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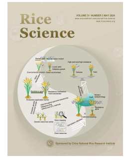

Review

Exploring Nutritional Compositions, Volatile Compounds, Health Benefits, Emerging Processing Technologies, and Potential Food Products of Glutinous Rice: A Review

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Abstract: Glutinous rice (*Oryza sativa* var. glutinosa) stands out as one of the most popular rice varieties globally, amidst thousands of rice cultivars. Its increasing popularity is attributed to its rich nutritional compositions and health benefits. This review aims to summarize the nutritional compositions, volatile compounds, and health benefits of glutinous rice. Further, in-depth studies are necessary to explore the utilization of glutinous rice in enhancing processing technologies and developing new food products. Glutinous rice has been shown to possess numerous health benefits, including antioxidant activity, bioactive compounds, anti-cancer properties, anti-inflammatory effects, anti-diabetic potential, and cholesterol-lowering effects. Besides its nutritional compositions, the major volatile compounds identified in glutinous rice could serve as a functional food for human consumption. Emerging processing technologies related to glutinous rice are elaborated to improve the latest developments for incorporating them into various food products.

Key words: glutinous rice; health benefit; volatile compound; nutritional composition; processing technology

Rice ranks as the second most cultivated grain after wheat, serving as a staple food for over half of world's population (Ramos et al, 2023). In many regions, rice serves as a primary staple, contributing to about 90% of the world's total production (Behera and Sutar, 2018). Glutinous rice (*Oryza sativa* var. glutinosa) holds significant importance alongside regular white rice for most nations worldwide, especially in East and Southeast Asian countries. Due its high phenolic, anthocyanin, and antioxidant pigmented glutinous rice, which comes in various colors like black, purple, red, and brown, has garnered significant interest as a raw material for developing commercial health food products and supplements (Phonsakhan and Kong- Ngern, 2015). Glutinous rice was initially cultivated in Southeast Asia, predominantly by Tai-speaking people, originating in the region between 1000 and 1500 years ago (Srisompun et al, 2013). Presently, the top glutinous rice-producing countries include China, Vietnam, Thailand, Laos, and Myanmar (Sattaka, 2019).

Despite having very low amylose and high amylopectin concentration, each glutinous rice cultivar contributes distinct eating and quality characteristics. Other physicochemical attributes, such as alkali digestibility, gel consistency, and rice starch gelatinization temperature, are associated with variations in the quality of glutinous rice products (Loyda et al, 2021).

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Understanding the nutritional content of glutinous rice is crucial for evaluating the potential development of food products. Despite limited information and knowledge about this crop, the full utilization of glutinous rice is anticipated to increase. Emerging technologies for processing glutinous rice-based products have evolved to meet the demands of modern consumers. To enhance the convenience of consuming and manufacturing food products, glutinous rice grains are often polished or milled into flour. However, the polishing or milling process results in polished grain flour with reduced nutrient and bioactive compound contents due to the removal of the outer bran layers (Li C M et al, 2021). The husk and outer bran layers of glutinous rice are removed during milling to produce grains.

In general, besides being a rich source of carbohydrates and gluten-free, glutinous rice contains higher levels of nutrients, vitamins, and minerals, along with an abundance of bioactive compounds such as anthocyanins, vitamin E, and flavonoids (Loypimai et al, 2015). These nutrients and bioactive compounds vary depending on the rice cultivar, geographical location, and postharvest processing and storage. Similarly, glutinous rice and its derivatives have shown numerous potential health benefits, including antioxidant, anti-diabetic, anti-cancer, anti-inflammatory, and cholesterol-lowering effects (Phonsakhan and Kong-Ngern, 2015; Situ et al, 2019). Consequently, nutritionists, food scientists, and medical experts have paid increased attention to the relationship between diet and human health. Several studies have established a link between the consumption of glutinous rice or processed food products and a reduced risk of chronic diseases (Ahmad Shakri et al, 2021). In developing glutinous rice-based food products, the primary consideration would be the health benefits associated with the nutritional composition of glutinous rice. Utilizing the crop to its full potential in the food industry leads to a wide range of glutinous rice-based food products with significant economic value. Hence, this review aims to provide a comprehensive overview of the nutritional compositions, volatile compounds, health benefits, emerging processing technologies, and potential food products of glutinous rice (Fig. 1). These findings may furnish researchers and food producers with sufficient foundational knowledge to explore new avenues for the evolution of glutinous rice-based products.

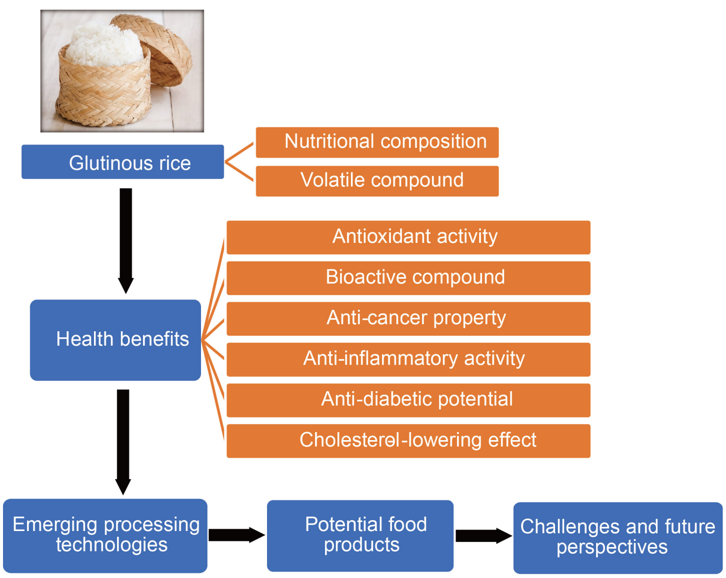

Fig. 1. Schematic diagram of the review article.

