et al., 2013). Studies suggest that C3G and P3G act as inhibitors of this process (Yao et al., 2013). It is known that the NPC1L1 cholesterol transporter, located at the brush border of the small intestine, plays a crucial role in cholesterol absorption (Hu et al., 2021). There is a proposal that anthocyanins may bind to the extracellular domain of NPC1L1, inducing conformational changes in the NPC1L1 protein, thereby inhibiting cholesterol uptake. Interestingly, additional data revealed that overnight exposure to black rice extract led to the suppression of NPC1L1 gene expression in Caco-2 cells (Poosri et al., 2019). In an animal study, it was confirmed that supplementing mice with whole-grain black rice for 12 weeks downregulated the mRNA expression levels of genes that regulate cholesterol absorption in the intestines, including NPC1L1 (Liu et al., 2020). This suggests that black rice extract not only inhibits cholesterol uptake but also downregulates the gene expression of intestinal NPC1L1, providing a comprehensive mechanism for its cholesterol-lowering effects. As illustrated in Fig. 3, black rice extract and its anthocyanins disrupt both fat digestion and absorption within the intestinal lumen, resulting in a decreased occurrence of postprandial hyperlipidemia.

The dietary fiber found in black rice includes both insoluble dietary fiber and soluble dietary fiber (S. Zhang et al., 2023a, 2023b). Research suggests that the soluble dietary fiber in black rice may possess binding properties similar to those of soluble fiber from other sources. This binding targets fatty acids, cholesterol, and bile acids in the intestine, leading to a reduction in the digestibility of dietary lipids and the absorption of fatty acids (Zawistowski et al., 2009). Furthermore, black rice also contains trace amounts of γ-oryzanol and phytosterols, particularly β-sitosterol. These components have established effectiveness in lowering cholesterol absorption and enhancing the excretion of bile acids (Goufo & Trindade, 2014; He et al., 2018; Suttiarporn et al., 2015) This highlights the significance of dietary fiber, γ-oryzanol and phytosterol, alongside other components of black rice, in the control of postprandial lipid responses. In summary, the combined action of anthocyanins in black rice anthocyanins and dietary fiber within the intestinal lumen emerges as a pivotal mechanism responsible for regulating postprandial lipid dynamics.

Potential applications of black rice in food products

Black rice exhibits a superior nutritional profile compared to brown and white rice. It possesses significantly higher levels of phytochemicals, especially anthocyanins (Rahim et al., 2022; Rathna Priya et al., 2019). Additionally, black rice is a rich source of essential vitamins (tocopherol, thiamin, riboflavin, and niacin) and minerals (phosphorus, potassium, magnesium, copper, iron, and zinc), along with protein and dietary fiber. These factors contribute to its status as a valuable and versatile functional food ingredient. Black rice flour presents a promising alternative to conventional wheat flour. Its incorporation demonstrably enhances the nutritional value of baked goods and staple foods. Furthermore, black rice flour facilitates the development of functional food products due to its unique bioactive constituents. Notably, black rice flour finds extensive use within the baking industry and staple food production. As detailed in Table 3, black rice and its anthocyanin-rich extracts boast a wide range of applications across various food products and contexts. Scientific research suggests that these applications hold promise for regulating postprandial glycemic and lipid responses, ultimately enhancing overall antioxidant properties.

Noodles

Noodles, a staple food in many Asian countries with a growing global presence, have come under scrutiny

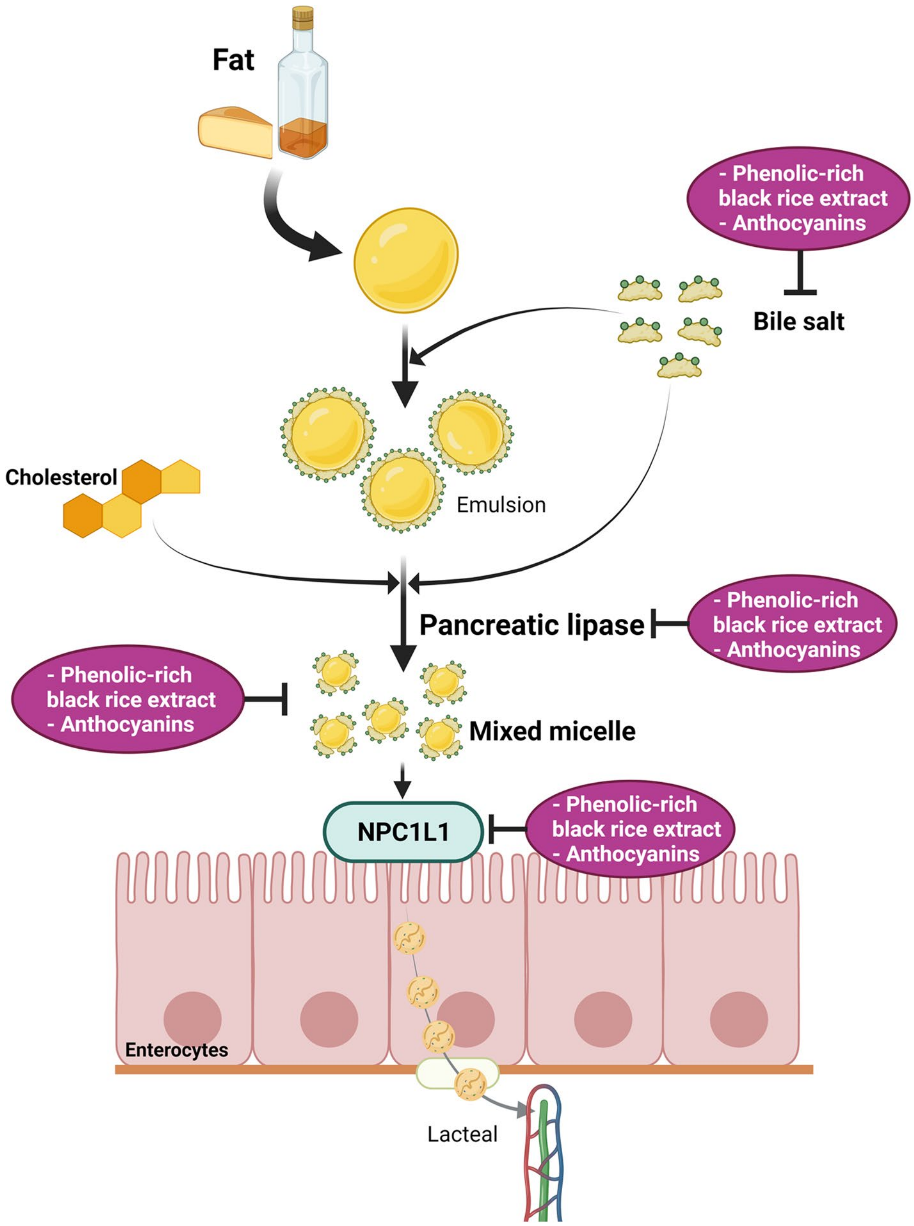


Fig. 3 The pivotal role of black rice extract and its anthocyanins in regulating postprandial hyperlipidemia involves inhibiting the fat digestive enzyme pancreatic lipase. Additionally, it disrupts crucial steps of fat absorption by interfering with cholesterol micelle formation, interacting with bile acids, inhibiting cholesterol uptake, and suppressing the expression of cholesterol transporters in enterocytes. NPC1L1: Niemann-Pick C1-Like 1

