

Processing effects on the nutritional and phytochemical properties of pigmented rice products: A comprehensive review

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ABSTRACT

Pigmented rice is rich in nutraceuticals and encompasses bioactive compounds such as anthocyanins and flavonoids. The bran layers of coloured rice grains, such as black and red rice, contain phenolic compounds. The health benefits of phenolic compounds of pigmented rice include their antioxidant, anticarcinogenic, antiallergic, anti-inflammatory, anti-atherosclerotic, and hypoglycemic actions. Consumption of pigmented rice can help reduce the risk of chronic diseases due to its high antioxidant capacity. This review emphasises the impact of various processing steps, such as milling, cooking, thermal treatments, fermentation, extrusion, and novel processing methods, on the retention of nutrients and bioactive compounds in pigmented rice. Rice milling intensity is influential, with minimal milling retaining significantly higher levels of phenolic compounds and nutrients. Thermal processing yields different effects, such as steaming preserves 85-90% of the anthocyanins, while boiling results in 40-50% losses. Among ready-to-eat forms, popped rice retains more phenolics than puffed or beaten rice, though toasting increases bound polyphenols at the expense of soluble forms. Innovative methods such as cold extrusion and fermentation can further enhance the functional value of pigmented rice. Future research should focus on standardising processes and evaluating storage stability to support their wider adoption as health-promoting foods.

1. Introduction

Consumers are increasingly interested in pigmented rice varieties, and demand is expected to grow further. The supply of rice pigment must be improved to meet existing dietary requirements, and opportunities in this value chain must be identified. The production of pigmented rice from landraces is insufficient to meet market demand, highlighting the need for genetic improvements in these materials. More than half of the world's population relies on rice as their primary food source. The production of pigmented rice from landraces is insufficient to meet market demand, highlighting the need for genetic improvements in these materials Food and Agriculture Organization of the United Nations (2019). Although white rice is enjoyed worldwide, several Asian nations also eat coloured rice such as red, black, purple, and brown rice (Samyot et al., 2017). Various pigmented rice varieties were found to have higher antioxidant capacities, attributed to their rich

phenolic and flavonoid content, especially when minimally processed (Shao et al., 2024). Different groups in Indian society enjoy various rice-based processed foods at breakfast, lunch, and dinner, including boiled, beaten, puffed, and popped rice (Pal et al., 2019). Generally, rice grains must be cooked for consumption, and high cooking temperatures may degrade bioactive substances and antioxidant properties in both pigmented and white rice (Massaretto et al., 2022).

The nutritional value and customer acceptance of coloured rice-based products can be significantly influenced by various processing techniques, including primary and secondary post-harvest methods such as milling, cooking, boiling, extrusion, puffing, and bioprocessing methods such as fermentation and germination. For instance, the outer layer of the rice grain, which contains the majority of pigments and bioactive substances, is removed during milling, a routine processing step. Therefore, the number of bioactive substances in the finished product can vary with the milling level. Reducing the degree of milling

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can help maintain the levels of anthocyanins and phenolic compounds in coloured rice (Choi et al., 2018). Pigmented types are qualitatively and quantitatively more abundant in polyphenolic structures than non-pigmented ones, which typically entirely contain phenolic acids. Procyanidins are characteristic of red rice in particular, although depending on the type, anthocyanins or both anthocyanins and procyanidins can be found in black rice (Zaupa et al., 2015). Pigmented rice contributes potential health benefits due to its antioxidant activity for protective effects against oxidative stress and chronic diseases (Cheng & Li, 2024; Paiva et al., 2016).

Pigmented rice is well known for a higher concentration of bioactive compounds, such as flavonoids, phenolic compounds, and anthocyanins, compared to non-pigmented rice. Cooking results in a profound reduction in bioactive compounds; specifically, in red rice, about 60% of phenolics are lost, while black rice retains more in selected cultivars (Massaretto et al., 2022). Post-harvest treatments and processing methods play a decisive role in determining the nutritional value. Rice milling removes the bran layer, leading to substantial losses of bioactive compounds and essential nutrients. Recent methods, such as microwave processing, preserve phenolics in black and purple rice (Bani et al., 2024). Despite inevitable nutrient loss during processing, pigmented rice continues to offer superior health-promoting properties, with higher antioxidant activity than white rice. Although pigmented rice is a rich source of bioactive compounds, processing it into diverse food products may affect its nutritive value and consumer acceptance. This study intends to assess how different processing techniques (such as milling, cooking, fermentation, extrusion, etc.) affect the nutritional benefits and customer acceptance of goods made from coloured rice. This review addresses a critical gap by systematically comparing how various processing methods, such as cooking, extrusion, fermentation, and germination, affect the nutritional, phytochemical, and sensory qualities of pigmented rice. Existing research is fragmented, often focusing on single methods or rice types, making it difficult to make practical recommendations. By synthesising recent, peer-reviewed studies, this review provides clear, evidence-based insights for researchers, industry, and policymakers. It highlights optimal processing strategies to maximise health benefits and consumer acceptance. It identifies key research gaps, such as conflicting data on phenolic retention after fermentation, thereby guiding future work and supporting the development of functional pigmented rice products.

2. Selection of references

References were systematically selected by searching authenticated databases, including Google Scholar, PubMed, Scopus, Web of Science, and ScienceDirect, using the keywords pigmented rice, processing methods, pigmented rice genotypes, functional foods, effects of processing on nutrients and bioactives, especially the effects of fermentation and germination. The recent research literature has prioritised underscoring research gaps and presenting results to highlight recent developments. During the search, both primary experimental research and comprehensive review articles were included for mechanistic insights and comparative analysis, and additional inclusion criteria included relevance to the rice genotype, processing impact, and quantitative outcomes using advanced analytical methods. This strategy aims to ensure transparent, recent studies and a comprehensive analysis of the most pertinent studies to functional food development.

3. Nutritional components of pigmented rice

Rice that has been coloured or pigmented is identified by a red, black (or purple or varied purple) aleurone layer and is filled with highly nutritious phytochemicals (Mbanjo et al., 2020; Samyor et al., 2017). The pigments of these pigmented rice varieties are made up of a variety of anthocyanins, and the colour of their grain ranges from different shades of red and purple to black (Tangsrinugul et al., 2019).

Consumption of coloured rice is growing due to its impact on human health, which is defined by the presence of phenolic compounds such as phenolic acids and anthocyanins (Shao et al., 2018). The potential health benefits of pigmented rice are presented in Fig. 1.

3.1. Macronutrients in pigmented rice

Pigmented rice varieties, such as black and red rice, contain higher levels of dietary fibre compared to white rice, which is important for digestive health and metabolic regulation (Idrishi et al., 2024; Tiozon et al., 2023). The protein content of pigmented rice is also superior in both quantity and quality compared with non-pigmented rice, supporting its role in addressing nutritional deficiencies. Fat content remains low and comparable across both pigmented and non-pigmented rice types (Sharma et al., 2024). Compared to non-pigmented rice, pigmented rice consistently demonstrates higher levels of dietary fibre, superior protein quality, and greater concentrations of micronutrients and bioactive compounds (Idrishi et al., 2024). While white rice is preferred for its sensory properties and shelf stability, it is nutritionally inferior due to the loss of bran and germ during milling, resulting in reduced phytochemical and micronutrient content (Bani et al., 2024). Pigmented rice is considered nutritionally richer in protein, dietary fibers and resistant starch and lipid-related bioactives than white rice; carbohydrate is the dominant staple (Oliveira et al., 2026). Pigmented rice is generally less digestible for its starch and dietary fiber compared to unpigmented rice. This contributes to lower glycemic response and slows down the increase in postprandial blood glucose level (Rebeira et al., 2022). It is demonstrated that red, black and purple rice have higher protein content than white rice. Lipid content in pigmented rice is not a distinguishing factor, but it contains saponifiable lipid fraction, including fatty acids and γ -oryzanol components in higher amounts than those in dehulled white rice (Tiozon et al., 2023). Although it is not a significant source of dietary fiber, the outer bran layer represents better lipid quality compared to normal white rice (Zhao et al., 2025). Pigmented rice generally had higher protein content and amino acid than normal white rice. Studies have shown that unpolished pigmented rice has more nutrients associated with bran and therefore has higher nutritional quality (Oliveira et al., 2026). Processing strongly affects nutrient retention in pigmented rice, especially during milling and cooking, significantly reducing fiber, protein and resistant starch depending on the type of processing (Farooq and Yu, 2025).

3.2. Micronutrients in pigmented rice

Pigmented rice is a notable source of essential micronutrients, including iron, zinc, and potassium, often with concentrations higher than those in white rice. These minerals are primarily located in the outer layers of the grain, which are better preserved in less-milled, pigmented varieties (Sharma et al., 2024). Pigmented rice is considered to be a significantly valuable source of micronutrients due to its improved micronutrient profile compared to non-pigmented white rice. These micronutrients are primarily concentrated in the bran layer, that are removed during processing and polishing of rice. Essential minerals, including iron, zinc, magnesium, phosphorus, selenium, copper and manganese and B-complex vitamins that contribute to human health (Tiozon et al., 2023). Iron content in pigmented rice has potential benefits over the non-pigmented rice, which ranges from 15-45mg/kg in black and red rice cultivars. The studies demonstrated that the iron content in colored rice is independent of anthocyanin pigment. Among pigmented Chinese rice varieties, red rice has the highest iron content, followed by purple, golden and white rice. Similarly, pigmented rice from the Philippines has higher levels of zinc, iron, manganese and phosphorus (Zhao et al., 2025). Iron content in black rice varieties of Northeast India encompasses 28.5mg/kg dry weight, whereas red rice showed 23.3mg/kg, which is three folds higher than normal white rice. It has been found that the presence of phytates may reduce iron