Nutritional compositions

The nutritional composition of glutinous rice serves as a crucial indicator for monitoring the quality and processing of the crop. Table 1 provides a comparison of the nutritional content of different glutinous rice varieties. Rini et al (2019) reported the nutritional values of black glutinous rice, including ash content, antioxidant activity, amylose content, and amylopectin content. The quantified nutritional values are ash content (1.19%), antioxidant activity (60.75%), amylose content (10.32%), and amylopectin content (89.67%), respectively. Glutinous rice differs from other rice varieties in its grain starch composition, with a high concentration of amylopectin and a low concentration of amylose (0% to 2% dry basis) (Kang et al, 2010). Glutinous rice contains more starch than regular rice, giving it an opaque whiteness and translucent appearance. Two main cultivars of glutinous rice, *japonica*, and *indica*, are illustrated in Fig. 2.

Glutinous rice bran, a by-product of the milling process, comprises a mixture of bran (brown layer) and germ, serving as a good source of dietary fiber, fatty acids, proteins, and minerals. It constitutes approximately 5% to 8% of the entire grain, containing 13% crude protein, 11% fiber, and up to 20% of its weight in oil (Gul et al, 2015). Additionally, glutinous rice and its by-products, such as defatted rice bran, rice bran wax, and rice

Table 1. Comparison of nutritional content of different glutinous rice.

Glutinous rice	Country	Main nutritional composition (Content)	Reference
Black glutinous rice	Indonesia	Ash (1.19%), amylose (10.32%), and amylopectin (89.67%)	Rini et al, 2019
Black glutinous rice	Indonesia	Amylopectin (95.27%)	Amrinola et al, 2021
Black glutinous rice	Thailand	Anthocyanins (0.26 to 2.54 mg/g)	Phonsakhan and Kong-Ngern, 2015
Brown glutinous rice	China	Total phenol (278.4 mg/g)	Xu et al, 2021
Burirum Sahasin Thai	Thailand	Total anthocyanin (112.1 mg/kg) and total phenolic (1.148 mg/kg)	Sompong et al, 2011
Dongjinchal	Korea	Potassium (44.5 mg/L) and calcium (3029.5 mg/L)	Kang et al, 2010
Hwasunchal and Dongjinchal	Korea	Amylose (0%–2%), crude protein (13%), and fibre (11%)	Kang et al, 2010; Gul et al, 2015
RD6	Thailand	Protein (7.6%) and ash (0.1%)	Anupapsamosorn and Charoenrein, 2015
Red glutinous rice	Indonesia	Amylopectin (94.94%)	Amrinola et al, 2021
Tenuo 2072	China	Total phenolic compounds (5.370 mg/g) and ferulic acid (0.194 mg/g)	Wang et al, 2022
White glutinous rice	Indonesia	Amylopectin (94.38%)	Amrinola et al, 2021
Yangzinuo 2101	China	Calcium (44.94%)	Xiong et al, 2022
Zinuo 18	China	Calcium (29.65%)	Xiong et al, 2022

bran oil, possess hydrolyzed ceramide content (Paosila et al, 2020). In another study, Anupapsamosorn and Charoenrein (2015) investigated the effect of sodium hydroxide and borax on the physicochemical properties of glutinous rice. The findings demonstrated significant differences in the physicochemical properties of glutinous rice with sodium hydroxide and borax treatments. The lower protein and lipid contents may be explained by the solubilization of proteins and lipids extracted from ungelatinized starch granules. Furthermore, Kang et al (2010) reported the potassium and calcium contents in eight different cultivars of glutinous rice, including Sangnamchal, Dongjinchal, Sangjuchal, Hangangchal, Milyang-167, Jinbuchal, Hwasunchal, and Seolhyangchal, and revealed that the Dongjinchal cultivar has the lowest values of potassium (44.5 mg/L) and calcium (3029.5 mg/L) content, respectively.

Moreover, Amrinola et al (2021) investigated the nutritional compounds of different cultivars of glutinous rice, including white, black, and red glutinous rice. It was revealed that the antioxidant activity of black glutinous rice is higher than that of white and red glutinous rice due to its increased phenolic, flavonoid, and anthocyanin contents. Significant differences are observed in the processes of saccharification, alcohol fermentation, acetic acid fermentation, and decoction during the fermentation of Zhenjiang aromatic vinegar with glutinous rice (Gong et al, 2021). The impact of fermentation on the nutritional value, flavour, and antioxidant activity of sweet fermented brown glutinous rice could be determined by calculating its unique physical and chemical properties (Xu et al, 2021). The outcomes demonstrated that starch and other macromolecular polysaccharides eventually break down into low-molecular-weight polysaccharides during the fermentation of brown glutinous rice. In a study conducted by Wang et al (2022), the bioactive components of glutinous brown rice were examined during a two-day germination period. The findings demonstrated that germination considerably increases the levels of ferulic acid (0.194 mg/g), gamma-aminobutyric acid (8 mg/kg), and total phenolic compounds (5.370 mg/g), respectively.

Fig. 2. Main cultivars of glutinous rice.
A, *Japonica* glutinous rice. **B**, *Indica* glutinous rice.