due to their high GI, leading to rapid postprandial glucose spikes (Seah et al., 2019; Zuñiga et al., 2014). This is particularly concerning for individuals with impaired glucose tolerance. In an effort to address this concern, Kong et al. conducted a study to explore the feasibility of incorporating black rice bran into noodle production and examine its impact on the chemical and functional properties of the resulting noodles (Kong et al., 2012). The study involved combining wheat flour with varying the black rice bran levels (2% to 15%) and assessing texture, polyphenolic, flavonoid, and anthocyanin content, as well as antioxidant activity. The addition of black rice bran resulted in a significant decrease in cohesiveness, attributed to the disruption of the structural network of starches, glutens, proteins, fibers, and other ingredients in the noodles. Despite this, the black rice bran-enriched noodles exhibited higher levels of polyphenols,

Table 3 Effect of black rice and its components on food products

Food Products	Materials	Physicochemical and textural findings	Functional properties	References
Noodles	2%-15% black rice bran in wheat noodles	Cooking loss ↑, water absorption ↓ Cohesiveness ↓	Antioxidant activity ↑ Polyphenols ↑ (7.57–20.64 mg GAE/25 g), Anthocyanins ↑ (0.15–1.57 mg C3GE/25 g)	Kong et al., 2012
	5%-30% black rice flour in rice noodles	Hardness ↓, springiness ↓, cohesiveness ↓	Antioxidant activity ↑ Polyphenols ↑ (0.29–1.03 mg GAE/g)	Park et al., 2021
	10%-40% black rice flour in wheat noodles	Cooking time ↓, cooking loss ↑, Water absorption ↓ Breaking length ↓	-	Sirichokworrakit et al., 2015
Pasta	5%-25% black rice bran (1,433 mg C3GE/100 g)	Cooking time ↓, cooking loss ↑, Water absorption ↓ Firmness ↓, stickiness ↓	Antioxidant activity ↑ Anthocyanins ↑ (62.62–300.15 mg C3GE/100 g)	Sethi et al., 2020
Biscuits	25%-100% black rice flour	Hardness ↓, spread ratio ↑	- pGI ↓ - Polyphenols ↑ (0.81- 3.01 mg GAE/100 g), anthocyanins ↑ (0.94–5.15 mg C3GE/100 g) - Antioxidant activity ↑	Klunklin & Savage, 2018
Bread	Black rice flour (2.68 mg GAE, and 293 C3GE/g) vs white rice flour	Cohesiveness ↓, gumminess ↓, chewiness ↓, adhesiveness ↓	- Starch hydrolysis ↓, pGI ↓ - Polyphenols ↑ (1.44 mg GAE/g), anthocyanins ↑ (92.4 mg C3GE/g) - Antioxidant activity ↑	Thiranusornkij et al., 2018, 2019
	Extruded black rice flour (0.023% TPC) vs black rice flour (0.049% TPC)	Volume ↑, firmness ↓, overall structure ↑	-	Ma et al., 2019
	1%-4% anthocyanin-rich extract from black rice	Hardness ↑, chewiness ↑, springiness ↓, cohesiveness ↓, resilience ↓	- Starch hydrolysis ↓	Sui et al., 2016b
	2%-8% black rice anthocyanin extract (240.6 mg C3GE/g)	Starch gelatinization ↓, starch crystallinity ↑, gluten network formation ↓	- Anthocyanins ↑ (60.3–274.5 mg C3GE) - Starch digestibility ↓	Ou et al., 2022
Cake	10%-100% black rice powder	Hardness ↑, cohesiveness ↑, gumminess ↑, adhesiveness ↑, chewiness ↑, springiness ↓	- Polyphenols ↑ (44.36-84.66 mg GAE/100 g), anthocyanins ↑ (3.60- 20.85 mg C3GE/100 g) - Antioxidant activity ↑	Mau et al., 2017
	0.25%-2% anthocyanin-rich black rice extract	Firmness ↔, springiness ↔	- Starch hydrolysis ↓, digestion rates of sucrose (12.8%-20.5%) ↓ - Polyphenols ↑ (11.32-61.26 mg GAE/100 g), anthocyanins ↑ (8.07–37.48 mg C3GE/100 g) - Antioxidant activity ↑	Huang et al., 2022
Yogurt	0.125%-0.25% anthocyanin-rich extract from black rice (67.0 mg GAE/g extract)	Syneresis ↓, Firmness ↓	- Polyphenols ↑ (6.50- 8.04 mg GAE/100 g), anthocyanin ↑ (2.88- 4.97 mg C3G, and 1.31–2.25 mg P3G/100 g) - Antioxidant activity ↑	Anuyahong et al., 2020a
Puddings	Black rice and purple sweet potato powder	Texture classification of IDDSI: Level 3 Moderately Thick	pGI of 51 and % hydrolysis index of 21	Suttireung et al., 2019

↓: Decrease, ↑: Increase, ↔: No significant change, *pGI* Predicted glycemic index (pGI), *IDDSI* International Dysphagia Diet Standard Initiative, *C3G* Cyanidin-3-glucoside, *P3G* Peonidin-3-glucoside. Total phenolic content (TPC) and total anthocyanin content are expressed as gallic acid equivalent (GAE) and cyanidin-3-glucoside equivalent (C3GE), respectively flavonoids, and anthocyanins, along with increased antioxidant activity compared to control noodles.

In another study, Park et al. investigated the advantages of integrating black rice (5%-30%) into rice noodles made from Dodamssal rice were investigated. Dodamssal rice is characterized by a high amylose content (40–45%) and contains RS (Park et al., 2021). This addition not only enhanced the functionality of the noodles by augmenting polyphenol content and antioxidant activity but also affected the texture by reducing the hardness, springiness, and cohesiveness of the noodles. Notably, GI value of rice noodles containing 5% black rice was recorded as 79.4. Since black rice has a lower amylose content, approximately 16–27% (W. Zhang et al., 2022a, 2022b), substituting Dodamssal rice with a higher proportion of black rice diminished the RS content, thereby elevating the GI value of the noodles.