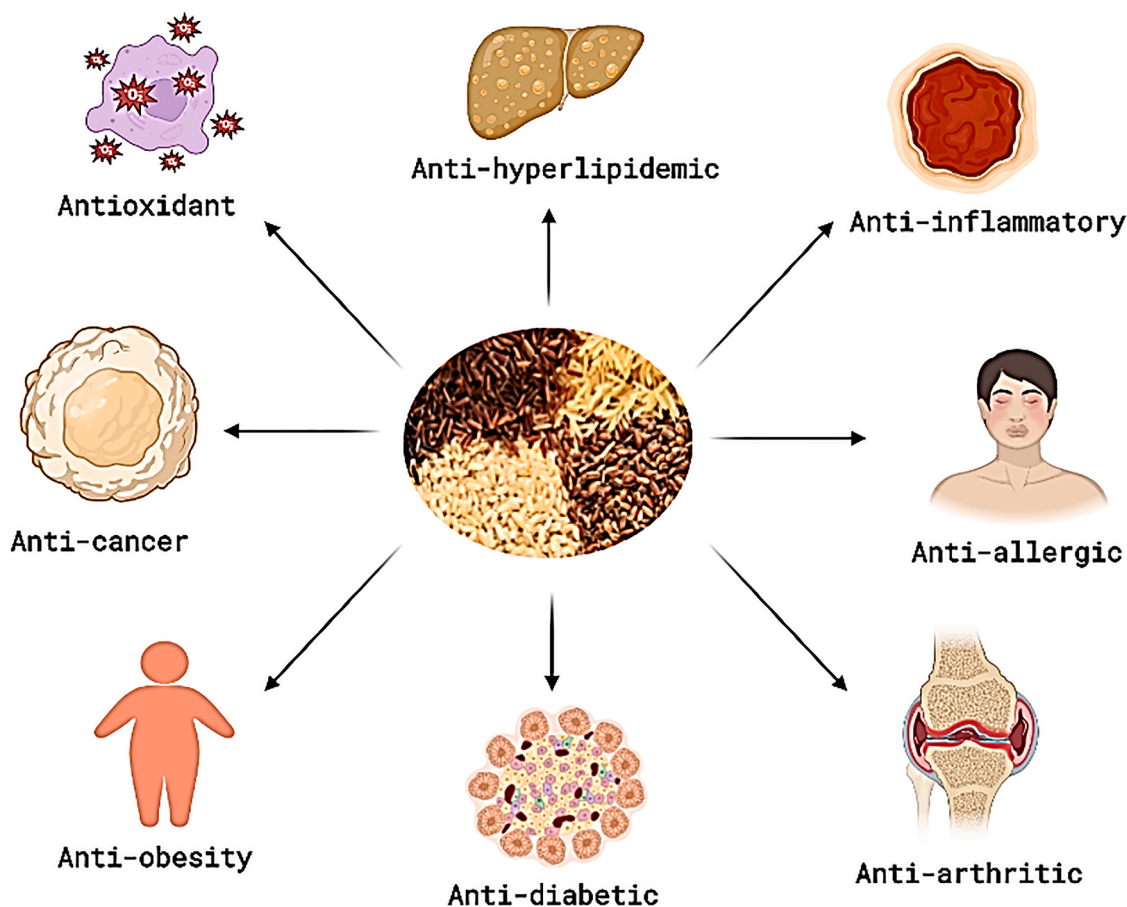


Fig. 1. Potential health benefits of pigmented rice.

absorption, and Vitamin C and other organic acids in the bran layer may partially counteract the antinutritional effect (Sudan et al., 2023).

Zinc represents another important micronutrient in pigmented rice, which demonstrates higher concentration, ranging from 20–35mg/kg, than white rice which contains 10–15mg/kg. Study unveiled that zinc accumulation in pigmented rice is genetically associated with metallothionein expression and zinc transporter genes (Verma et al., 2025). In a study, the pigmented rice varieties from India, the Philippines and China exhibited higher zinc content, about 26.8mg/kg; certain bio-fortified varieties reported 38mg/kg zinc through conventional breeding approaches. Bioavailability of zinc in pigmented rice is particularly influenced by phytate to zinc molar ratios (Gogoi et al., 2024). Pigmented rice consists significantly higher concentration of Vitamin E than white rice, which occurs in the form of tocopherol and tocotrienols. A study documented that black rice is a functional food due to its phytochemical profile, and total vitamin E content in black rice ranges from 150–250mg/kg, mostly in the form of tocotrienols, which are more biologically active than tocopherols. Moreover, γ -Tocotrienol is found to be the most abundant form in pigmented rice, which ranges from 80–150mg/kg; on the other hand, α -tocopherol usually ranges from 20–40mg/kg (Javed et al., 2025). It has been studied that Vitamin E content can be greatly influenced during processing, like milling, which may reduce it by 60–80% in all types of rice. This suggests the whole grain offers significant health benefits in lowering oxidative stress and inflammation (Zhao et al., 2025). Vitamins belonging to the B-group in pigmented rice, including thiamine (B1), riboflavin (B2), niacin (B3), pyridoxine (B6), and folate (B9), are higher compared with white rice. Thiamine content in the pigmented rice ranges between 2.5–3.5 mg/kg compared to 0.5–0.8 mg/kg in white rice, whereas riboflavin in pigmented rice ranges between 0.3–0.5 mg/kg and 0.05–0.1 mg/kg in white

rice, respectively (Duan et al., 2024). It is evident from the study that retention of B-vitamins in pigmented rice is positively associated with the retention of the bran layer during processing, such as milling and polishing. 20–30% of B vitamins are lost in polished white rice after milling. The folate content in pigmented rice ranges from 40–60 ug/100g in white rice, compared to 10–20 ug/100g in white rice. The biological activities of B-vitamins in pigmented rice plays significant role in energy metabolism and neurological processes (Zhao et al., 2025).

Pigmented rice is notably rich in macrominerals, consisting of magnesium in the range of 1000–1400 mg/kg and phosphorus from 2500–3500 mg/kg. A study showed that 150 grams of prepared pigmented rice provides 25–35% of the daily magnesium requirement (Liu et al., 2024). Study shows that the accumulation of magnesium in pigmented rice does not decrease when the plant is subjected to salt stress. Phosphorus is mainly present as myo-inositol hexaphosphate (phytic acid). Traditional preparation procedures, including soaking, fermentation, and germination, can lower phytate concentration by up to 30–50% (Oo et al., 2025). Pigmented rice is richer in trace minerals than white rice, specifically selenium, copper, and manganese. Selenium levels vary widely (0.02–0.08 μ g/g), which can be influenced by soil content and rice genotype (Tiozon et al., 2023). A study highlighted that selenium biofortification, especially via foliar application, can enhance concentrations to 0.1–0.2 μ g/g, enough for a single serving to cover 30–50% of daily needs. Copper (2–4 mg/kg) and manganese (10–20 mg/kg) are consistently elevated, often two to three times higher than in white rice. It is evident that minerals are not just nutritional extras: they serve as essential cofactors for antioxidant enzymes such as superoxide dismutase, helping the body neutralize harmful free radicals, and they support key metabolic pathways. In short, pigmented rice offers more than color; it provides a meaningful boost to trace mineral intake that

supports resilience and cellular health (Zhao et al., 2025).

3.3. Bioactive compounds in pigmented rice

The distinctive colouration of pigmented rice is due to its high levels of anthocyanins, flavonoids, and phenolic acids, potent antioxidant compounds (Sudan et al., 2023). Black rice, in particular, is recognised for its elevated anthocyanin levels, while red and brown rice are rich in various phenolic acids such as ferulic and protocatechuic acids. These bioactive compounds contribute to rice’s status as a functional food (Tiozon et al., 2023). The role of bioactive compounds present in various rice cultivars and the effect of these bioactive compounds on health are presented in Table 1. Pigmented rice contains plenty of bioactive compounds like anthocyanins, phenolics, flavonoids, proanthocyanins and γ -oryzanol, primarily present in the bran layer, which exhibits antioxidant, anti-inflammatory and anti-mutagenic properties (Hu, 2025; Kang et al., 2022). Total phenolics, flavonoids and antioxidant content increase during germination of pigmented rice improve nutritional quality of rice (Yamuangmorn & Saenjurn, 2024). Flavonoids in pigmented rice encompass quercetin, apigenin and myricetin glycosides present in the aleurone layer. Black rice consists of a 2-5 fold increased level over normal rice. Flavonoids possess strong antioxidant activity for superoxide quenching that directly correlates positively with total phenolic content. Roasting may enhance flavonoid extractability, synergizing with anthocyanins for improved DPPH inhibition (Pradipta et al., 2020).

Anthocyanins a strong flavonoid pigment commonly located in bran and pericarp layers, responsible for red, purple and black colour to pigmented rice with cyanidin-3-O-glucoside and peonidin-3-O-glucoside as dominant compounds in black and red rice (Jun et al., 2012). These bioactive compounds possess superior radical scavenging activity. Health benefits offered include anti-carcinogenic properties by inducing apoptosis in cancer, besides cardiovascular prevention by reducing oxidation of LDL and blood pressure control (Sharma et al., 2024). Treatment like germination enhances anthocyanins by 20-50% for improved bioavailability for functional foods (Jia et al., 2025). Pigmented rice varieties consists phenolic compounds includes ferulic acid, p-coumaric, vanillic and protocatechuic acids, present primarily in the bound form in the bran layer, make upto 60-80% of the total phenolics with enhanced antioxidant properties compared to non-pigmented rice (Gogoi et al., 2025). Phenolic acids exhibits by lipid peroxidation for antioxidant defence. Studies have shown that pre-treatments like germination and roasting enhance free phenolic content by 30%, thereby improving stability and gut absorption (Nafisah et al., 2023). Proanthocyanidins like procyanidins B1/B2 found in red rice tannins contribute 10-20 times the antioxidant activity of Trolox due to higher radical scavenging. It helps in gut modulation, inhibit α -amylase/ α -glucosidase for glycaemic control, and ion chelation to prevent oxidative damage. It has been shown to possess an anticancer mechanism by PAC-induced autophagy and metastasis blockade. Thermal processing has an effect on proanthocyanidins that polymerizes that reduces solubility but improving bioaccessibility in the colon (Kang

et al., 2022). Pigmented rice contains γ -Oryzanol, a ferulic acid ester of sterol possess hypocholesterolemic effect by alleviating CoA reductase and enhancing bile extraction. It has been found to scavenge peroxy radicals and protects erythrocytes from hemolysis. Synergistic relation with Phenolics amplifies LDL antioxidant protection by more than 70% inhibition. It is stable at roasting temperature and enhances the functional properties (Gogoi et al., 2025; Nafisah et al., 2023). The heatmap illustrating phytochemical compounds in different pigmented rice cultivars is presented in Fig. 2

3.4. Antioxidant activity of pigmented rice

Pigmented rice exhibits significant antioxidant activity, attributed to its phenolic and anthocyanin content, which neutralises reactive oxygen species and reduces oxidative stress (Mbanjo et al., 2020). Animal and in vitro studies indicate that regular consumption of pigmented rice can mitigate inflammation and may lower the risk of chronic diseases, including cardiovascular disease, type 2 diabetes, and certain cancers (Sharma et al., 2024). Anthocyanins, though present in milligram quantities, exert potent antioxidant effects at physiologically relevant doses, enhancing plasma antioxidant capacity and contributing to the reduction of oxidative stress and inflammation in vivo (Mbanjo et al., 2020). Pigmented rice is a good source of a variety of nutrients, including vitamins, minerals, carbohydrates, and protein. Pigmented rice has been discovered to contain more fibre, minerals, and antioxidants than white rice types. For instance, red and black rice have been found to contain higher levels of potassium, zinc, and iron than white rice (Saji et al., 2020). Additionally, coloured rice varieties exhibit stronger antioxidant activity than white rice varieties, which may help protect against oxidative stress and chronic illnesses (Kalita et al., 2021).