Xiong et al (2022) discussed the amino acid content as well as the interactions between nutritional compositions and metabolites in four different cultivars of glutinous rice. The findings showed that pantothenic acid and ginger glycolipid B are significant metabolites produced by the nutritional composition of purple glutinous rice. Phonsakhan and Kong-Ngern (2015) investigated the anthocyanin content in black glutinous rice, which has anti-oxidative effects and is beneficial to health. Thirty different types of black glutinous rice have anthocyanin accumulation in their grains analyzed, and the findings showed that the anthocyanin content ranges from 0.26 to 2.54 mg/g. Mahmood et al (2018) explored the nutritional values of five different types of traditional

Table 2. Main volatiles and key odorants in different glutinous rice.

Glutinous rice	Main volatile	Key odorant	Reference
Black glutinous rice	Aldehydes and alcohols	Pentanal, hexanal, heptanal, 2-pentylfuran, octanal, nonanal, (*E*)-2-octenal, nonanal, 1-octen-3-ol, decanal, (*E*)-2-nonenal, 1-octanol, and vanillin	Sansenya and Wechakorn, 2021
Thai black glutinous rice	Pyroline	2-Acetyl-1-pyrroline	Sansenya et al, 2017
Thai glutinous rice	Alcohols and aldehydes	Hexanal, heptanal, and 3-methylbutanal	Loyda et al, 2021
Thai glutinous rice	Esters and alcohols	Ethyl hexadecanoate, ethyl tetradecanoate, β-phenylethyl alcohol, and 3-(methylthio)-1-propanol	Zou et al, 2022
White glutinous rice	Aldehydes and alcohols	*iso*-Amyl-alcohol, benzyl-alcohol, phenylethyl-alcohol, and 3-hydroxy-2-butanone	Sulieman et al, 2019
White glutinous rice	Esters and alcohols	2-Methoxy-4-vinylphenol, palmitic acid ethyl ester, and 4-ethyl-2-methoxyphenol	Xu et al, 2020
White glutinous rice	Esters and alcohols	2,3-Butanediol, 2-fenchanol, phenethyl alcohol, and terpinen-4-ol	Liu et al, 2020
White glutinous rice	Aldehydes and alcohols	Hexanal, octanal, non-anal, (*E*)-2-octenal, 1-octen-3-ol, guaiacol, and vanillin	Mohidem et al, 2022
White glutinous rice	Aldehydes	Hexanal, nonanal, octanal, *trans*-2-octenal, *trans*-2-nonenal, heptanal, decanal, (*E*,*E*)-2,4-nonadienal, (*E*,*E*)-2,4-decadienal, 2-pentyl-furan, 2-*n*-butylfuran, 1-octen-3-ol, 2-ethylhexyl acrylate, 2-decanone, and 2-nonen-4-one	Hu et al, 2023
White and black glutinous rice, and Japanese rice	Aldehydes and esters	1-Propanal, 1-propanol-2-methyl, 1-butanal-3-methyl, and acetic acid ethyl ester	Wongsa et al, 2018

Malaysian kuih made from glutinous rice, including Pulut Serunding, Tepung Gomak, Badak Berendam, Kuih Dangai, and Pulut Berinti. The results showed that all varieties of kuih contain a significant quantity of sodium ranging from 660 to 710 mg/kg, except Badak Berendam.

Sompong et al (2011) determined the total anthocyanin content, total phenolic content, and antioxidant activity of glutinous rice using the spectrophotometric technique. Based on a barrel temperature of 150 ºC the values quantified are total anthocyanin content (112.1 mg/kg), total phenolic content (1.148 mg/kg), and antioxidant activity (66.2%), respectively. Thomas et al (2014) examined several parameters of glutinous rice, including gelation characteristics, water activity, pH, emulsion stability, pasting properties, and foaming capacity as well as oil and water absorption rates. The findings related to the functional properties of glutinous rice are expected to be helpful in utilizing the potential of glutinous rice grain variations in the global market to create new food products. Thus, it is crucial to explore the nutritional compositions of glutinous rice to assess their potential uses and applications in food processing.

Volatile compounds

The volatile compounds of glutinous rice have garnered significant attention, playing a crucial role in defining the sensory notes of food aromas. The variety and distinct aroma of glutinous rice represent appealing qualities for consumers and provide valuable insights for ongoing food aroma research. Especially during storage and the shelf life of glutinous rice, monitoring the volatile compounds and aroma profile is useful for quality control of both raw and processed glutinous rice-based food products. Table 2 presents the main volatiles and key odorants in different cultivars of glutinous rice.

A preliminary study aimed at identifying the volatile compounds of fermented glutinous rice added with Fu brick tea revealed a total of 35 volatiles, including esters, alcohols, aldehydes, and acids (Xu et al, 2020). Liu et al (2020) investigated the volatile compounds of *Hong Qu* glutinous rice wine during the conventional fermentation process using headspace solid-phase microextraction coupled with gas chromatography-mass spectrometry. They identified a total of 84 volatiles, with esters, alcohols, aldehydes, alkanes, ketones, acids, lactones, and cycloalkanes being the potent contributors. In another study, Sulieman et al (2019) analyzed the volatile compounds of gluten-free bread made from glutinous rice flour and identified a total of 40 volatile compounds, including propanoic acid, acetic acid, undecane, hexanal, and tetradecane.

Investigating volatile compounds in glutinous rice is beneficial for identifying aroma profiles, although detecting the key odorants contributing to the aroma of glutinous rice has been challenging due to the abundance of volatile compounds. The characteristics of glutinous rice aroma can be linked to the volatiles found in the grains, as well as those formed during cooking (Tharanon and Peerapattana, 2020). Loyda et al (2021) conducted a more extensive examination, studying the volatile compounds of four different glutinous rice cultivars: Khao Dawk Mali105, Chainat1, Kor-khor6, and Pathumtani1. They found alcohols to be the most potent volatiles, followed by aldehydes, furans, ketones, sulfur, and terpenes. The major volatiles detected in all glutinous rice cultivars are heptanal, hexanal, and 3-methylbutanal.