In wheat noodles, Sirichokworrakit et al. observed significant alterations in various attributes of the noodles when incorporating black rice flour (10, 20, 30, and 40%) into formulations (Sirichokworrakit et al., 2015). As the proportion of black rice flour increased, water absorption, cooking time, breaking length (a measure of noodle texture), and sensory attributes of the cooked noodles decreased, while cooking loss increased. These alterations primarily arise from the disruption of the matrix and the dilution of gluten protein induced by the inclusion of higher-fiber constituents. This leads to diminished water retention and a weakened overall noodle structure. Kraithong et al. further reveal that black rice noodles exhibit an extended cooking time and higher cooking loss in comparison to white rice noodles, primarily attributed to the higher protein and fiber content in the colored rice noodles (Kraithong & Rawdkuen, 2021). This compositional disparity influences the structural properties of the noodles, resulting in prolonged cooking times and an increased likelihood of starch leaching into the cooking water. These changes can be elucidated by the interaction between the high protein and lipid content in white rice noodles and amylose during noodle processing, hindering water absorption. It is important to consider that cooking time significantly impacts the texture and quality of rice noodles. Prolonged cooking time can result in an undesirable soft and mushy texture, while increased cooking loss can lead to loss of shape and texture, ultimately compromising the overall quality of the noodles (Kraithong & Rawdkuen, 2021). To address these challenges, the use of starches emerges as a promising solution to improve the cooking characteristics of black rice noodles. Jin et al. observed a significant increase in cooking time when incorporating different sources of starches (mung bean, potato, or corn starch) at 30 w/w of black rice flour (Jin et al., 2022). However, this approach demonstrably improved the cooking resistance of black rice noodles, evidenced by a reduction in cooking loss of 31–65%, and provided the desired texture and quality (Jin et al., 2022). This phenomenon is attributed to the interaction between starch and black rice components, hindering the reassociation of starch chains and stabilizing the microstructure of black rice noodles. This approach offers a potential avenue to enhance the overall appeal and consumer acceptance of black rice noodles. In term of functional properties, the addition of starch helps maintain the low starch digestibility of black rice noodle and reduces the loss of polyphenol content during cooking (Jin et al., 2022). In conclusion, the utilization of black rice bran in noodle production offers an opportunity to create healthier options with enhanced antioxidant properties. While the inclusion of black rice flour may induce changes in texture and cooking characteristics, ongoing research and the exploration of starches can mitigate these challenges, optimizing the quality of black rice noodles.

Pasta

Pasta, a globally beloved staple, is cherished for its taste, convenience, and easy preparation. Primarily composed of wheat flour, it provides a rich source of carbohydrates and substantial post-digestion calories. Nevertheless, the inclusion of dietary fiber from black rice presents a promising opportunity to enhance the nutritional profile of pasta. For instance, introducing 5%-25% black rice bran into wheat pasta leads to notable changes in its physicochemical characteristics (Sethi et al., 2020). These modifications reduced water absorption, shorter cooking times, and a decrease in firmness and stickiness, accompanied by a slight increase in cooking losses. Importantly, enriching pasta with black rice bran results in enhanced nutritional content and increased antioxidant activity, attributed to the presence of anthocyanins and dietary fibers. It is important to note that adding black rice bran at a 15% level emerges as a practical approach to enhance the nutritional composition of conventional pasta in the food industry, while still preserving the quality of the pasta product.

In addition to nutrient composition, various pretreatment methods for dough preparation also impact the physicochemical and phytochemical attributes of black rice pasta (Laishram & Das, 2017). Pretreating the pasta dough using the microwave method at various power levels notably elevates water absorption and solubility compared to conventional incubation. While conventional treatment enhances cooking yield, microwave treatment diminishes it. Elevated pretreatment temperatures and microwave power increase cooking losses but shorten cooking time. Conventional treatment better conserves anthocyanin and phenolic compounds, exhibiting higher antioxidant activity than microwave treatment (Laishram & Das, 2017). The degradation of these compounds during the pretreatment of the dough can be hastened by microwave radiation, as evidenced by a previous study investigating the impact of cooking methods on the phytochemical composition in red cabbage (Xu et al., 2014). This highlights that microwave pretreatment might not be optimal for black rice pasta dough preparation, as it can potentially diminish phytochemicals, antioxidant activity, and adversely affect cooking characteristics.

Biscuits

Biscuits, a widely consumed snack composed of wheat flour, sugar, and fat, often lack essential nutrients such as fiber, vitamins, and minerals. To address this nutritional gap, researchers have explored substituting wheat flour with black rice flour (25% to 100%), creating biscuits enriched with antioxidants and dietary fiber (Klunklin & Savage, 2018). However, this substitution led to variations in physical characteristics, leading to reduced hardness and an increased spread ratio. Remarkably, biscuits made exclusively from black rice flour exhibited the lowest pGI among all tested biscuits. Compared to wheat biscuits with a pGI of ~ 72, biscuits with black rice flour substitutions ranging from 25 to 100% demonstrated an intermediate pGI range of ~ 60 to 69. Although sensory scores for blended flour biscuits were slightly lower than those of the wheat biscuits, consumers still found them acceptable with up to a 50% black rice flour substitution. These findings suggest that incorporating up to 50% black rice flour can produce biscuits with added nutritional value, providing individuals with prediabetes or diabetes a viable option for consuming lower digestibility starch-containing foods. While prior studies have explored the use of pigment-enriched anthocyanins from black rice, this particular study focused on processing a hydroalcoholic extract from Italian black rice (Papillo et al., 2018). This extract was processed using both spray-drying with maltodextrins and arabic gum and freeze-drying to create stable ingredients suitable for bakery foods. Consequently, the enriched biscuits containing this extract demonstrated significantly higher concentrations of polyphenols, anthocyanins, and antioxidant activity compared to a control biscuit. Conversely, some degradation of the phytochemicals still occurred during the baking process.

Bread

Recent scientific research has revealed a growing interest in exploring alternative flours for gluten-free bread production (Padalino et al., 2016). Among these alternatives, black rice flour stands out due to its distinctive composition and properties. Being naturally gluten-free, black rice flour caters to individuals with celiac disease or gluten sensitivity, eliminating the potential for adverse immune reactions linked to gluten consumption (Culetu et al., 2021; Rai et al., 2018). Compared to traditional white rice flour, black rice flour boasts several advantages. It possesses elevated levels of bioactive compounds, including total polyphenolics and anthocyanins, which contribute to its enhanced antioxidant activity (Thiranusornkij et al., 2018, 2019). Additionally, black rice flour also exhibits unique starch characteristics, with higher levels of RS and lower levels of slowly digestible starch. This distinctive composition translates into black rice bread exhibiting lower starch hydrolysis and pGI values, coupled with elevated levels of beneficial polyphenols and anthocyanins, distinguishing it from white rice bread (Thiranusornkij et al., 2018, 2019). The texture of black rice bread also differs from white rice bread. It exhibits lower cohesiveness, gumminess, chewiness, and adhesiveness. Remarkably, black rice bread demonstrates similarities in hardness, springiness, and specific volume when compared to white rice bread (Thiranusornkij et al., 2018, 2019). Consequently, black rice flour emerges as a favorable choice for individuals seeking healthier alternatives in gluten-free bread, particularly those aiming to manage blood glucose levels.