Pigmented rice, especially varieties rich in anthocyanins like black and purple rice, positively modulates gut microbiota composition. Studies show that anthocyanins from pigmented rice can increase beneficial bacteria such as *Bifidobacterium* and *Lactobacillus*, while also promoting a favourable shift in the Firmicutes/Bacteroidetes ratio, which is associated with improved gut health (Chakkaravarthi et al., 2025; Kraithong et al., 2025). The dietary fibre and polyphenols in pigmented rice are fermented by gut bacteria, leading to increased production of SCFAs (acetate, propionate, and butyrate). These metabolites are crucial for maintaining colon health and have anti-inflammatory properties. Components from rice bran, such as feruloylated arabinoxylan oligosaccharides (FAXO) and rice bran polyphenolics (RBPP), exhibit prebiotic-like properties. They enhance SCFA production and selectively promote the growth of beneficial microbiota, supporting a healthier gut environment (Verediano et al., 2021). The gut microbiome can bioconvert rice polyphenols into smaller phenolic acids, potentially increasing their bioavailability and health benefits. Beyond gut health, pigmented rice consumption is linked to anti-inflammatory, antioxidant, and anti-diabetic activities, suggesting broader systemic benefits (Mbanjo et al., 2020). Fermentation of pigmented rice significantly increases its antioxidant capacity by improving the extraction and

Table 1
Role of Bioactive compounds present in various rice cultivars on health.

Rice Type	Pigments	Main Phytochemical Compounds	Color	Potential Health Benefits	References
Black Rice	Anthocyanins	Cyanidin-3-glucoside, Peonidin-3-glucoside	Black/Purple	Antioxidant, anti-inflammatory, anti-cancer, anti-diabetic, improves cholesterol and liver function, supports immune health.	Rasool et al. (2024); Kong et al. (2023)
Red Rice	Proanthocyanidins, Anthocyanins	Catechins, Cyanidin, Delphinidin, Pelargonidin	Red	Antioxidant, anti-inflammatory, cardiovascular health, improves circulation, promotes healthy skin.	Baptista et al. (2024)
Purple Rice	Anthocyanins	Cyanidin-3-glucoside, Peonidin-3-glucoside	Purple	Antioxidants support eye health and cardiovascular benefits and enhance memory and cognitive function.	Duan et al. (2024)
Brown Rice	Flavonoids, Carotenoids	Lutein, Zeaxanthin, β -carotene	Light Brown	It supports eye health, antioxidant, and reduces the risk of chronic diseases like diabetes and hypertension.	Ghasemzadeh et al. (2018); Zhou et al. (2023)
White Rice	Minimal pigments	Trace amounts of flavonoids and other minor compounds	White	Lower in antioxidants compared to pigmented varieties, it provides quick energy and aids in digestive health.	Rebeira et al. (2024)

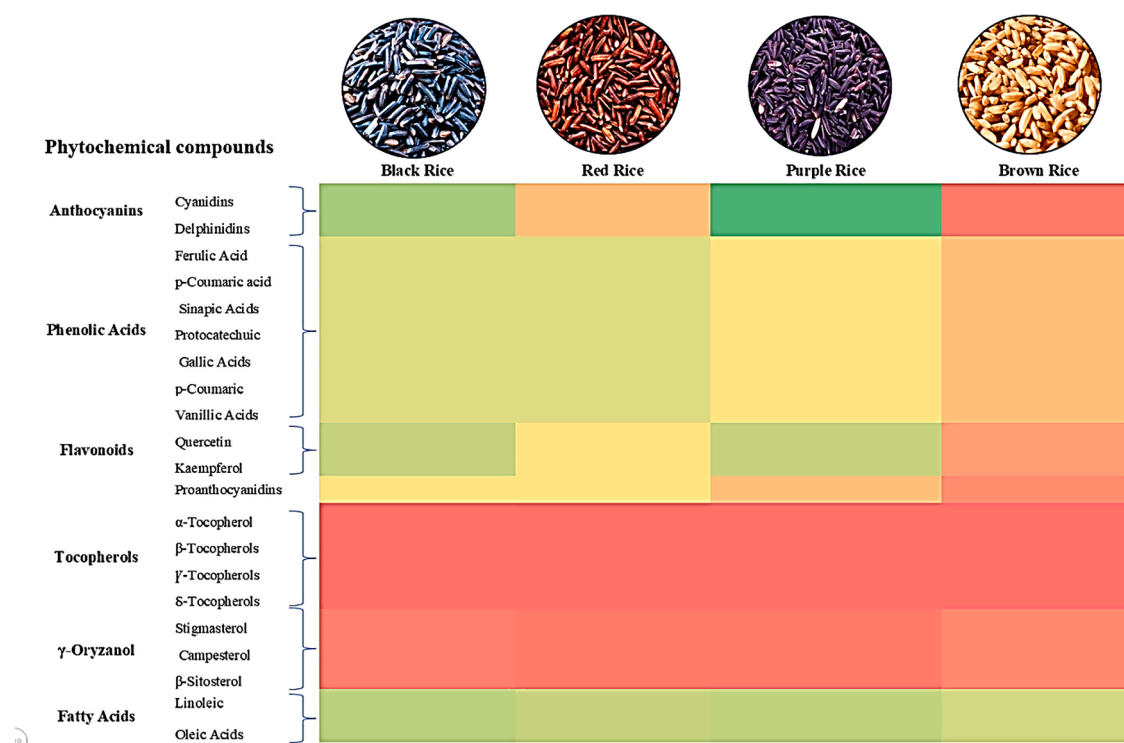


Fig. 2. Heatmap illustrating phytochemical compounds in different pigmented rice cultivars.

bioavailability of phenolic compounds and flavonoids, such as anthocyanins and proanthocyanidins (Cheirsilp et al., 2023). The fermentation process increases levels of health-promoting bioactive molecules, including phenolic acids and gamma-aminobutyric acid (GABA), which support stress reduction, improved sleep, and overall wellness. Fermenting pigmented rice increases fibre content and makes nutrients more bioavailable, supporting digestive health and potentially helping prevent constipation (Mishra et al., 2024).

4. Effect of various processing on the properties of pigmented rice

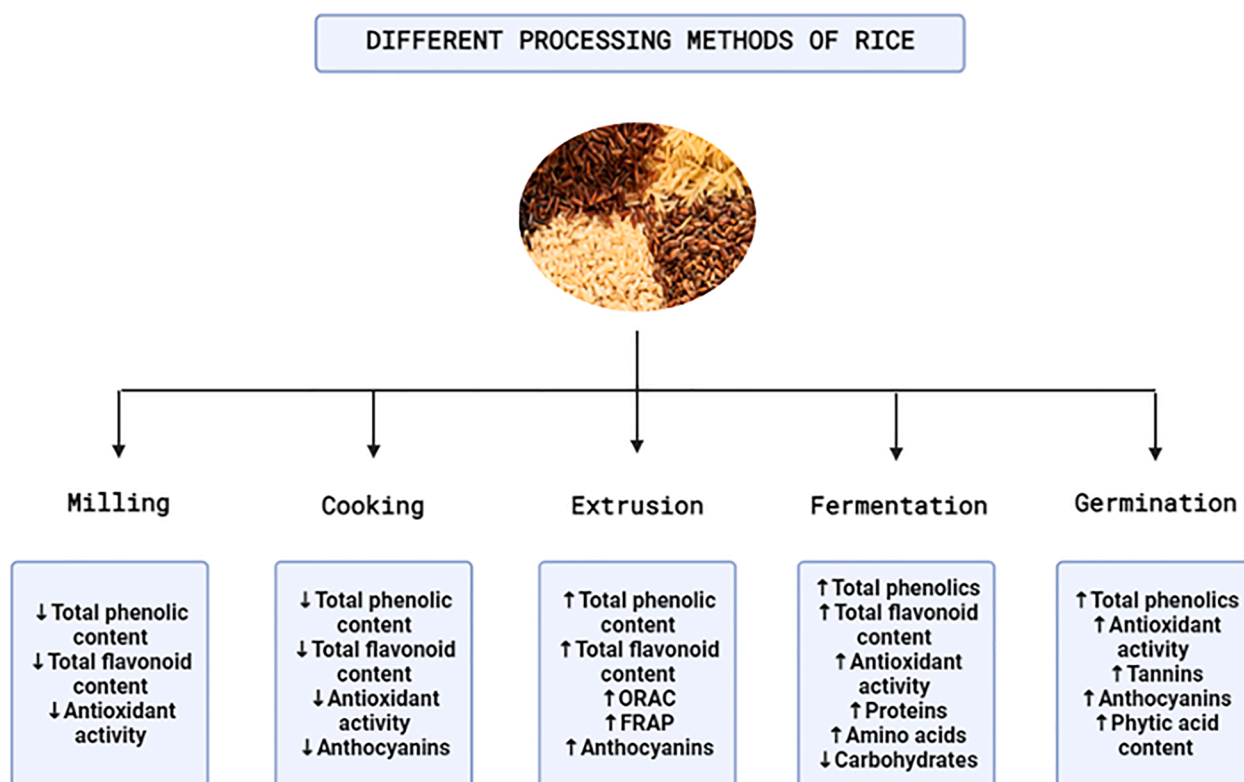
4.1. Effect of milling on nutritional properties