There are more than 100 aroma volatile compounds in glutinous rice, with 2-acetyl-1-pyrroline (2AP) denoted as the primary feature (Hu et al, 2020). The volatile compounds in glutinous rice are typically influenced by several environmental aspects, including temperature, moisture content, and cultivation area. Sansenya et al (2017) investigated the influence of gamma irradiation during plant development on grain weight and 2AP content in Thai black glutinous rice. They found that glutinous rice roots and shoots acquire 2AP, transferring from the roots in the seedling to other parts of the plant. Hexanal is found in higher concentrations than the other detected compounds. The flavor intensity of glutinous rice is correlated with hexanal and other aldehyde compounds, including nonanal, heptanal, 2-pentylfuran, (*E*)-2-octenal, and octanal. Temperature, drought, sun intensity, flooding, and other environmental conditions can impact the flavor characteristics during the production of glutinous rice. Variations in environmental conditions may also impact the synthesis of flavor intensity during the growth of glutinous rice. Nevertheless, the flavor of glutinous rice remains due to the aromatic intensity produced by a combination of all volatile compounds.

Zou et al (2022) detected 38 volatile compounds in glutinous rice wine, including 7 esters, 7 olefins, 6 alcohols, 5 carboxylic acids, 4 aldehydes, 4 ketones, 3 phenolic compounds, and 2 benzenes. They found that glutinous rice aroma is highly correlated with nonanal, hexanal, octanal, vanillin, (*E*)-2-octenal, guaiacol, and 1-octen-3-ol (Mohidem et al, 2022). In a recent work by Hu et al (2023), the major volatile compounds are nonanal, octanal, heptanal, decanal, hexanal, (*E*,*E*)-2,4-nonadienal, (*E*,*E*)-2,4-decadienal, *trans*-2-octenal, *trans*-2-nonenal, 2-decanone, 2-nonen-4-one, 2-pentyl-furan, 2-*n*-butylfuran, 1-octen-3-ol, and 2-ethylhexyl acrylate. Acetic acid ethyl ester, 1-propanal, 1-propanol-2-methyl, and 1-butanal-3-methyl were reported as the key volatiles in Khao Mak (sweet fermented glutinous rice), contributing to wine-like, fruity, and sweet aromas (Wongsa et al, 2018). Hence, the identification of volatile compounds in glutinous rice-based food products can facilitate potential applications in food formulations, especially in the food and pharmaceutical industries.

Health benefits

Glutinous rice is abundant in nutrients such as anthocyanins, vitamin E, flavonoids, and oryzanol, which support human health. The potential health benefits of glutinous rice include providing antioxidant activity, bioactive compounds, anti-cancer, anti-inflammatory, anti-diabetic, and cholesterol-lowering effects, as illustrated in Fig. 3.

Antioxidant activity

Anthocyanins, belonging to the flavonoid family, are plant pigments valued for their anti-inflammatory and medicinal activities (Sen et al, 2020). Black glutinous rice contains anthocyanins, gamma oryzanol, iron, vitamins A, and vitamin B, contributing to overall health and preventing heart disease (Phonsakhan and Kong-Ngern, 2015). As antioxidants, the anthocyanins in glutinous rice can reduce cholesterol and blood

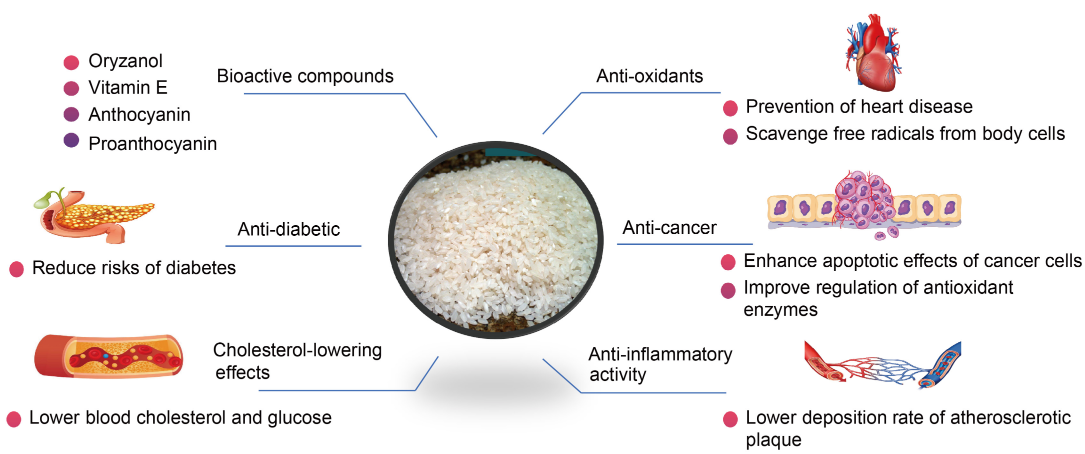

Fig. 3. Potential health benefits of glutinous rice.

sugar levels, promote blood flow, slow tissue damage and aging, inhibit platelet aggregation, and inhibit inflammation throughout the body (Ngamdee et al, 2016). Due to their high pigment content and low toxicity, anthocyanins are potential replacements for synthetic colorants in food coloring (Laokuldilok and Kanha, 2015). Anthocyanins have proven to be powerful functional foods, beneficial to human health. Black glutinous rice, in particular, has larger quantities of anthocyanins and high phenolic content, making it a rich source of phytochemicals with anticarcinogenic properties. Antioxidants are associated with protecting against inflammation caused by reactive oxygen species, which can lead to various diseases.