Studies exploring the utilization of different black rice flours obtained through extrusion and milling processes reveal variations in flour quality and their impact on wheat-based dough characteristics. For bread-making, extruded black rice flour demonstrates substantial advantages over raw black rice flour (Ma et al., 2019). The extruded black rice flour exhibits significant enhancements in dough rheology, leading to improved bread quality by increasing volume, reducing firmness, and enhancing overall structure. These improvements can be attributed to the functional properties inherent in the extruded black rice flour, including protein weakening, reduced starch gelatinization, improved gel stability, and decreased retrogradation. These functional attributes significantly influence dough characteristics, ultimately shaping the overall quality of the resulting bread. Additionally, the higher moisture content and viscosity observed in the dough of extruded black rice flour contribute to improved gas retention, resistance, and texture, further adding to the overall favorable attributes of the bread.

Beyond its use in gluten-free bread, anthocyanin-rich extract from black rice (at concentrations of 1%, 2%, and 4%) has gained interest as a fortifying ingredient in wheat bread (Sui et al., 2016b). As the levels of anthocyanin-rich extract from black rice increase, noticeable alterations in the bread's texture occur, including increased hardness and chewiness of the crumb, coupled with reduced springiness, cohesiveness, and resilience. These changes can be attributed to the presence of anthocyanins in the extract, which weaken the gluten network and impede gas retention within the bread structure. Moreover, the rate of starch digestion in the bread was found to decrease, ranging from 12.8 to 20.5%, with the addition of anthocyanin-rich extract from black rice. Consistent with this, Ou et al. recently reported similar microstructure modifications of wheat bread when incorporating black rice anthocyanin extract (BRAE) at concentrations ranging from 2 to 8%. Physicochemical analysis revealed that the addition of BRAE reduced the degree of starch gelatinization, increased starch crystallinity, and interfered with the gluten network formation in bread in a concentration-dependent manner, ultimately retarding starch digestion (Ou et al., 2022). These findings are supported by in vitro experiments demonstrating that specific anthocyanin, like C3G, inhibits carbohydrate digesting enzymes, particularly pancreatic α-amylase, which breaks down starch (Akkarachiyasit et al., 2010).

The combination of black rice anthocyanin extracts with bread or fortifying bread with these extracts raises crucial questions about optimizing anthocyanin accessibility and minimizing starch digestibility, considering the modulatory effects of anthocyanins with commonly consumed food matrices. Studies, like one by Ou et al., investigating co-digestion of black rice extract with bread, suggest advantages over simple fortification. These advantages include increased anthocyanin availability and reduced starch breakdown (Ou et al., 2023a). One reason for this difference is the gluten network in bread acts as a natural barrier (Capuano & Janssen, 2021). This network, composed of starch, protein, and anthocyanins, facilitates non-covalent interactions that delay or prevent interactions between starch granules, anthocyanins, and digestive enzymes like pancreatic α-amylase and intestinal α-glucosidase. Consequently, it limits the availability of free anthocyanins that could potentially inhibit starch digestion. However, co-digestion of bread with black rice extract allows these free anthocyanins to interact with carbohydrate-hydrolyzing enzymes or starch granules. This interaction further inhibits bread digestion through enzymatic and non-enzymatic mechanisms, leading to decreased starch breakdown (Ou et al., 2023a). The acquired knowledge provides a comprehensive understanding of the interaction between anthocyanin in black rice extracts, bread, and digestive processes in carbohydrate digestion. This insight is crucial for devising effective strategies to improve anthocyanin accessibility and diminish starch digestibility in various food applications.

Cake

Batter-type cakes, laden with cultural and traditional significance, often take center stage in celebrations and rituals. However, a note of caution arises regarding their health impact, especially when consumed excessively within an unhealthy dietary context. These cakes tend to be high in refined carbohydrates, added sugars, and unhealthy fats, potentially lacking essential nutrients. In addressing this concern, Mau et al. investigated the formulation of chiffon cakes by substituting wheat flour with black rice powder in varying proportions, ranging from 10 to 100% w/w (Mau et al., 2017). The results showed that increasing the level of black rice powder significantly impacted the cake's texture, leading to increased hardness, cohesiveness, adhesiveness, gumminess, and chewiness, with a decrease in springiness. While total polyphenols, anthocyanins and free radical scavenging ability all increased with higher levels of black rice powder, sensory evaluation revealed that partial substitution with up to 60% black rice powder remained acceptable (Mau et al., 2017).

Huang et al. investigated the health implications of incorporating 0.25%-2% anthocyanin-rich black rice extract powder into chiffon cake batter (Huang et al., 2022). Interestingly, adding up to 2% of the extract powder did not noticeably affect the cake's firmness and springiness. However, the cake fortified with anthocyanin-rich black rice extract powder exhibited reduced levels of released glucose and fructose during a 2-h period of simulated intestinal digestion. This suggests that the mechanism behind the slowed sucrose digestion involves the inhibition of the intestinal α-glucosidase enzyme, specifically sucrase (Akkarachiyasit et al., 2010; Huang et al., 2022). Additionally, the incorporation of anthocyanin-rich black rice extract powder increased the lipase inhibitory activity of the cake in a concentration-dependent manner, indicating the potential role of anthocyanins in slowing down the fat digestion rate within the cake matrix (Huang et al., 2022).

Moreover, introducing anthocyanin-rich black rice extract powder to the batter cake improved the total polyphenol and anthocyanin content, specifically C3G and P3G. This enhancement contributed to elevated DPPH radical scavenging activity and hydroxyl radical scavenging activity, indicating heightened antioxidant properties (Huang et al., 2022). However, it is crucial to acknowledge that the baking process resulted in some degradation of anthocyanins due to exposure to high temperatures. At the 2% fortification level, approximately 75% of initial amount added to the formulation degraded during baking (Huang et al., 2022). Despite this degradation, anthocyanin-fortified foods like batter cakes hold potential therapeutic applications in reducing postprandial glucose levels or enhancing plasma antioxidant capacity for individuals who consume these types of cakes.