The effect of processing methods on bioactive compounds of pigmented rice is presented in Fig. 3(A), and the effect of various processing methods on biochemical, nutritional, and phytochemical changes is presented in Fig. 3(B). Varying levels of nutrients such as fat, fibre, protein, carbohydrates, and vitamins are concentrated in different parts of rice. The dehulling process alters the nutritional value of rice by removing various layers. The outer bran layer (pericarp), seed coat, and aleurone layer are eliminated during the milling of brown rice. Thus, a significant proportion of vitamins, minerals, fibre, essential fatty acids, and some proteins are destroyed during the milling process (Gul et al., 2015). The effect of milling on the nutritional value of pigmented rice showed that lower milling retained more anthocyanin, and a higher milling degree resulted in substantial nutrient losses. The nutritional value of raw and parboiled Ranjit rice, dehulled using modern milling techniques and the traditional “Dhenki” method, was compared by Kalita et al. (2021). The study revealed greater losses of fat, protein, and fibre in milled rice than in Dhenki dehulled rice. Nutritional content was enhanced by parboiling before dehulling, allowing nutrients such as iron and vitamins to diffuse from the hull into the grain. Carbohydrate content was influenced more than in raw rice. Research using animal models showed a slower digestion rate for Dhenki dehulled parboiled rice, indicating its potential as a source of healthy carbohydrates.

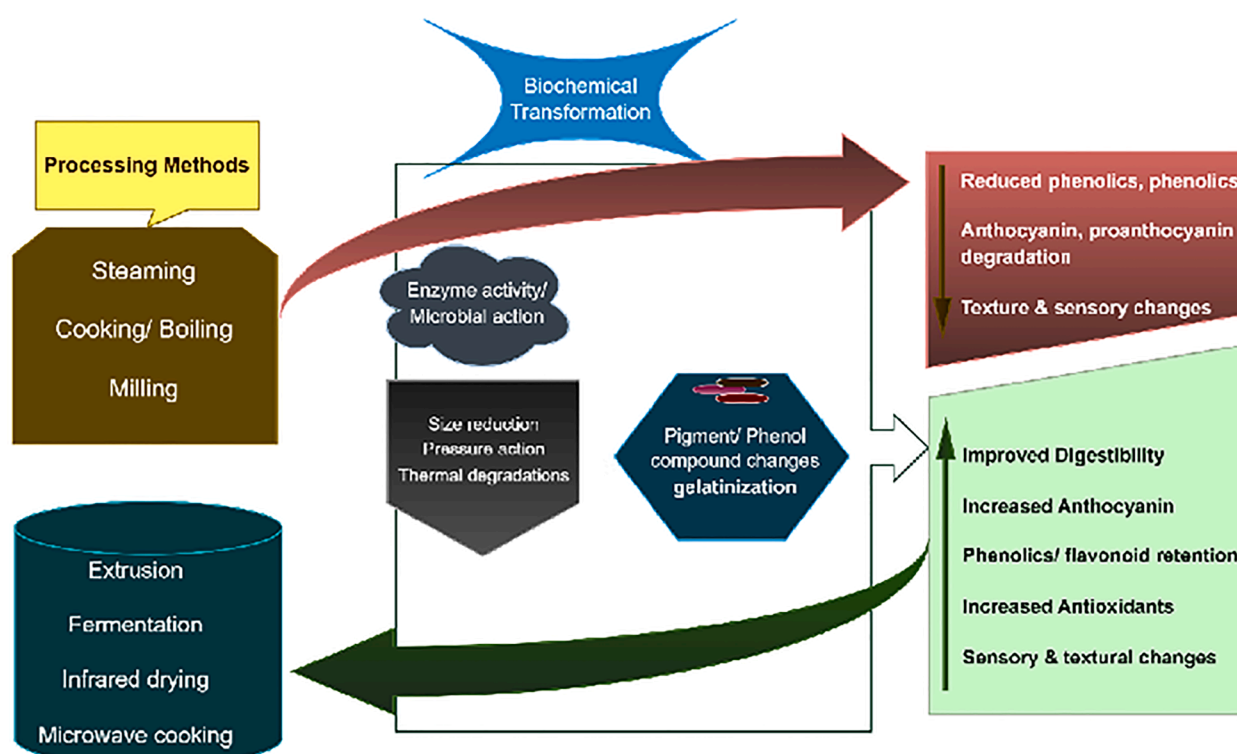
Another study highlights the influence of various black rice cultivars and milling degrees on phenolic compounds, as examined by Choi et al. (2018). Significantly higher total phenolic and total flavonoid contents, antioxidant activity, phenolic acid levels, and anthocyanin levels were observed in the unpolished cultivar Sintoheugmi. Decreases in total phenolic and total flavonoid contents, antioxidant activity, phenolic acid concentrations, and anthocyanin concentrations were observed with increasing milling degree. Higher levels of free phenolic fractions than bound phenolic fractions were generally contained in black rice extract. Ferulic acid is considered the main phenolic acid, while cyanidin-3-O-glucoside was the primary anthocyanin detected in the free phenolic fractions of black rice samples.

The influence of the degree of milling on brown rice's total phenolic content and cellular antioxidant activity decreased with increasing degree of milling, as shown in the study by Liu et al. (2015). The study revealed that the percentage of contributions from bound forms to total phenolics and flavonoids decreased with increasing milling levels. Additionally, significant decreases in the amounts of specific phenolic compounds, such as quercetin, ferulic acid, and coumaric acid, were observed with increasing milling levels. The findings suggest the importance of carefully monitoring milling intensity to preserve sensory quality and phytochemical content. Paiva et al. (2014) examined the proximate composition, phenolic content, and antioxidant activity of black and red rice at varying degrees of milling. Results showed that red rice had a thinner bran layer than black rice, and that the bran contributed to higher ash content in both varieties. About 47% decrease in fat content was observed in red rice with a 4% degree of milling, while black rice required a 7% degree of milling to achieve the same reduction. Free phenolics were found to be approximately 6 and 7 times higher than bound phenolics in black and red rice, respectively. Non-milled red rice exhibited more potent antioxidant activity, but non-milled black rice showed higher free and bound phenolic levels.

The effects of milling and thermal treatment on the phenolic components and antioxidant activities of pigmented rice flours were explored by Sapna et al. (2019). Results showed that plate milling increased insoluble polyphenols, oryzanol, and anthocyanin in red and



A. Effect of processing methods on bioactive compounds of pigmented rice



B. Effect of processing methods on biochemical transformation, nutritional and phytochemical changes

Fig. 3. Effect of processing methods on (A) bioactive compounds of pigmented rice and (B) Biochemical transformation, nutritional and phytochemical changes

3A. Effect of processing methods on bioactive compounds of pigmented rice

3B. Effect of processing methods on biochemical transformation, nutritional and phytochemical changes.

black rice varieties while reducing soluble, bound, and total polyphenols in red rice and increasing antioxidant activity in black rice. Conversely, toasting decreased total, soluble, and insoluble polyphenols, as well as anthocyanin and antioxidant activity, while increasing bound polyphenols and retaining flavonoids and oryzanol. During processing, HPLC analysis revealed changes in the concentrations of phenolic compounds, including catechin, caffeic acid, vanillic acid, protocatechuic acid, and ferulic acid. The mineral content of dehulled and well-milled rice was examined in a study by [Hurtada et al. \(2018\)](#) on pigmented and non-pigmented rice varieties in the Philippines. Pigmented rice cultivars showed higher mineral content compared to non-pigmented rice, regardless of the array. Non-pigmented rice had higher phosphorus content, with Jasmin rice exhibiting the highest zinc level among the non-pigmented cultivars. The highest iron content was observed in Sinandomeng, manganese in IR 64, and phosphorus in Milagrosa. Among the pigmented rice types, Malagaya Tapul had the highest manganese level, Perurutong had the highest iron level, and Dinorado had the highest zinc and phosphorus levels. Dehulled pigmented rice had higher mineral content than well-milled rice, with ballatinao and malagaya tapul having high levels of zinc and manganese. In contrast, dehulled rice contained significant levels of iron and phosphorus.

Across the literature surveyed, a clear pattern emerges: reducing the degree of milling in pigmented rice significantly enhances the retention of bioactive compounds such as anthocyanins, flavonoids, and phenolic acids ([Choi et al., 2018](#); [Liu et al., 2015](#); [Paiva et al., 2014](#)). This is primarily because these compounds are concentrated in the bran layers (pericarp, seed coat, and aleurone), which are removed during polishing. For example, black rice with minimal polishing (e.g., 0–4% milling) retains over 80% of its original anthocyanin content, while extensively milled samples (>10%) show drastic reductions ([Sapna et al., 2019](#)). However, these nutritional gains come with trade-offs. Less milled rice tends to have a rougher texture, a longer cooking time, and lower shelf stability due to its higher lipid content, which promotes rancidity ([Kalita et al., 2021](#)). In contrast, heavily milled rice is more palatable and has a longer shelf life, but is nutritionally inferior. Therefore, an optimal milling degree should balance nutrient preservation with consumer preferences and storage requirements. Bound phenolics refer to phenolic compounds that are chemically attached to the structural components of the plant cell wall, such as cellulose or lignin. These compounds are not immediately bioavailable and require enzymatic or microbial hydrolysis (e.g., via digestion or fermentation) to be released and absorbed ([Liu et al., 2015](#)).

There is a lack of comprehensive studies evaluating how different processing methods affect the bioavailability of nutrients and bioactive compounds in pigmented rice. Most of the literature tends to highlight individual processing techniques, such as milling, cooking, or fermentation, often limited to specific rice varieties. This shows significant gaps in understanding the combined effects of various processing methods on pigmented rice varieties, thereby preventing clear, generalised recommendations for maximising nutritional and sensory quality in processed products derived from pigmented rice ([Tiozon et al., 2021](#)). Recent studies highlight the genotype-specific responses in pigmented rice to various processing methods, but these are seldom integrated into broader comparative analyses. For instance, a 2025 study on bio-processed red and black rice revealed substantial variations in physical and sensory characteristics, with black rice indicating up to a 30% increase in gumminess post-processing, and different milling yields among genotypes. Such studies underscore the need for integrated evaluations that consider both genotype effects and processing types to understand their interactive impact on quality attributes ([Tanzeem & Jayadeep, 2025](#)).