The antioxidant activities described for oryzanol and vitamin E in glutinous rice bran have demonstrated cell protection from deoxyribonucleic acid, cellular proteins, and oxidative damage of low-density lipoprotein (Gul et al, 2015). Moreover, antioxidants aid in the prevention of cancer and coronary heart disease as well as slowing the progression of diabetes and Alzheimer's disease (Shahidi and Yeo, 2018). Tocotrienols have been shown to address free radicals in cell membranes and aid in the prevention of coronary artery disease. Xu et al (2019) applied the addition of Fu brick tea incorporated with fermented glutinous rice products. The fermentation of this glutinous rice product improves antioxidant activity and increases the ability to scavenge free radicals, as well as demonstrating ferric-reducing antioxidant power. A study performed by Zou et al (2023) evaluated the flavor-related metabolites and amino acids in a traditional glutinous rice ferment drink that also contains chestnuts as lactic acid bacteria. Improved neutralization of reactive oxygen species *in vitro* and protection against oxidative damage in cells can improve the antioxidant activity as well as increase the diversity of flavor-related metabolites.

So et al (2020) examined the antioxidant and antiproliferative activities of glutinous rice sprouts. Due to its higher phenolic and anthocyanin contents, glutinous rice sprouts exhibit better antiproliferant through its antioxidation capacity. It can be noted that glutinous rice sprout a source of physiologically active compounds, beneficial to human health. The abundant antioxidant compounds of glutinous rice, including vitamin E, anthocyanins proanthocyanins, ferulic acid, gallic acid, protocatechuic acid, and hydroxybenzoic acid, are cardioprotective and play a major role in health promotion (Sen et al, 2020). The various phytochemical properties of glutinous rice have a wide range of antioxidant activities associated with their potential health benefits. In another approach, Poomanee et al (2021) reported the impact of cold plasma on the anti-aging activity of the extract and systematically optimized the anthocyanins extraction from Thai purple glutinous rice. The extract demonstrates exceptional anti-aging properties through its ability to scavenge free radicals, inhibit the tyrosinase enzyme, and lipid peroxidation, as well as contribute to the proliferation of skin fibroblasts without causing cellular toxicity.

Zhu et al (2022) discussed the impacts of processing metabolites, flavonoids, black pigments, and the overall antioxidant potential of purple glutinous rice grains, and revealed that the amount of total antioxidant capacity and flavonoids can help in preventing disease and aiding recovery, as well as regulating the body's nutrition. Summpunn et al (2022) investigated different cultivars of Thai glutinous rice for antioxidant and *in vitro* antioxidative activities. Different cultivars and processing methods had an impact on the antioxidant and antioxidative activities of Thai glutinous rice. To meet the demands of farmers who want to produce glutinous rice as a functional ingredient and for food consumption, the results could be used as a reference to choose the best glutinous rice cultivar and primary processing methods. Glutinous rice contains a variety of antioxidant compounds such as phenolic compounds and melatonin. For both pigmented and non-pigmented rice types, the composition of antioxidant compounds was examined in both glutinous and non-glutinous rice grains (Setyaningsih et al, 2015). It was noted that the total phenolics and melatonin content in non-glutinous rice are higher than those in glutinous rice.

Bioactive compounds

Apart from natural antioxidants including tocopherols, tocotrienols, oryzanols, phytosterols, and phenolic compounds, pigmented glutinous rice such as black, purple, and red contains acetylated procyanidin, and anthocyanins that have high free radical scavenging action (Suttiarporn et al, 2015). Consuming pigmented glutinous rice is thought to be healthier for people since it has anti-allergic, anti-mutagenic, and anti-carcinogenic properties (Amrinola et al, 2021). As a result, glutinous rice is emerging as a valuable source for nutraceuticals and food additives. The recognition that other gene products co-regulated with quinone reductase induction are anti-inflammatory and cyto-protective agents comes from screening methanolic bran extracts of black glutinous rice as a response to infer promising health benefits (Ngamdee et al, 2016). Phytochemicals in glutinous rice bran have potential health advantages in reducing the risk of severe diseases. Oryzanol is denoted as a form of ferulic acid esters of phytosterols (Gul et al, 2015). It has been linked to a variety of positive health benefits, including stimulation of the hypothalamus, growth promotion, and a hypolipidemic effect (Mohidem et al, 2022). Furthermore, oryzanols act as antioxidants and blood cholesterol-lowering agents among other biological and physiological benefits. It has been demonstrated that gamma-oryzanol inhibits tumor growth in mice, inactivating macrophages, and inhibiting angiogenesis as well as being helpful in lowering serum cholesterol levels (Sen et al, 2020).

Glutinous rice is well-known as a source of various bioactive compounds such as flavonoids, carotenoids, phenolic compounds, phytosterols, vitamin E isoforms etc (Verma and Srivastav, 2020). In addition to its nutritional benefits, glutinous rice has the potential to be a source of bioactive secondary metabolites. A recent study focused on using pigmented glutinous rice as a successful functional diet due to its bioactive content, in which phenolics represent the early material in the biosynthetic pathway for flavonoids (Hanifa et al, 2020). Phenolics demonstrate promising health benefits in terms of lowering the risks of severe diseases such as diabetes, heart disease, and inflammation (Shahidi and Yeo, 2018). The phenolic compounds may also be helpful for the treatment of type 2 diabetes mellitus because they control blood glucose levels by increasing glucokinase activity and its generation in the liver (Saleh et al, 2019). The flavonoid group of naturally occurring pigments includes anthocyanins, which could be found in the glutinous rice bran layer and have antioxidant activity as well as free radical-scavenging ability.