Yogurt

Probiotic dairy products, especially yogurt, have shown promise in reducing postprandial blood glucose levels through mechanisms like inhibiting α-amylase and α-glucosidase enzymes, regulating glucose utilization, and influencing incretin secretion (Chen et al., 2014; Panwar et al., 2014). These positive effects are attributed to the direct action of probiotic cultures and the presence of bioactive peptides in these products. Nonetheless, the growth and proliferation of beneficial bacteria in probiotic dairy requires prebiotics, which generate short-chain fatty acids (SCFAs) as an energy source for the bacteria (You et al., 2022). Recent studies have unveiled that black rice extract and C3G possess prebiotic properties, fostering the growth of *Bifidobacteria* and *Lactobacilli*, and promoting the production of organic acids, including phenolic acids and SCFAs (Zhu et al., 2018). These findings imply that the anthocyanins in black rice can be utilized by beneficial bacteria. The presence of β-D-glucosidases in probiotics may contribute to the breakdown of anthocyanins, releasing phenolic compounds that act as an energy source for bacterial growth. Additionally, the insoluble dietary fiber from black rice, which comprises approximately 75% of its total dietary fiber (Marlett et al., 2002), is noteworthy as it facilitates the conversion of C3G into potent phenolic compounds, amplifies the production of SCFAs, and influences the gut microbiota, particularly *Prevotella* and *Bacteroides* (S. Zhang et al., 2023a, 2023b). These microorganisms release enzymes like β-D-glucosidases, crucial in the deglycosylation of anthocyanins. Interestingly, the combination of soluble dietary fibers with C3G helps retain the antioxidant active components and further enhances the production of SCFAs. This is associated with a higher relative abundance of the gut microbiota *Bifidobacterium* and *Lactobacillus* after 24 h of in vitro colonic fermentation (Yang et al., 2021). This discovery underscores the synergistic interplay between dietary fiber and anthocyanins in black rice, contributing to the promotion of gut health. It emphasizes the importance of consuming whole black rice, with its anthocyanins and dietary fiber, for optimal enhancement of gut microbiota and SCFA production, surpassing the effects observed with black rice extract alone.

Recent research has explored the potential for fortifying probiotic yogurt containing *Bifidobacteria* and *Lactobacilli* with black rice extract (0.125%—0.25% w/w) (Anuyahong et al., 2020a). Surprisingly, even at these low concentrations, the viability of *Lactobacilli* remained largely unaffected. Incorporating black rice offers several advantages, including increased levels of polyphenols, anthocyanins, and antioxidant activity in the yogurt. Additionally, it improves the yogurt's water-holding capacity, resulting in decreased syneresis. This effect is attributed to the interaction between polyphenols in the extract powder and proteins, leading to a firmer gel network. Notably, C3G and P3G present in the fortified yogurt remain intact even after simulated digestion, suggesting their potential role in enhanced antioxidant activity. It is worth noting that incorporating black rice extract at a concentration of 0.25% proved effective in enhancing the beneficial phytochemical compounds and antioxidant activity in yogurt without compromising its sensory characteristics, including flavor, texture, and overall acceptability.

Puddings

Black rice pudding is an exemplary low glycemic food, specifically tailored to the needs of the elderly population. This makes it a suitable option for elderly individuals facing challenges in consuming regular textured food, which can put them at a risk of malnutrition (Suttireung et al., 2019). This unique pudding is crafted by combining black rice powder and purple sweet potato powder, boasting a fiber content of 0.8 g per 100 g of the sample. The pGI of this product is 51, with a percent hydrolysis index of 21, indicating a moderate level of starch breakdown. Additionally, in line with the texture classification of the International Dysphagia Diet Standard Initiative (IDDSI), the pudding is categorized as Level 3-moderately thick, facilitating better control and consumption for individuals with swallowing challenges.

Potential applications of black rice and its food products and clinical research on managing postprandial glycemia and lipidemia

While promising findings from food studies pave the way, substantial clinical research is required to solidify the impact of black rice and its food derivatives on postprandial glycemia and lipemia. Existing studies have shown encouraging results in this regard. These benefits extend beyond just post-meal responses potentially contributing to a balanced antioxidant defense system within the body. Table 4 summarizes compelling clinical evidence showcasing the impact of black rice and its food products, encompassing both short-term postprandial effects as well as potentially longer-term health outcomes.

Table 4 Clinical findings of different black rice food product consumption in human subjects

Food products	Interventions	Subjects	Clinical findings	References
Streamed black rice	100 g black rice vs. white rice	Healthy ($n = 6$, males)	Gastric emptying rate ↓ Postprandial glucose ↓ GIP ↑ GLP-1 ↔ (vs white rice) GLP-1 ↔ (vs baseline) Postprandial insulin ↔	Muangchan et al., 2022
	200 g black rice vs. white rice (pre-exercise study)	Healthy ($n = 12$, males)	Postprandial glucose ↓ (vs white rice) GLP-1 ↔ (vs white rice) GLP-1 ↑ (vs baseline) Fullness ↑ and hunger ↓ (after exercise)	Silalertdetkul, 2023
	50 g available carbohydrate black rice vs. white rice (Overnight soaking method)	Healthy ($n = 10$, young females)	Postprandial glucose ↔	Zhu et al., 2019
	100 g black rice (149–806 mg GAE, and 711–614 mg cyanidin/100 g) vs. brown rice	Healthy ($n = 19$, 11 male, 8 females)	Postprandial polyphenols and flavonoid ↑ Postprandial antioxidant capacity ↑	Vitalini et al., 2020
Boiled black rice	100 g black rice vs. white rice	Children with type 1 diabetes ($n = 8$, 4 males and 4 females)	Postprandial glucose ↓	Colasanto et al., 2023
Black rice waffle	100 g black rice waffle vs. wheat waffle	Healthy ($n = 10$, males and females)	Postprandial glucose ↔	Tongkaew et al., 2021
Black rice bread	50 g available carbohydrate black rice bread vs. white rice bread	Healthy ($n = 16$, 6 males and 10 females)	Postprandial glucose ↓ Postprandial insulin ↓ GLP-1 ↔ Postprandial antioxidant capacity ↑ Postprandial malondialdehyde ↔ Fullness and hunger ↔	Chusak et al., 2020
BRAE-fortified wheat bread	4% BRAE-fortified wheat bread (127 mg C3GE/100 g) vs control wheat bread (50 g available carbohydrate)	Healthy ($n = 22$, males and females)	Postprandial glucose ↔ Postprandial insulin ↓	Ou et al., 2023b
	A high-carbohydrate/high-fat mixed meal prepared with 4% BRAE-fortified wheat bread (127 mg C3GE/100 g) vs control wheat bread (50 g available carbohydrate)	Healthy ($n = 24$, males and females)	Postprandial glucose ↔ Postprandial insulin ↔ Postprandial triglyceride, cholesterol ↔ Postprandial lipoprotein profiles (LDL ↔, HDL ↑, Apo-A1 ↑, Apo-B ↑	
Black rice probiotic yogurt	350 g black rice probiotic yogurt (0.25% w/w black rice extract containing 17.4 mg C3G, 7.9 mg P3G) vs. control yogurt	Healthy ($n = 19$, 8 males and 11 females)	Postprandial glucose ↓ Postprandial plasma antioxidant capacity↑ Postprandial malondialdehyde ↓ Fullness and hunger ↔	Anuyahong et al., 2020b

Table 4 (continued)