Some studies report contradictory findings in the literature regarding the fate of bioactive compounds, such as phenolics and anthocyanins, during processing. While some literature reports increased bioavailability of free phenolics during extrusion processing and fermentation due to cell wall breakdown, others indicate significant reductions in

these compounds, potentially caused by microbial metabolism and thermal degradation. These variations highlight the importance of standardised, comparative research to reconcile divergent results and guide the development of functional pigmented rice products ([Hu, 2025](#); [Ma, Li, Xue et al., 2023](#)). Integrated research evaluating nutritional retention, bioactive stability, and sensory outcomes remains limited. Cooking methods such as boiling and steaming have differential effects on phenolic content and antioxidant activity, with steaming generally preserving higher levels of bioactive compounds and sensory colour attributes, especially in black rice varieties. However, these nutritional and sensory effects are rarely studied together in a genotype-comparative manner, restricting the practical application of research findings to industry and consumer guidelines ([Massaretto et al., 2022](#)). The effects of milling degrees on anthocyanin retention and sensory attributes in pigmented rice are presented in [Table 2](#).

4.2. Effect of cooking on nutritional properties

Phytochemical and antioxidant compounds in coloured rice may vary due to the high cooking temperatures used, as examined by [Massaretto et al. \(2022\)](#) and [Nayeem et al. \(2021\)](#). The degree of stability of anthocyanins in pigmented rice was affected by cooking temperature, as reported by [Ti, Zhang, Li, et al. \(2015\)](#). Nutritional value may be reduced during cooking, whether pigmented or not, as reported by [Nayeem et al. \(2021\)](#). These pigmented rice varieties contain polyphenols, flavonoids, and other bioactive substances with antioxidant properties. However, reducing the phenolic content of pigmented rice can lead to a decrease during cooking ([Chmiel et al., 2018](#)). It has been shown that steaming pigmented rice has better antioxidant capacity than boiling, retaining higher levels of phenolics and anthocyanins ([Wang & Chen, 2024](#)).

The impact of cooking on pigmented rice varieties available in the Italian market was evaluated in a study conducted by [Melini et al. \(2019\)](#). Lutein was detected in all samples, while anthocyanins were only present in black rice. Phenolic compounds were predominantly free, with higher levels in raw samples. However, cooking reduced total lutein, free phenolic compounds, and anthocyanins, while some samples showed an increase in insoluble-bound phenolic compounds. Red rice varieties are shown to have lower nutraceutical potential than black rice varieties.

Similarly, [Zaupa et al. \(2015\)](#) investigated the antioxidant potential and phenolic profile of white, red, and black rice varieties and assessed the impact of boiling and the “risotto” cooking methods. Phenolic acids were found in all varieties, with anthocyanins and flavanols present in black rice and flavan-3-ols in red rice. Black rice showed the highest antioxidant capacity. After cooking, all three varieties showed decreases in (poly)phenolic compounds and antioxidant capacity, with the risotto method resulting in a greater reduction. Thus, cooking wholemeal rice using the risotto method could be an effective way to preserve (poly)phenolic components and antioxidant capacity. A comparative study of cooking methods found that steaming and risotto-style cooking better preserve the antioxidant properties of pigmented rice varieties, whereas boiling results in greater nutrient losses ([Yasmin & Noor, 2024](#)).

The phenolic and flavonoid profiles, as well as the antioxidant activity, phytic acids, vitamin E, γ -oryzanol, anthocyanin, and other compounds in various processed rice products (popped, beaten, puffed, and boiled rice), were investigated by [Bagchi et al. \(2021\)](#) in a study on black and white rice cultivars. Black rice-based products had higher concentrations of phenolic compounds than reference cultivars, with popped rice showing the highest content. This study emphasises the importance of selecting appropriate processing techniques to preserve the nutritional qualities of coloured rice. Similarly, [Fracassetti et al. \(2020\)](#) examined the impact of cooking methods on bioactive compounds and antioxidant activity in pigmented rice cultivars. The Artemide cultivar exhibited higher levels of total phenolic index, total flavonoids, total anthocyanins, and antioxidant capacity compared to

Table 2
Effects of milling degrees on anthocyanin retention and sensory attributes in pigmented rice.

Milling Degree	Anthocyanin Retention	Phenolic Content	Texture Quality	Shelf Life	References
0–2% (Minimal)	High (>80%)	High (rich in free & bound phenolics)	Coarse, chewy	Low (high lipid → rancidity)	Choi et al. (2018); Liu et al. (2015); Paiva et al. (2014)
4–6% (Moderate)	Moderate (50–70%)	Moderate	Slightly firm, acceptable	Moderate	Sapna et al. (2019); Kalita et al. (2021)
>8% (High)	Low (<40%)	Low (loss of bran-bound phenolics)	Soft, consumer preferred	High (lipid layer removed)	Liu et al. (2015); Paiva et al. (2014); Kalita et al. (2021)

the Venere cultivar. The rice cooker and water bath methods resulted in lower phenolic losses, and the leftover cooking water from the rice cooker was rich in phenolic compounds. Consuming rice cooked in a rice cooker with its cooking water can provide significant amounts of catechin and cyanidin 3-O-glucoside, which have potential health benefits. A study highlights the impact of cooking methods on black rice's antioxidant properties. It has been found that steaming preserves more anthocyanin content, whereas boiling results in significant losses of pigmented rice (Shah & Varshney, 2024). Another study characterised antioxidant compounds in pigmented rice, showing that boiling and frying degrade phenolic compounds, whereas steaming retains higher antioxidant levels, as Zaupe & Pellegrini (2023) reported. Nayeem et al. (2021) conducted a study on Indian rice landraces to investigate the bioactive compound content and antioxidant activity of pigmented and non-pigmented rice varieties. Results showed that pigmented rice cultivars exhibited higher concentrations of anthocyanin, total flavonoids, total phenolic compounds, total protein, and total antioxidant activity compared to non-pigmented cultivars. Phytochemicals and antioxidant activity decreased during cooking and straining of the cooking water. Navara cultivar showed the highest concentrations of phytochemicals and antioxidant activity, and pressure-cooking without straining the water was found to be the best method for preserving nutrients. In a separate study, Thuengtung et al. (2019) investigated the effects of steam and microwave cooking on the morphological structure, starch fractions, and starch digestibility of Thai pigmented rice cultivars. The cooking method influenced the morphological structure and rate of starch breakdown during digestion. Significant changes in the X-ray diffraction pattern and crystallinity level were observed in steam-cooked rice after simulated digestion, compared to microwave-cooked rice. Steam-cooked rice also showed a lower proportion of equilibrium starch hydrolysis than microwave-cooked rice.

The effects of risotto and boiling cooking techniques on three types of pigmented wholemeal rice were studied by Zaupe et al. (2016). Cooking was found to lead to the formation of voids in the grains, with black rice showing the highest void percentage. Furthermore, the tannin inclusions in the endosperm increased after cooking, indicating a partial resorption of leached chemicals. These findings suggest that analysing the anatomical structure of grains can provide insights into their behaviour during cooking, thereby influencing their nutritional content and the accessibility of their compounds. In a separate study by Massaretto et al. (2022), a comparison was made between black and red rice genotypes developed by Epagri and commercially available rice in Brazil. Black rice exhibited stronger antioxidant properties, a higher phytochemical profile, and a higher chemical composition compared to red rice. Cooking reduced phenolic content by 28% in Epagri black rice, whereas commercial black rice remained unaffected. Red rice experienced a 60% reduction. Flavonoids decreased by 50% after cooking in both commercial and Epagri genotypes. Proanthocyanidins decreased by 79% and 64% in commercial and Epagri red rice, respectively, while anthocyanins decreased by 56% and 51% in commercial and Epagri black rice, respectively. Sensory evaluations indicated 70% acceptance of raw-coloured rice and 80% acceptance of cooked rice.

Various studies consistently show that boiling pigmented rice leads to significant losses of phenolic compounds and antioxidant activity due to the leaching of water-soluble compounds into the cooking water. In

contrast, steaming is more effective at preserving phenolics and anthocyanins, as it minimises direct water contact and reduces leaching, thereby increasing their retention and antioxidant capacity. Risotto-style cooking, which involves gradual addition of liquid, offers intermediate preservation of phenolics—better than boiling and, in some cases, nearly as effective as steaming, especially for wholemeal rice—steaming consistently preserved more anthocyanins than boiling, likely due to reduced water contact and lower leaching losses. Pressure cooking and risotto methods led to intermediate retention, with boiling resulting in the greatest losses. Cooking affects sensory attributes such as colour and aroma, which influence consumer acceptance. For example, boiling tends to dull the colour of black rice, which may reduce its visual appeal—a key determinant of acceptance.

4.3. Effect of extrusion on nutritional properties

Extrusion is a versatile food processing technique that combines several unit operations, such as mixing, shaping, kneading, and forming, to create a wide range of food items, including breakfast cereals, snack foods, and ready-to-eat foods (Ruiz-Gutiérrez et al., 2018). Studies have shown that the nutritional composition, phenolic components, and antioxidant capacity of pigmented rice are all affected by extrusion (Rivero Meza et al., 2021). Extrusion processing can be optimised to enhance nutritional value and physical properties, while minimising anthocyanin losses in pigmented rice-based snacks. The thermal characteristics of rice flour were also impacted by the extrusion process, as reported by Samyor et al. (2018). Although the impact of extrusion on pigmented rice has occasionally been researched, further studies are required to fully comprehend the effects of extrusion on this type of rice (Blandino et al., 2022). Extruded pigmented rice has retained significant levels of bioactive compounds, making it valuable for the development of new products (Sari & Palupi, 2024).