Apart from that, several additional nutritional components are normally found in other parts of glutinous rice, such as the bran. These additional nutrients are known as bioactive compounds, which contain higher concentrations in the glutinous rice bran (Suttiarporn et al, 2015). Although these substances are very helpful for human health, the growth of the human body does not depend on them. Fermented glutinous rice bran is employed as a new dietary supplement because it provides important amino acids for humans. High-quality proteins make up roughly 10% to 15% of glutinous rice bran (Wang et al, 2022). It is noted that protein supplements made from glutinous rice bran could aid people with protein-related eating. Glutinous rice bran proteins are superior to cereal proteins in addition to having distinct hypoallergenic and anti-cancer characteristics (Jayaprakash et al, 2022). However, glutinous rice bran is still in its early stages of development as a food supplement or medicine.

Anti-cancer and anti-inflammatory activities

At present, nutraceutical products derived from glutinous rice have attracted a lot of interest because of their safety and potential nutritional and therapeutic benefits. Bioactive phytochemicals in glutinous rice bran extract have shown anti-cancer activity in a leukemic cell line (Suttiarporn et al, 2015). After being saponified with potassium hydroxide, the unsaponified fraction is separated, producing four sub-fractions with varying levels of anti-proliferative activity ranging from 2.8 to 467.1 μg/mL against a mouse leukemic cell line. As a localized immune response to the invasion of pathogens or tissue injury, inflammation plays a role in a number of chronic diseases such as cancer, cardiovascular disease, and neurological disorders (Fuloria et al, 2022).

Ngamdee et al (2016) investigated the methanolic extracts from black glutinous rice bran via cellular bioassays for quinone reductase activation. Following the semi-preparative high-performance liquid chromatography fractionation of the crude extract, distinct fractions enriched in phenolic acids, anthocyanins, and proanthocyanins are produced. This implies that anti-inflammatory agents can work synergistically through partial purification. No generation was observed by binary mixes of gallic acid or caffeic acid with the anthocyanin-rich fraction. These findings call for further research into the active ingredients and support synergistic interactions using isobologram analysis. Ongoing research is exploring alternative treatments that can lessen the toxicity of chemotherapy by reducing the medication concentration while maintaining efficacy against cancer cells (Suttiarporn et al, 2015). A study, conducted by Peanparkdee and Iwamoto (2019), evaluated glutinous rice bran and its by-products, which could potentially be used to inhibit the development of oral, liver, and colon cancers caused by carcinogens.

The potential health benefits of glutinous rice have been widely recognized by researchers, who have isolated bioactive rice components such as gamma-aminobutyric acid, anthocyanins, proanthocyanins, sterols, tricin, beta-sitosterol, caffeic acid, methoxycinnamic acid, ferulic acid, cycloartenyl ferulate, and phytic acid (Sen et al, 2020). The constituents of glutinous rice are likely to inhibit the growth of cancer and tumors due to the down-regulation of lipid peroxidation, the scavenging of oxygen and nitrogen radicals, and the improved regulation of antioxidant enzymes (Sulieman et al, 2019). Glutinous rice functions as a natural anti-inflammatory, lowering the rate of atherosclerotic plaque accumulation within blood vessel walls. Consequently, this reduces the chance of developing significant heart conditions, including heart attacks or strokes. Moreover, the anthocyanin, found in glutinous rice may have anti-inflammatory, anti-cancer, blood circulation- enhancing, anti-aging, and cholesterol- and blood-sugar-lowering properties, as well as the ability to prevent gastric acid secretion and platelet aggregation (Ahmad Shakri et al, 2021).

Black glutinous rice is one of the most popular functional foods globally and offers several health advantages. Mapoung et al (2023) investigated the relationships between black glutinous rice germ and bran extracts in terms of their phytochemical content, antioxidants activity, and anti-inflammatory capability. Compared with non-glutinous bran rice extracts, glutinous bran rice extracts have higher levels of cyanidin-3-*O*-glucoside, peonidin-3-*O*-glucoside, antioxidants, and anti-inflammatory activities. Thus, valuable information can be provided to the food industry to choose the type of glutinous rice for functional foods based on anthocyanin concentration, assisting consumers in adopting a healthy lifestyle. Special cultivars of glutinous rice have been produced to offer higher nutrient values and exhibit biological activities beneficial to consumers, supporting the rising trend of consumer interest in foods that promote good health.

Anti-diabetic and cholesterol-lowering effects

Typically, glutinous rice has a high amylopectin content and a high glycemic index, indicating that it can lead to a rapid rise in blood glucose levels and quick digestion. Due to the presence of bran, which contains fiber and phytochemicals including tocopherols, tocotrienols, gamma-oryzanols, sterols, and carotenes, glutinous rice is a healthier option than regular white rice (Peanparkdee and Iwamoto, 2019). Moreover, it also contains free fatty acids, comprising 31% linoleic acid and 44% oleic acid (Amrinola et al, 2022). The majority of the proteins in glutinous rice bran consist of essential amino acids, including leucine, phenylalanine, valine, threonine, and isoleucine (Peanparkdee and Iwamoto, 2019). Glutinous rice has a thick layer of bran, high in fiber, which protects the endosperm. The glycemic index is connected to the carbohydrates in particular foods, positively impacting on decreasing blood sugar levels.