Food products	Interventions	Subjects	Clinical findings	References
Black rice beverage	A high-carbohydrate and moderate-fat meal + 2 g black rice beverage (134 mg GAE, 4 mg C3G, and 1.6 mg P3G) vs. control beverage	Overweight and obese men (*n* = 13)	Postprandial glucose ↓ Postprandial insulin ↓ Postprandial triglyceride ↓ Postprandial plasma antioxidant capacity ↑ Postprandial malondialdehyde ↓ Postprandial pro-inflammatory cytokines (IL-1β, IL-6 and TNF-α) ↓ Fullness and hunger ↔	Anuyahong et al., 2022
Black rice extract supplementation	500 mg black rice extract twice daily, 12-week study vs placebo	Obese postmenopausal women (*n* = 88)	Trunk fat, total fat mass ↓ (vs placebo) Trunk fat, total fat mass, BMI, weight, visceral fat area ↓ (vs baseline) Triglyceride ↓ (vs placebo) Fasting plasma glucose ↔	Jung et al., 2021
Black rice extract supplementation	Black rice extract (320 mg anthocyanins), 28-day study vs placebo	Hypercholesterolemic individuals (*n* = 52, males and females)	LDL, HDL, cholesterol, triglyceride ↔ Fasting plasma glucose and fructosamine ↔	Aboufarrag et al., 2022

↓: Decrease, ↑: Increase, ↔: No significant change, *GIP* Gastric inhibitory polypeptide, *GLP-1* Glucagon-like peptide 1, *LDL* low-density lipoprotein, *HDL* high-density lipoprotein, *Apo-A1* Apolipoprotein-A1, *Apo-B* Apolipoprotein-B, *IL-1β* Interleukin-1 beta, *IL-6* Interleukin-6, *TNF-α* Tumor necrosis factor-alpha, *BMI* Body mass index, *BRAE* Black rice anthocyanin extract, *C3G* Cyanidin-3-glucoside, *P3G* Peonidin-3-glucoside. Total phenolic content (TPC) and total anthocyanin content are expressed as gallic acid equivalent (GAE) and cyanidin-3-glucoside equivalent (C3GE), respectively

Streamed and boiled black rice

Mungchan et al. investigated the influence of black rice on post-meal glucose levels and the regulation of glucose-related hormones in a study involving healthy volunteers (Muangchan et al., 2022). The participants consumed either 100 g of steamed black rice (with a carbohydrate content of 75.5 g and fiber content of 4.1 g) or steamed white rice (with a carbohydrate content of 79.4 g and fiber content of 1.7 g). Remarkably, those who consumed black rice exhibited a significantly decelerated gastric emptying rate alongside lower levels of postprandial plasma glucose compared to those who consumed white rice. This impressive effect can be attributed to the inherent fiber content present in black rice, contributing to a delayed gastric emptying process facilitated by the modulatory action of glucose-dependent insulinotropic polypeptide (GIP), a hormone produced by enteroendocrine K-cells in the intestines. It is noteworthy that this process occurs without interfering with insulin or glucagon-like peptide 1 (GLP-1) levels. These findings reveal not only the potential of black rice consumption for managing postprandial blood glucose levels and gastric emptying but also provide valuable insights into the critical role of dietary fiber in optimizing physiological responses to food.

Silalertdetkul (2023) explored the potential benefits of consuming 200 g of black rice compared to white rice on GLP-1 levels in participants engaging in cycling at 80% of their maximal heart rate. Remarkably, black rice consumption resulted in an increased secretion of GLP-1 within 30 min post-consumption, with elevated levels persisting even 30 min after exercise. This finding contrasts with the study by Mungchan et al. (2022) where participants consumed half the amount of black rice (100 g). While the Mungchan et al. study did not observe the same magnitude of GLP-1 increase, it did demonstrate positive effects on postprandial glycemia and gastric emptying. Consequently, this disparity in consumption showcased its influence by manifesting as an amplified perception of fullness following black rice ingestion, corresponding with the concurrent suppression of hunger perception immediately subsequent to exercise (Silalertdetkul, 2023). These observations collectively suggest that the incorporation of black rice into the pre-exercise diet holds the potential to stimulate the release of appetite-related hormones, notably GLP-1, and promote an enhanced sense of fullness, while concurrently reducing the surge in glucose concentration and mitigating hunger perception. By prolonging appetite-related hormone release like GLP-1 through black rice consumption, appetite control could improve. This potentially leads to reduced food intake and can aid in weight management (Hazell et al., 2016). This emphasizes the potential of black rice as a valuable nutritional resource for improving metabolic health and addressing weight-related concerns.

The study by Colasanto et al. (2023) investigated the effects of black rice on blood sugar levels (glycemia) after meals in children with type 1 diabetes, a condition where the body cannot produce insulin. Children who consumed 100 g of boiled white rice experienced a significant spike in postprandial glucose, whereas those who consumed 100 g of boiled black rice had a lower rise in postprandial glucose at all measured points. The average peak blood glucose level after boiled black rice consumption is below 180 mg/dL. The improved glycemic response of black rice can be attributed to several factors, such as higher fiber content and the presence of antioxidants like anthocyanins. These components contribute to a slower rate of carbohydrate digestion, leading to more controlled postprandial glucose levels after consumption. This study supports existing evidence suggesting that black rice could be a beneficial dietary option for individuals with type 1 diabetes, assisting in the management of glycemic responses.

Contrasting postprandial responses have been observed with various methods of cooking black rice (Zhu et al., 2019). Soaking black rice overnight before cooking results in similar postprandial glucose in healthy subjects, leading to a high glycemic index (GI) classification, comparable to white rice. Interestingly, the duration of cooking time itself did not significantly affect blood sugar levels or the GI of black rice. It seems that the pre-soaking treatment effectively addressed black rice's natural difficulty absorbing water, potentially leading to increased starch gelatinization and consequently a higher glycemic response (He & Suzuki, 1987). Careful selection for black rice varieties, minimal time for pre-soaking, and precise cooking techniques may contribute to efficiently managing postprandial glycemic responses in individuals with impaired glucose regulation.

Black rice consumption also enhances the body's antioxidant capacity after meals (Vitalini et al., 2020). Studies involving healthy individuals showed that eating 100 g each of two black rice varieties (Venere and Artemide) significantly increased their antioxidant activity compared to brown rice (Carnaroli). This increased antioxidant capacity is likely due to the presence of anthocyanins and other phenolic compounds in black rice. The results aligned with varieties' phenolic content. Venere and Artemide cultivars contained higher levels of polyphenols (149 and 806 mg of gallic acid/100 g, respectively) compared to Carnaroli rice (29 mg of gallic acid/100 g). This translated to an elevation of total phenolics and flavonoids in the blood plasma following black rice consumption, with peak concentrations observed at

60 and 120 min after the meal. Therefore, incorporating black rice with a meal rich in lipids and/or carbohydrates may contribute to mitigating postprandial oxidative stress and promoting overall diet-related health benefits in humans, potentially by maintaining a balanced cellular environment (Sies et al., 2005).