Extrusion is a high-temperature, high-shear process that transforms rice flour into ready-to-eat products. The mechanical shear and heat disrupt cell walls, gelatinise starch, and can break down complex phenolic structures. While these conditions often reduce total phenolic content and anthocyanins due to thermal degradation, they can also increase the bioavailability of certain phenolics by releasing bound forms from the food matrix (Rivero Meza et al., 2021). Additionally, extrusion improves starch digestibility by disrupting crystalline regions, making nutrients more accessible for enzymatic breakdown. High temperatures and intense shear forces during extrusion degrade heat-sensitive compounds, such as anthocyanins and some phenolic acids. Processing conditions break down starch granules and cell wall structures, increasing the rate and extent of starch digestion (Ti, Zhang, Zhang, et al., 2015; Zhang et al., 2018).

A study characterised the nutrient profiles, phenolic compounds, antioxidant capacity, technological properties, and colour features of coloured rice flours and their extruded products. The optimal conditions for black and red rice extrudates were determined using twin-screw extruders. Red rice snacks exhibited superior expansion and texture qualities, while black rice snacks had better nutritional and phenolic profiles. Both breakfast cereals were palatable, gluten-free, hypoallergenic, naturally coloured, and well-accepted by consumers. The behaviour of coloured rice during extrusion was investigated by

Blandino et al. (2022). Snacks made from brown, red, and black rice were compared to those made from white rice. Black rice was reported to have the highest levels of anthocyanins and antioxidant activity post-extrusion, while red rice performed well in terms of biometric and textural qualities. Optimising extrusion conditions can significantly enhance the nutritional and physical characteristics while reducing anthocyanin degradation in pigmented rice. The impact of extrusion on phenolic profiles and antioxidant activity in different milled fractions of brown rice was investigated by Zhang et al. (2018). The total phenolic content, flavonoids, ferric-reducing antioxidant power (FRAP), and oxygen radical absorbance capacity (ORAC) were found to be increased in rice bran, while decreased in polished and brown rice due to extrusion. Different fractions of rice exhibited variations in phenolic content without changes in composition. Research conducted by Ti and Zhang examined the phytochemical composition and antioxidant properties of unprocessed and extruded milled fractions of black rice. It was observed that ORAC, anthocyanins, and free phenolics improved by extrusion, whereas the bound phenolic forms were reduced. Higher ORAC, anthocyanins, and total phenolics were exhibited in bran, while reductions were observed in polished and brown rice. Various phenolic acids and cyanidin compounds were detected in both forms, with cyanidin 3-glucosides (Cy-3-G) being the most abundant in both raw and extruded rice bran. Zhang et al. (2023) investigated the impact of extrusion on the functional properties of pigmented rice. Extrusion was found to improve the bioavailability of phenolic compounds and enhance the texture, making it a suitable method for producing pigmented rice-based food products with improved nutritional profiles.

Extrusion is a high-temperature, high-shear process that alters rice's nutritional and functional properties by disrupting cell walls, gelatinising starch, and modifying phenolic compound profiles. At the molecular level, extrusion can increase the bioavailability of phenolics by breaking down cell walls, though excessive heat can degrade sensitive compounds such as anthocyanins. Optimal extrusion conditions (moderate temperature, controlled moisture) maximise nutrient retention while enhancing textural properties—for example, black rice extrudates retain more anthocyanins and antioxidant activity than red or white rice under these conditions. Extrusion at 120–140°C with 18% moisture using a twin-screw extruder optimises both texture and phenolic retention in pigmented rice snacks (Sari & Palupi, 2024). Black rice extrudates retain the highest levels of anthocyanins and antioxidant activity, whereas red rice extrudates offer superior expansion and texture. Moderate extrusion temperatures and controlled moisture levels are critical for balancing nutritional preservation with desirable product qualities (Zhang et al., 2018). While high-temperature extrusion can degrade some phenolics, it also liberates bound forms, making them more accessible for absorption, as shown by increased ORAC and free phenolic content in extruded rice bran (Rivero Meza et al., 2021). Red rice extrudates produced under these conditions show superior expansion and crispness, making them attractive for snack applications. Black rice, processed at moderate temperatures and moisture levels, retains higher levels of anthocyanins and antioxidant capacity, supporting the development of functional foods with health benefits (Sari & Palupi, 2024; Zhang et al., 2018). The effect of processing methods on bioactives and nutrients in the pigmented rice genotype is presented in Table 3.

5. Effect of processing on nutritional properties of pigmented rice products

5.1. Fermented rice

Fermentation affected the nutritional value of pigmented rice. Fermentation significantly enhanced the antioxidant properties and the bioavailability of nutrients, making pigmented rice an ideal candidate for functional food products, as investigated by Saritaş et al. (2024). Fermentation enhances the nutritional value of phenolic compounds and antioxidants, thereby improving their bioactivity. Fermentation

Table 3

Effect of processing methods on bioactives and nutrients in pigmented rice genotype.

Processing methods	Pigmented rice Genotypes	Effects on Nutrients and Bioactive compounds	Mechanistic insights	References
Cooking (boiling, rice cooker)	Black, red, purple and Epagri black and red rice genotypes	Reduced phenolics, flavonoids, anthocyanins; higher losses due to excess boiling.	Water solubility causes leaching of phenolics; longer time and higher heat increase degradation.	Nayeem et al. (2021); Fracassetti et al. (2020); Massaretto et al. (2022); Tiozon et al. (2021)
Steaming	Black and red pigmented varieties	Decrease in phenolics and antioxidants; less loss compared to boiling	Less leaching without direct water contact; heat/time degrade sensitive compounds	Tiozon et al. (2021).
Microwave Cooking	Riceberry and other pigmented rice varieties	Higher retention of bioactive compounds than conventional methods	Rapid heating reduces cooking time and limits leaching	
Extrusion	Red and black rice genotypes	Increase in antioxidants, phenolics and dietary fiber; while reducing anti-nutrients	Shear and heat break bonds, releasing bound phenolics and converting fiber	Tiozon et al. (2021).
Infrared drying	Infrared drying tested on pigmented varieties	Increased phenolics, flavonoids, tocopherols and antioxidants compared to hot air drying	Mild thermal activation enhances extractability and reduces oxidation	Tiozon et al. (2021)
Fermentation	Pigmented rice varieties with different microbial fermentations	Enhanced phenolic acids and antioxidant activity	Microbial enzymes degrade cell walls, release bound phenolics; fermentation metabolites stabilize bioactives	Hu (2025)

enhances rice's nutritional value and antioxidant and antibacterial activity. Antioxidants, including phenolics and flavonoids, were reduced due to cell wall breakdown. Also, antibacterial activity can be enhanced by fermenting secondary chemical compounds (Yudiarti et al., 2019). It suggests that fermentation is an efficient method for improving the bioavailability of phenolic compounds in rice (Barathikannan et al., 2023). Another study found that fermentation positively affected sensory properties, while extrusion affected rice texture and retained antioxidants, as investigated by Ma, Li, Xue et al. (2023).

The processing of pigmented rice has a dual impact, since it may enhance the functionality, edibility, and storage quality of the product, yet on the other hand, it may also lead to a decrease in the activity of important bioactive compounds in the grain (Lin et al., 2024). The high content of health-related compounds in the bran layer and their

processing will definitely impact the nutritional composition. Thus, the impact of processing on pigmented rice cannot be associated solely with a modification of the composition of the grain since it leads to biochemical modifications (Bani et al., 2024). The significance of fermentation lies in its capability to release the bioavailability of bound phenolics, enhancing digestibility, as well as generating new metabolic products, which have different bioactivities (Xiao et al., 2025). Fermentation of brown rice by Lactic Acid Bacteria enhanced the activity of amylase, protease, and cellulase, hence making starch granules porous and reducing the cooking time, while also enhancing sensory qualities. Likewise, the use of LAB for the fermentation of black rice bran not only increased the availability of bioactive compounds but also affected the antioxidant and functional properties according to the milling fractions of the rice. It can be seen that fermentation is not just a process for preservation but a biochemical change that occurs in the grain's physicochemical makeup and affects its phytochemical release in the digestive system (Lin et al., 2024).

The issue of anthocyanin retention in colored rice becomes an important one because these molecules provide coloration and antioxidant properties in significant amounts (Chakkaravarthi et al., 2025). During the fermentation process, anthocyanins are more likely to be extracted from cells; however, harsher conditions will cause the molecules to degrade due to changes in pH, oxidative stress, enzymatic reactions, and microbial metabolism. For instance, fermentation of black rice bran using *Saccharomyces cerevisiae* led to the conversion of cyanidin-3-glucoside and peonidin-3-glucoside to aglycones, changing the antioxidant characteristics (Trinovani et al., 2020). The same effect was observed in red rice fermented; although the amount of total pigment was reduced, the bioavailability of antioxidants increased during digestion simulation (Zhu et al., 2024). Pigmented rice processing results in the transformation of phenolic compounds present in pigmented rice from bound to free forms. This is important since bound forms of phenolics are poorly bioavailable from the whole grain (Zhu et al., 2024). During fermentation, enzymes produced by microbes, including β -glucosidase, rhamnosidase, and other hydrolytic enzymes, break down the glycosidic bonds, disrupt cell wall structures, and release phenolic compounds, producing new metabolites. The production of active metabolites through enzyme action accounts for the increased biological activity of certain fermented pigmented rice products despite decreased amounts of native anthocyanins. Thus, a thorough analysis would be incomplete without a distinction between compositional factors, such as total content and physiological bioavailability, which may not increase or decrease simultaneously (Chaiyasut et al., 2017). Pigmented rice, upon undergoing fermentative and processing techniques, has been made into powder, beverage, flour, functional food, and bran-derived products. Fermented black rice flour shows higher protein concentration, damaged starches, acid formation, and altered free amino acid composition, which contribute to improved dough properties and overall functionality of products (Jung et al., 2022). Also, fermented rice products have become more appreciated as sources of probiotics and synbiotics, as these are able to deliver beneficial bacteria and phenolic compounds as well as resistant starch to the lower gastrointestinal tract due to their ability to harbor microbes within the rice matrix. What makes these products valuable is the fact that they are much more than just by-products (Fuloria et al., 2022; Lin et al., 2024).

5.2. Idli (A fermented rice-based steamed food)

The nutritional value, texture, and phenolic composition of idli (a rice-and-lentil-based popular fermented steamed food) made with white rice have been studied by Susmitha et al. (2022). Results of a comparative study revealed that pigmented rice idlis had superior nutritional quality compared to white rice, including higher protein, amino acids, total phenolic acids, total flavonoids, and antioxidant activity. However, lower values were shown for adhesiveness, cohesiveness, and resilience.