In fact, glutinous rice has a lower amylose/amylopectin ratio than non-glutinous rice, resulting in a higher glycemic index score. Generally, glutinous rice with higher resistant starch content has a lower glycemic index value. It has been revealed that parboiling the glutinous rice could reduce the glycemic index, resulting from the formation and slower digestion of amylose-lipid complexes in the small intestine (Wiruch et al, 2019). The antioxidant compounds in glutinous rice bran are promising candidates to be developed as medicinal agents. In glutinous rice bran, several bioactive compounds such as gamma-oryzanol, gamma-tocotrienols, ferulic acid, phytosterols, tocols, triterpenic alcohol, fibers, unsaturated fatty acids, and tocotrienols have shown hypolipidemic and hypocholesterolemic abilities in humans (Sen et al, 2020). Additionally, positive effects have demonstrated significant cardio-metabolic protective advantages for several groups (obese, diabetic, hypercholesterolemic, and healthy) through clinical trials of glutinous rice bran (Saleh et al, 2019).

In glutinous rice bran, dietary fiber is defined as edible plant components that are partially or totally fermented in the large intestine but not digested in the small intestine of humans (Gul et al, 2015). Several health benefits of dietary fiber, including increasing fecal bulk, lowering blood cholesterol and glucose, and reducing the risks of heart disease, colon cancer, and type 2 diabetes, have been recognized (Hu et al, 2022). Soluble dietary fiber from glutinous rice bran has various applications in the food industry due to its high capacity to hydrate well with food. From a health perspective, it is essential for glycemic control, especially for diabetes mellitus, a chronic metabolic disease caused by insufficient or ineffective insulin production (Saleh et al, 2019). Lowering postprandial blood glucose is crucial for treating diabetes and preventing chronic vascular complications. Eating a diet high in complex carbohydrates and fiber has been shown to be effective. Currently, the *in vitro* assessment of the hypoglycemic activity of soluble dietary fiber primarily focuses on three main factors: 1) reducing bio-accessible glucose in the digestive tract; 2) delaying glucose diffusion by increasing the viscosity of gastrointestinal contents; and 3) inhibiting alpha-amylase activity.

Eating quality of glutinous rice in association with sensory profile

The eating quality of glutinous rice and its derivatives depends on its complex sensory profile, encompassing distinct attributes that define their appeal and satisfaction. Glutinous rice, known for its stickiness and chewiness when cooked, offers a unique textural experience. This characteristic texture, owing to its higher amylopectin content compared with regular rice, significantly contributes to its eating quality (Rini et al, 2019). Similarly, derivatives like rice cakes or mochi inherit this chewy texture, appealing to consumers seeking novel sensory experiences (Qiu et al, 2022).

Beyond texture, the aroma and flavor profile of glutinous rice or its derivatives play a pivotal role in their eating quality. Cooked glutinous rice emits a subtle sweetness and nutty aroma, attributes to its unique composition and preparation methods. These sensory attributes vary based on factors such as glutinous rice variety and cooking techniques, influencing the overall gustatory experience (Hu et al, 2020). Moreover, when glutinous rice is transformed into bakery products, the sensory profile can be further enriched through the addition of flavors or fillings, expanding the range of sensory experiences for consumers (Chueamchaitrakun et al, 2011).

Visual appeal is another crucial component of the sensory profile, particularly in glutinous rice. Typically, cooked glutinous rice grains exhibit translucency and a glossy appearance due to starch gelatinization (Loyda et al, 2021). This visual attribute is often associated with the perceived quality of glutinous rice-based dishes. Furthermore, innovations in glutinous rice-based products maintain or enhance visual appeal, offering products that entice consumers not only through taste and texture but also through their aesthetic appeal. Overall, the sensory profile of glutinous rice and its derivatives is associated with texture, aroma, flavor, and appearance, creating a multi-dimensional eating experience that resonates with consumers seeking diverse sensory encounters in their culinary choices.

Emerging processing technologies

It has been well documented that glutinous rice possesses numerous bioactive compounds with huge potential for use in the creation of functional foods, pharmaceuticals, and for medicinal purposes. Advanced emerging technologies for glutinous rice processing have been developing rapidly, providing many benefits over conventional methods, such as high efficiency, simultaneous multiple evaluations, and real-time decision-making. Generally, glutinous rice is obtained after milling, despite the fact that the germ part is largely lost during the process. To improve the efficiency of the processing operation, several emerging technologies have been swiftly investigated for the assessment of glutinous rice. Kobayashi and Nishimura (2007) investigated the production of new glutinous rice cake products to develop cultivars with distinctive processing characteristics. Potential gene sources for the development of a new cultivar of glutinous rice could come from these mutations for manufacturing rice cakes in the waxy mutant lines. Spray drying is a practical and cost-effective method frequently used for food coloring and micro-encapsulation (Thamacharoensuk et al, 2020). In a similar approach, Laokuldilok and Kanha (2015) discovered that the maltodextrins from black glutinous rice could be used in the micro-encapsulation process to extract anthocyanin. The findings imply that glutinous rice could be used in place of commercially available maltodextrin for anthocyanin micro-encapsulation. Thamacharoensuk et al (2020) aimed to maximize the micro- encapsulation of bacteria by employing whey protein and glutinous rice starch as encapsulating agents. Response surface method is used to assess the composition ratio of whey protein and glutinous rice starch as well as the spray drying parameter of inlet temperature.