Food products made from black rice flour

The study by Tongkaew et al. explored a new gluten-free waffle made from black rice flour and its effects on postprandial glucose responses in humans (Tongkaew et al., 2021). Interestingly, the black rice flour used contained a substantial amount of total phenolic compounds, measuring 3,014 μg/g gallic acid equivalent. However, this phenolic content dropped significantly to 83 μg/g gallic acid equivalent when the black rice flour was transformed into cooked waffles. To understand how these black rice waffles affect postprandial glucose, researchers conducted a comprehensive human study. Participants consumed 100 g of the black rice waffle and a waffle made from wheat flour for comparison. Surprisingly, both the black rice waffle and the wheat waffle showed similar postprandial glycemic responses, with high GI values (94.73 ± 7.60 for black rice waffle and 91.96 ± 6.93 for wheat waffle). This similar response suggests that the waffle's overall composition, which includes tapioca flour, corn flour, and glutinous rice flour, may play a role in the glycemic response. Despite the high GI of both waffles, the black rice waffle's similarity to the wheat waffle highlights the complexities of managing blood sugar levels Nevertheless, these results do not diminish the significance of the black rice waffle, particularly for people with celiac disease (Aljada et al., 2021). Celiac disease is an autoimmune disorder triggered by gluten. Due to its unique features, like the initial high phenolic content, the black rice waffle remains a valuable option for those seeking gluten-free alternatives, even though its glycemic impact may be comparable to other options. This study contributes to the diversification of dietary options for people with gluten restrictions.

The subsequent study by Chusak et al. (2020) explored the impact of black rice bread on postprandial glucose, insulin, and antioxidant levels in healthy individuals, comparing it with wheat bread and white rice bread (Chusak et al., 2020). Compared to white rice bread, black rice bread consumption resulted in a significant decrease in both postprandial plasma glucose and insulin levels. Interestingly, there wasn't a significant difference between black rice bread and wheat bread in this effect. Surprisingly, there was no observable increase in postprandial GLP-1 for any of the bread types. The GI of black rice bread was approximately 69, while wheat bread was 77 and white rice bread was a much higher 130. Black rice bread's lower blood sugar response compared to white bread is likely due to its unique starch composition, especially the presence of undigestible starch. Additionally, black rice bread's ability to suppress an enzyme that breaks down carbohydrates (intestinal α-glucosidase) and the presence of beneficial compounds contribute to this reduced postprandial glucose effect. Fascinatingly, consuming black rice bread resulted in the highest the ferric-reducing ability of plasma (FRAP) value, a measure of blood antioxidant capacity, compared to the other breads. While FRAP levels decreased after consuming wheat and white bread, black rice bread consumption led to the highest increase in antioxidant capacity. The findings of this study highlight the advantageous potential of black rice bread, rich in antioxidants due to its polyphenol and anthocyanin content, in mitigating the oxidative stress associated with postprandial hyperglycemia during carbohydrate metabolism (Lamb & Goldstein, 2008). This is particularly relevant in reducing the risk of oxidative stress-induced degenerative diseases.

Food products supplemented with black rice extracts

A recent study by Ou et al. examined how black rice anthocyanin extract (BRAE) affects glycemic and lipidemic responses in healthy people. The study involved healthy individuals who consumed either plain wheat bread or wheat bread fortified with 4% BRAE, both alone and as part of a standardized high-carbohydrate/high-fat mixed-nutrient (beef burger) (Ou et al., 2023b). Both options provided the same amount of available carbohydrate content (50 g). The BRAE-fortified bread contained 127 mg of C3G/100 g. The results indicated a slight improvement in postprandial glucose and insulin responses when people consumed BRAE-fortified bread compared to plain wheat bread. While this improvement was not statistically significant, the GI did decrease from 95 for plain bread to 68 for BRAE-fortified bread. This effect is likely due to anthocyanin in BRAE inhibiting α-amylase and α-glucosidase enzymes, which slows down carbohydrate digestion (Akkarachiyasit et al., 2010; Ou et al., 2023b). Interestingly, when the 4% BRAE-fortified bread was included as part of the high-carbohydrate/high-fat meals, it did not significantly affect postprandial glucose and insulin responses, even though both options had the same amount of available carbohydrates. This suggests that the complex mix of foods in a meal can influence how effectively the body absorbs and utilizes anthocyanins from BRAE.

The study also tested BRAE's ability to block fat digestion in vitro experiment. The study found that adding BRAE to the high-carb/high-fat meal significantly reduced the activity of fat-digesting enzymes by 62% compared to the control meal. However, BRAE did not significantly impact postprandial triglyceride, total cholesterol, and low-density lipoprotein (LDL) responses to the meal, it did increase levels of high-density lipoprotein (HDL), apolipoprotein-A1, and apolipoprotein-B over a 4-h period in healthy subjects. Apolipoprotein-A1 is a major component of HDL particles and plays a critical role in reverse cholesterol transport (Chistiakov et al., 2016), while the synthesis of apolipoprotein-B is essential for postprandial clearance of triglycerides from chylomicrons in the intestines and endogenous triglyceride catabolism (Behbodikhah et al., 2021). These findings suggest that black rice anthocyanins may offer protection against dyslipidemia and potentially enhance hepatic and arterial clearance of excess lipids.

Another study investigated the postprandial glycemic response and antioxidant capacity after black rice probiotic yogurt consumption. Participants consumed a standardized 350 g of black rice yogurt, formulated with whole milk, skimmed milk powder, sucrose, and a 0.25% w/w anthocyanin-rich extract from black rice (Anuyahong et al., 2020b). The yogurt fermentation process involved a defined consortium of probiotic bacteria, including *Streptococcus thermophilus*, *Lactobacillus delbrueckii* subsp.bulgaricus, *Lactobacillus acidophilus* LA-5 and *Bifidobacterium animalis* subsp. lactis BB-12. Significantly, black rice yogurt consumption led to a reduction in postprandial blood glucose levels. This effect is likely attributable to the yogurt's unique phytochemical profile, potentially including anthocyanins, phenolic acids, and dietary fiber, which have demonstrated inhibitory effects on α-amylase and α-glucosidase enzymes in the small intestine. The black rice yogurt exhibited substantial antioxidant capacity, suggesting potential benefits in mitigating oxidative stress associated with postprandial hyperglycemia. This is likely due to the presence of bioactive compounds in black rice, such as anthocyanins and phenolic acids, which act as free radical scavengers and enhance overall plasma antioxidant activity. Consumption of the yogurt also resulted in reduction in malondialdehyde (MDA) levels, a marker of lipid peroxidation and oxidative stress. Interestingly, despite the potential of anthocyanins to stimulate glucagon-like peptide-1 (GLP-1) secretion in vitro (Kato et al., 2015), consuming black rice yogurt did not appear to influence subjective feelings of hunger in healthy adults. Two possible explanations exist for the absence of observed hunger influence. Firstly, the yogurt may have possessed a relatively low anthocyanin content, potentially limiting their bioavailability and subsequent impact on GLP-1 secretion (Anuyahong et al., 2020b). Bioavailability refers to the proportion of a substance that enters the bloodstream and can exert its effects.