The insoluble bound form of phenolic acids and flavonoids played a significant role. The study identified the Mamihunger (MH)-idli made from black rice as a promising alternative to traditional white rice. In another study by Dela Rosa & Medina (2022), the fermentation process of rice wine (Tapuy) made from black, red, brown, and white rice was investigated. The pH profiles showed similar trends among the different rice varieties, with a drop in acidity on the first day and stable acidity throughout fermentation. Tapuy made from black rice had a lower alcohol content than tapuy made from white rice. Black rice-based Tapuy exhibited significantly higher total phenolic content and antioxidant activity compared to Tapuy made from other pigmented rice varieties. The black rice Tapuy had a total phenolic content of 9.73 mg GAE/mL and a DPPH radical scavenging activity of 70.63%.

5.3. Fermented rice flour

Various studies have examined the effects of fermentation on the physicochemical properties of fermented dehusked rice flour. One study examined the impact of Solid-State Fermentation with *Rhizopus oligosporus* on three types of rice: non-pigmented Mentik Wangi Susu, red Cempo Merah, and black Jowo Melik. The fermentation process increased the ash, protein, and fat content, as well as antioxidant capacity and total phenolic content. The Jowo Melik variety had the highest total phenolic content and antioxidant capacity after 72 hours of fermentation, while anthocyanin and carbohydrate concentrations decreased with longer fermentation time (Suarti et al., 2020).

5.4. Pigmented rice wine

Studies were conducted for the comparison of conventional and multi-parallel fermentation techniques using different starter cultures to produce rice wine from pigmented and non-pigmented rice varieties. Regardless of the fermentation technique, rice wine made from pigmented rice had higher total phenolic content and antioxidant activity than that made from non-pigmented rice. The culture type had a less significant impact on the rice wines' total phenolic content, antioxidant activity, and copper reduction antioxidant capacity. These findings indicate that rice wine made from pigmented rice, such as Cambodian waxy rice, contains bioactive substances with potential antioxidant properties, making it a healthier alcoholic beverage option (Chay et al., 2020). A study examined the effects of rice type and fermentation process on the quality of rice wine. Two waxy pigmented and non-pigmented rice varieties were fermented using traditional and multi-parallel fermentation techniques. The conventional fermentation method yielded a higher alcohol concentration for the non-pigmented rice variety, but a lower yield than the fermented rice variety using the multi-parallel method. Wines made from both types of rice were well accepted by consumers. Further investigation is needed to evaluate the impact of additional elements on rice wine's stability and shelf life (Chay et al., 2017). Another study analysed fermented red brown rice for its antioxidant activity, DNA damage-prevention effects, and polyphenol content. Fermented red brown rice exhibited higher levels of polyphenol compounds compared to unfermented rice. It demonstrated stronger antioxidant activity and inhibited DNA damage caused by reactive oxygen species. However, at high concentrations, fermented rice extract had the potential to cause reductive DNA damage. Unfermented red brown rice had a lesser effect on preventing DNA damage (Kong et al., 2015). Germination improved the nutritional quality of pigmented rice, thereby enhancing its antioxidant properties and imparting health benefits (Mok & Mahiuddin, 2024). Dela Rosa & Medina (2022) showed that black rice-based Tapuy wine had significantly higher total phenolic content and antioxidant activity compared to wines made from other rice varieties. Susmitha et al. (2022) demonstrated that idlis made from pigmented rice had higher protein, amino acids, phenolic acids, flavonoids, and antioxidant activity than those made from white rice.

Solid-state fermentation with *Rhizopus oligosporus* increased ash,

protein, and fat content, and antioxidant capacity, especially in black rice, while anthocyanin levels decreased with longer fermentation time. Pigmented rice, compared to white rice, offers superior nutritional and health benefits due to its rich content of phenolic compounds, flavonoids, and dietary fibre. Studies show that incorporating pigmented rice into foods such as gluten-free bread significantly increases total dietary fibre and phenolic content, thereby enhancing antioxidant capacity. Acute consumption of pigmented rice boosts plasma antioxidant activity and lowers postprandial glucose and insulin levels. At the same time, chronic intake is associated with reductions in fasting glucose, weight, and diastolic blood pressure. However, no significant effects were observed on cholesterol, triglycerides, or body mass index. The health-promoting effects are attributed to the rice's polyphenols, particularly anthocyanins, which neutralise reactive oxygen species and reduce oxidative stress, potentially lowering inflammation and cardiometabolic risk. Additionally, pigmented rice exhibits anti-diabetic, anti-inflammatory, and even anti-cancer properties, as supported by both traditional knowledge and modern research. Despite these benefits, the bioavailability of some antioxidants remains low, and more high-quality studies are needed to confirm long-term effects. Overall, pigmented rice is a nutritionally superior option for improving antioxidant status and managing certain metabolic risk factors.

Across fermented rice, idli, rice wine, and rice flour, fermentation increases the bioavailability of nutrients—especially phenolic compounds and antioxidants—making pigmented rice a strong candidate for functional foods. For example, Saritaş et al. (2024) found that fermentation significantly improved antioxidant activity and nutrient bioactivity. Similarly, Barathikannan et al. (2023) and Suarti et al. (2020) reported increased protein, fat, ash, and phenolic content, especially in black rice varieties, after fermentation, though anthocyanin levels declined with prolonged fermentation. Fermented rice-based foods like idlis made from pigmented rice showed higher protein, amino acids, phenolic acids, flavonoids, and antioxidant activity compared to those made from white rice, as demonstrated by Susmitha et al. (2022). In beverages, black rice-based Tapuy wine exhibited the highest total phenolic content and antioxidant activity among rice wines, regardless of fermentation technique (Chay et al., 2020; Dela Rosa & Medina, 2022). These findings consistently highlight that fermentation, particularly with pigmented rice, delivers superior nutritional and antioxidant benefits, supporting its use in functional foods and beverages.

5.5. Lactic acid fermentation

Lactic acid fermentation of pigmented rice, often involving lactic acid bacteria (LAB), leads to acidification and enzymatic breakdown of cell wall components. This process increases the bioavailability of phenolic compounds by degrading cell walls and releasing bound phenolics. It also enhances protein digestibility and can improve the sensory profile of rice-based foods. For example, in the production of idli (a fermented, steamed food), pigmented rice varieties showed higher levels of protein, amino acids, total phenolic acids, flavonoids, and antioxidant activity than white rice. However, textural properties like adhesiveness and cohesiveness were slightly lower (Susmitha et al., 2022).

5.6. Alcoholic fermentation

Alcoholic fermentation, as used in rice wine production, involves yeasts that convert sugars into ethanol and secondary metabolites. This process can increase total phenolic content and antioxidant activity, particularly in pigmented rice varieties. For instance, black rice-based Tapuy wine exhibited significantly higher total phenolic content and antioxidant activity than Tapuy made from red, brown, or white rice. The increase in bioactive compounds is attributed to yeast-mediated cell wall breakdown and the release of phenolics into the fermenting medium (Dela Rosa & Medina, 2022).

5.7. Solid-state fermentation

Solid-state fermentation (SSF), often using molds like *Rhizopus oligosporus*, results in marked increases in ash, protein, fat, total phenolics, and antioxidant capacity, especially in black and red rice varieties. The process involves enzymatic hydrolysis of macromolecules and further cell wall degradation, which liberates phenolics and enhances antioxidant properties. However, prolonged fermentation may decrease anthocyanin and carbohydrate content due to microbial metabolism (Barathikannan et al., 2023; Suarti et al., 2020). Phenolic bioavailability increases in all fermentation types due to cell wall degradation and enzymatic activity. Pigmented rice (especially black rice) consistently outperforms white rice in phenolic retention and antioxidant enhancement after fermentation. Solid-state fermentation yields the greatest increases in phenolics and antioxidant capacity but may reduce anthocyanin levels with prolonged processing. Lactic acid and alcoholic fermentations both improve nutritional and functional properties, with alcoholic fermentation (rice wine) showing the greatest increase in phenolic and antioxidant content in black rice. These findings support the use of fermentation to enhance the functional and nutritional value of pigmented rice, with the method and rice type influencing the magnitude of the effect.

5.8. Effect of germination on nutritional properties

The nutritional value and bioactive component contents, including flavonoids, phenolic content, and antioxidant activity, are enhanced by germination in pigmented rice (Chung et al., 2016; Müller et al., 2021). Germination can potentially enhance the texture and eating quality of brown rice. The texture was softened, and the nutritional value was improved. Germinated brown rice has become more prevalent in Asia due to its greater levels of phytochemicals (Kang et al., 2022). The impact of germination on the nutritional value may vary depending on environmental factors such as temperature and humidity (do Nascimento et al., 2022). A study revealed the effect of germination, fermentation, and extrusion on brown rice's nutritional and sensory properties. Germination has significantly improved nutritional value, increased phenolic content, and antioxidant properties, as reported by Ma, Li, Xue et al. (2023). Kang et al. (2022) investigated the effects of germination and roasting on the physicochemical, bioactive, and microbiological properties of red-pigmented rice. It was observed that germination improved crude protein and fat, total phenolics, flavonoids, and antioxidant activities. In contrast, levels of γ -aminobutyric acid increased during germination and decreased after roasting. Bacterial, yeast, and mould counts increased during germination but decreased after heat treatment, ensuring microbiological stability in red-pigmented rice. In another study by Susanti et al. (2022), the effect of the germination period on the antioxidant activities and angiotensin-I converting enzyme (ACE-I) inhibitory properties of Indonesian black rice was examined. Germination was used to modify proteins and create bioactive peptides over 0, 2, 4, and 6 days. A study highlights the effects of germination periods ranging from 8 to 40 hours on red rice grains. It was found that longer germination times resulted in decreased ash and moisture content and a lower pH. Additionally, the levels of caffeic, coumaric, and ferulic acids, myricetin, and gamma-aminobutyric acid (GABA) increased during germination. The GABA levels further increased after baking the rice into cupcakes. The cupcakes were highly consumer-acceptable (Müller et al., 2021).

The impact of germination on the secondary metabolite profiles and antioxidant activity of brown and red rice has been studied by Nurnaistia et al. (2018). Results showed that Germination for 2 days at 26°C and 99% humidity altered metabolite profiles, including the appearance and disappearance of peaks. The findings showed that germination induced changes in the secondary metabolite profiles of brown and red rice, with the appearance of new peaks and the disappearance of specific peaks. Moreover, brown rice showed a slight

increase in antioxidant activity from 11.2% to 22.5% after germination, whereas red rice showed a decrease from 73.8% to 60.0%. In another study, [Park et al. \(2018\)](#) examined the changes in chemical components during the germination of pigmented rice. Germination at 30°C increased crude protein and crude fat content. Glucose content increased over time, and no significant trend was observed in sucrose or fructose concentrations. Germination also enhanced GABA, alanine, glutamic acid, asparagine, aspartic acid, and lysine levels in pigmented rice. Notably, lysine was detected in all varieties from the second day of germination onwards, with concentrations of 6.24 mg/100 g for normal rice and 15.58 mg/100 g for pigmented rice on the sixth day of germination.

Multiple studies consistently show that germination markedly enhances the nutritional and functional properties of pigmented rice. The most significant benefits—including increases in γ -aminobutyric acid (GABA), free phenolic content, antioxidant activity, and some vitamins—are typically observed within the first 48–72 hours of germination. Prolonged germination beyond this window often results in diminishing returns or even nutrient loss due to metabolic consumption by the sprouting seed. Most studies report that GABA, free phenolics, and antioxidant activity peak at 48–72 hours of Germination ([Susmitha et al., 2022](#)). Pigmented rice varieties (especially black and red) show higher increases in phenolic content and antioxidant capacity compared to white rice during germination. Germination reduces anti-nutritional factors (such as phytic acid) and increases the digestibility and bioavailability of micronutrients ([Suarti et al., 2020](#)). The effect of germination on the antioxidant activity of pigmented and non-pigmented rice varieties was studied by [Chung et al. \(2016\)](#). Significant increases in antioxidant activity and higher anthocyanin, tannin, phenolic, phytic acid, tocopherol, and tocotrienol were noticed in germinated rice compared to non-germinated rice. Pigmented brown rice varieties displayed better antioxidant capacities and higher antioxidant compound concentrations than non-pigmented types. Similarly, [Vichit & Saewan \(2016\)](#) examined the effects of germination on bioactive compounds, antioxidants, anti-inflammatory agents, and keratinocyte proliferation in different rice types. Germinated rice exhibited higher concentrations of bioactive substances and increased antioxidant activity compared to ungerminated rice. Standardising germination parameters (e.g., 30°C, 48–72 hours, controlled humidity) can maximise nutritional benefits while minimising spoilage risk ([Suarti et al., 2020](#)). Implementing rigorous sanitation and Hazard Analysis Critical Control Point (HACCP) protocols can reduce microbial risks, making large-scale germination safer and more reliable. Use of automated sprouting systems with precise environmental controls can ensure uniformity and scalability.

5.9. Consumer acceptance of pigmented rice-based products

Consumers' acceptance of pigmented rice is currently gaining attention. According to studies, pigmented rice, like red and black rice, is more nutritious than white rice ([Mbanjo et al., 2020](#)). Due to factors such as texture and colour, consumer adoption of pigmented rice still needs to grow. According to a survey in India, customers preferred Jasmine rice over low-GI and medium-grain rice, and white rice over brown rice, because of its texture and colour ([Gondal et al., 2021](#)). Consumers in India were discovered to be willing to purchase black rice at a specific price range, according to another study ([Putri et al., 2019](#)). In conclusion, consumer acceptance of pigmented rice remains very low due to factors such as texture and colour. The nutritional advantages of pigmented rice, however, are generating more interest and could eventually enhance market adoption. The most effective strategies for boosting consumer acceptability of pigmented rice require more investigation.

5.10. Factors influencing consumer preference

Sensory attributes, including colour, taste, and aroma, primarily drive consumer acceptance of pigmented rice. Studies have shown that pigmented rice varieties, especially black and red rice, are highly valued for their vibrant colour and distinctive aroma, which are perceived as indicators of quality and health benefits. However, processing methods significantly influence these sensory properties. For instance, boiling tends to dull the colour of black rice, reducing its visual appeal—a key determinant of consumer preference—while steaming better preserves both colour and aroma, thereby enhancing consumer acceptance. Taste and texture are also important: pigmented rice often has a nuttier flavour and firmer texture, which may be preferred or rejected depending on cultural expectations and individual preferences. Cultural perceptions play a significant role in acceptance. In regions where colored rice is associated with tradition, health, or festive occasions, such as parts of Asia, pigmented rice is more readily accepted. Conversely, in areas where white rice is the staple and coloured varieties are less familiar, consumers may be hesitant to adopt pigmented rice because of its appearance or perceived unfamiliarity. [Massaretto et al. \(2022\)](#) reported that cooked pigmented rice had an 80% acceptance rate, compared to 70% for raw rice, indicating that processing can improve palatability. Surveys and market research further explore consumer attitudes, willingness to pay, and perceptions of health benefits, often revealing that clear labelling and communication of health benefits can enhance acceptance.

5.11. Phenolic retention post-fermentation

There is conflicting data regarding the stability of phenolics after fermentation. Some studies report increases in free phenolic content due to cell wall degradation, while others note losses attributed to microbial metabolism or prolonged fermentation. This inconsistency highlights the need for standardised methodologies and comparative studies across rice types and fermentation approaches, making this area a top research priority ([Barathikannan et al., 2023](#); [Suarti et al., 2020](#)). Further research should directly link specific processing methods (e.g., boiling, steaming, extrusion) to consumer acceptance, particularly by examining how sensory and nutritional changes influence preferences across different cultural and economic contexts ([Massaretto et al., 2022](#)). There is a need for studies that develop validated, scalable protocols for Germination, fermentation, and extrusion, including microbial safety, process control, and product uniformity, to support industrial adoption of pigmented rice foods ([Sari & Palupi, 2024](#); [Suarti et al., 2020](#)).

6. Future prospects of pigmented rice

Future studies on the impact of processing techniques on the nutritional qualities and consumer acceptance of products made from pigmented rice could focus on several topics. To maximise the nutritional content of pigmented rice-based products while preserving consumer acceptance, further research is first required to identify the optimal processing techniques ([Tiozon et al., 2021](#)). Second, research could concentrate on creating new, more appealing pigmented rice-based products. This could mean adding pigmented rice to everyday foods like bread, spaghetti, and snacks to boost their nutritional content ([Bhat et al., 2020](#)). Thirdly, studies might examine the potential health benefits of consuming products made from pigmented rice ([Mbanjo et al., 2020](#)). To enhance the consumption of pigmented rice-based products and promote their potential health benefits, additional research is needed to examine the impact of processing methods on their nutritional characteristics and consumer acceptance. These research areas could help optimise processing methods, develop new pigmented rice-based products, and investigate the potential health benefits of consuming them ([Xia et al., 2019](#)). Various studies indicate that bioactive compounds such as GABA and phenolics tend to peak between 48 and 72

hours of germination, but the precise optimal duration for maximal GABA enrichment, especially across different pigmented rice varieties, remains unclear (Suarti et al., 2020; Susmitha et al., 2022). While extrusion at moderate temperatures (120–140°C) and moisture levels (15–20%) has been shown to optimise both texture and phenolic retention, the specific influence of varying moisture content on anthocyanin stability and retention has not been systematically studied and warrants controlled investigation (Blandino et al., 2022; Sari & Palupi, 2024). Fermentation and extrusion are promising processing methods for developing functional foods from pigmented rice. Fermentation enhances the bioavailability and retention of important bioactive compounds, including phenolics, flavonoids, and gamma-aminobutyric acid (GABA), thereby enhancing antioxidant, anti-inflammatory, and stress-reducing health benefits. The extrusion puffing process improves nutritional value and flavonoid content, enhances texture and flavour, and makes it suitable for the preparation of functional snacks. Both extrusion and fermentation reduce anti-nutritional factors and improve digestibility, with black and purple rice varieties showing particularly favourable outcomes due to their inherent high anthocyanin content. These processing technologies offer a scalable path to develop nutrient-enhanced, health-promoting pigmented rice products that combine improved functional and sensory attributes, catering to consumer demand for advanced dietary options.

7. Conclusions

Pigmented rice is a nutritionally rich grain with great potential to enhance nutritional quality and public health. It has distinctive health benefits attributable to the fact due to its enhanced bioactive components, such as anthocyanins, phenolics, flavonoids, topherol, and antioxidant activity, with a favourable amount of essential micronutrients and macronutrients. Post-harvest processing substantially influences the nutritional value, antioxidant activity, and bioactive compounds and reduces their overall functionality. This study highlights that milling, polishing, cooking, steaming, parboiling, extrusion, and fermentation processes exhibit positive and negative impacts on nutritional and functional properties depending on processing factors, duration, and intensity. Greater losses of nutrients can be seen during milling and polishing, which remove the bran layer, containing most of the micronutrients and phytochemicals, which are generally concentrated in the outer layer of pigmented rice. Heat-labile compounds like anthocyanins and some phenolics degrade during thermal processing but enhance digestibility by starch gelatinization. It appears to be a beneficial effect of bioprocessing methods to increase nutrient bioavailability, develop new bioactive compounds, and enhance the bioaccessibility of micronutrients by reducing phytates. Overall, it is suggested that controlled processing with mild conditions minimizes bran removal and induces functional treatments such as controlled fermentation, enzyme-assisted treatments, encapsulation, and optimized extrusion and heat processing, which would provide enhanced nutritive value and significant retention of bioactive compounds like anthocyanins and phenolics. In conclusion, pigmented rice is therefore viewed not only as a colored grain but also as a bioactive functional food whose nutritional value can be either preserved or diminished through processing. Using improved and optimized processing techniques integrated with quality control could recognize pigmented rice as a functional food to contribute substantial health benefits. By addressing these gaps, pigmented rice can evolve from a niche grain to a widely consumed functional food, supporting global nutrition goals and sustainable food systems. Future research should integrate interdisciplinary approaches to unlock its full potential.

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Declaration of competing interest

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

Data availability

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

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