A recent clinical trial by Anuyahong et al. (2022) investigated the effects of a black rice extract beverage on various physiological markers in overweight/obese individuals after consuming a high-carbohydrate, moderate-fat meal. Participants received a controlled diet with 67% of energy from carbohydrates, 25% from fat, and 6% from protein. Alongside this diet, they consumed a beverage containing 2 g of black rice extract dissolved in a 400 mL sugary drink (10% sucrose). The postprandial response was monitored for a period of 6 h. Significantly, consuming the black rice beverage led to a suppressed peak in both postprandial glucose and insulin levels after the high-carbohydrate, moderate-fat meal. This was accompanied by an enhancement in overall plasma antioxidant capacity. Increased levels of FRAP, Trolox equivalent antioxidant capacity, and sulfur-containing antioxidant molecules, coupled with reduced MDA, point towards this beneficial effect. These findings suggest that the polyphenols, flavonoids, and anthocyanins in black rice extract may help defend against oxidative stress induced by high-carbohydrate and moderate-fat meals in overweight/obese individuals (Gregersen et al., 2012).

The black rice beverage effectively reduced postprandial triglyceride concentrations at both 3 and 6 h marks after meal. These decreases coincided with lower levels of pro-inflammatory cytokines IL-1β, IL-6, and TNF-α. The way this might work is by the black rice extract, particularly anthocyanins, interfering with how fat is broken down and absorbed in the gut. Anthocyanins in black rice seems to block pancreatic lipase, prevent cholesterol from forming structures for absorption, and bind to bile acids (Poosri et al., 2019; Yao et al., 2013). These combined effects help reduce the post-meal surge of fats in the blood, leading to lower inflammation and potentially a reduced overall inflammatory response (Masson & Mensink, 2011; Morandi et al., 2017). This suggests that anthocyanin-rich black rice has promising potential as a new ingredient for functional beverages. Black rice anthocyanins may offer a multi-faceted approach for managing postprandial hyperglycemia and hyperlipidemia, while concurrently mitigating the rise in pro-inflammatory cytokines.

Black rice extract supplementation

A recent study by Jung et al. (2021) investigated the potential of black rice extract as a natural approach to weight management in obese postmenopausal women. (Jung et al., 2021). The study aimed to determine if a daily dosage of 1000 mg of black rice extract (500 mg twice daily) could induce weight loss in comparison to a placebo group. The key findings demonstrated significant reductions in trunk fat (both in mass and as a percentage), total fat (both in mass and as a percentage), and triglyceride levels in the group supplemented with black rice extract when compared to placebo. These improvements are noteworthy because they are associated with a decreased risk of heart disease and other metabolic complications (Lee et al., 2017). While body weight, body mass index, and visceral fat area significantly decreased after 12 weeks in the black rice-treated group, these parameters did not exhibit significant differences between the groups at the end of the study. These less favorable results could be attributed, at least in part, to the relatively short duration of the study and the intricate nature of obesity during the postmenopausal phase. In light of these findings, black rice extract demonstrates promise as a potential approach for reducing body fat; however, its broader impact on other metabolic biochemical markers requires further comprehensive and extended investigations.

Despite the potential benefits suggested by previous studies, a noteworthy long-term investigation by Aboufarrag et al. examined the effects of a black rice extract containing 320 mg of predominantly cyanidin/dihydroxy-type anthocyanins on hypercholesterolemic individuals (Aboufarrag et al., 2022). The study aimed to evaluate various biomarkers associated with CVD risk over a 28-day period. However, contrary to some expectations, it revealed that supplementation with black rice extract did not lead to significant changes in LDL, other cardiovascular risk-related biomarkers, HDL functionality, or glycemic control among individuals. The study did not report any serious adverse events. The complex interplay of factors influencing outcomes, in such studies intervention's duration, dosage, genetic variability, and the potential difference in impact between whole foods and isolated compounds, highlights the need for further investigation into the potential benefits of black rice on cardiovascular health.

Conclusion

Black rice and its food products are abundant sources of phytochemical compounds, primarily anthocyanins. Both in vitro and clinical studies demonstrate the potential of black rice and its derivatives to effectively manage postprandial glycemic and lipidemic responses, presenting an avenue ripe for further investigation. Although existing long-term studies underline the positive effects of black rice on metabolic responses, certain aspects remain inconclusive and require in-depth exploration. Additional research is imperative, concentrating on pivotal scientific aspects. Firstly, determining the ideal dosage and duration of consumption is essential for establishing a well-defined dose–response relationship regarding health benefits. Comprehensive long-term studies are essential to evaluate sustained effects over extended periods, while also accounting for individual variabilities such as such as obesity, diabetes, hypertension, and other non-communicable diseases (NCDs). Equally important is the examination of their effects on inflammation, oxidative stress, and other cardiovascular risk factors to provide a holistic understanding of their potential contributions to overall health. It is imperative to monitor the potential adverse effects of long-term consumption of black rice, whether as part of a regular diet or as food products derived from black rice and its extracts. Finally, translating these research findings into practical recommendations and tailored dietary strategies for diverse populations, including individuals with distinct metabolic profiles and specific cultural preferences, will undoubtedly increase their relevance in real-world contexts.

Abbreviations

BRAE	Black rice anthocyanin extract
C3G	Cyanidin-3-glucoside
C3R	Cyanidin-3-rutinoside
CVDs	Cardiovascular diseases
FRAP	Ferric-reducing ability of plasma
GIP	Gastric inhibitory polypeptide
GLP-1	Glucagon-like peptide 1
GLUT2	Glucose transporter 2
HDL	High-density lipoprotein
IL-1β	Interleukin-1 beta
IL-6	Interleukin-6
TNF-α	Tumor necrosis factor-alpha
LDL	Low-density lipoprotein
M3G	Malvidin-3-glucoside
NF-κB	Nuclear factor-κB
NPC1L1	Niemann-Pick C1 Like 1
P3G	Peonidin-3-glucoside
GI	Glycemic index
pGI	Predicted glycemic index
ROS	Reactive oxygen species
RS	Resistant starch, SCFAs; short-chain fatty acids
SGLT1	Sodium-dependent glucose transporter 1
TLR	Toll-like receptors

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Authors' contributions

T.T.: conceptualization, validation, visualization, writing—original draft, and writing—review & editing. T.S.: software; writing—original draft, and writing—review & editing. C.C. and P.S.: roles/writing—original draft. S.A.: conceptualization, funding acquisition, resources, supervision, visualization, writing—original draft, and writing—review & editing. All authors read and approved the final manuscript.

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