One of the most promising techniques for removing the anthocyanin color from glutinous rice bran is ohmic heating. The majority of food substances comprise ionic components such as acids and salts, which could permit the conduction of electrical current (Baudoin et al, 2013). Through ohmic heating, labile materials like vitamins and pigments are protected from extreme thermal degradation. Loypimai et al (2015) studied the application of ohmic heating-assisted solvent extraction in identifying bioactive compounds obtained from glutinous rice bran. For the preparation and preservation of glutinous rice-based products like tang-yuan, the water desorption isotherm of glutinous rice flour is required. Further technical assessments are necessary to confirm the predictions of the theoretical model, even though mechanism-based isotherm models can provide more information on the distribution of water molecules (Zhang et al, 2016).

In the field of food processing, ultrasonication has been recognized as a diffusion-enhancing unit process. Setyawati et al (2016) discussed the breakdown of the mechanical force from the ultrasonic wave to allow amylose to diffuse out more readily at lower processing temperatures. High hydrostatic pressure technology is a novel approach to food processing that offers significant benefits for food safety, modification, and shelf life extension. As a promising food processing approach, high hydrostatic pressure is efficient in enhancing the extracorporeal digestibility of glutinous rice. High hydrostatic pressure alters the gelatinization properties, enzyme activity point, and crystalline structure of glutinous rice starch (Jiang et al, 2019). Qiu et al (2022) explored the potential of pulsed electric field processing to increase the quality and stability of glutinous rice gels and sweetened glutinous rice cakes during 14 d of storage.

To produce biologically active chemicals, an extraction technique is crucial. Since a low extraction temperature is significant, the physiologically active compounds may be lost or damaged during extraction. Surin et al (2020) used ultrasonic-assisted extraction to optimize the crude polysaccharide extraction of purple glutinous rice bran. The modified Langmuir-diffusion model for the adsorption of glutinous rice flour demonstrated that the free water does not follow the well-established bell-like diffusivity when plotted against the relative humidity curve (Zhao et al, 2020). The water sorption kinetics of glutinous rice flour under prolonged water vapor exposure was studied with the difference in the reaction order between desorption and adsorption based on the kinetic responses. This knowledge may be used to improve numerous food processes requiring water transfer economically and in terms of product quality. Additionally, the impact of physical modification via planetary ball mill processing on several physicochemical properties was investigated to increase the value of glutinous rice starch for future pharmaceutical applications (Tharanon and Peerapattana, 2020).

Parboiled glutinous rice is highly nutritious but possesses an unpleasant taste palatability. It is more nutritious than uncooked rice because it retains more minerals and water-soluble vitamins (Behera and Sutar, 2018). Steaming during the parboiling process greatly reduces glutinous rice stickiness, whereas steaming beyond a certain point has no further effect (Li H Y et al, 2021). Additionally, Hapsari and Eun (2016) monitored the microstructure changes during the parboiling of partially milled glutinous rice before and after cooking. While the cooking does not considerably alter the microstructure of the partially milled glutinous rice, the modified parboiling approach significantly changed the microstructure of the samples. Hapsari et al (2016) studied the modified parboiling technique on parboiled glutinous rice, which could lead to increased milled rice yield. The ideal conditions for glutinous rice powder modification using the pre-gelatinization technique have proven to enhance the physical properties of cooked glutinous rice (Oupathumpanont and Wisansakkul, 2021). Rattanamechaiskul et al (2017) evaluated the starch gelatinization process and fluidized drying method to enhance the textural qualities of black sticky rice. Following this process, it was discovered that the amount of starch gelatinization positively correlates with the initial moisture content and the drying temperature of the glutinous rice. It is possible to explore the glutinous rice grain processing properties such as grain temperature and moisture profile using computational and numerical modeling methods. For example, the understanding and knowledge of water absorption kinetics can assist in decreasing the soaking time of glutinous rice. Thus, to help in creating more diversified functional food products and speed up the development of emerging processing technologies, additional studies should emphasize the relationship between health benefits and the composition of glutinous rice.

Potential food products of glutinous rice

In recent years, the production of glutinous rice has witnessed an increase in food business endeavors. Due to its diverse health advantages, glutinous rice holds significant potential as a novel food ingredient in the food industry. The high nutritional values of glutinous rice have captured the attention of researchers and food manufacturers, leading to its incorporation into various food products. This section further elaborates on the development of glutinous rice-based food products, which is summarized in Table 3.

Glutinous rice serves as a primary source of

Table 3. Development of glutinous rice-based food products.

Food product	Country of origin	Description	Processing method	Reference
Ampiang	Indonesia	Flakes glutinous rice	Roasting, flattening	Amrinola et al, 2022
Butter cake	Thailand	Mixed with Hom-Mali and glutinous rice flours	Pasting, gelatinisation	Chueamchaitrakun et al, 2011
Dandelion wine	China	Mixed with dandelion powder, dried schisandra fruit, and glutinous rice	Fermentation	Wu et al, 2016
Dumpling	China	Made with glutinous rice flour and water	Pasting, freezing	Wang et al, 2019
Dumpling	China	Made from glutinous rice flour	Annealing, freezing	Shi et al, 2021
Hong Qu glutinous rice wine	China	Brewed from glutinous rice with fermentation starters	Fermentation	Lv et al, 2012
Hong Qu glutinous rice wine	China	Alcoholic beverage by fermenting cooked rice using starters	Fermentation	Huang et al, 2021
Hong Qu glutinous rice wine	China	Brewed from glutinous rice with fermentation starters	Fermentation	Liu et al, 2022
Jiu-niang	China	Sweet fermented glutinous rice	Steaming, fermentation	Huang et al, 2017
Khao Mao	Thailand	Pounded unripe glutinous rice	Pounding, shredding	Sattaka, 2019
Khao-Mak	Thailand	Sweetened glutinous rice with fermentation starter	Fermentation	Mongkontanawat and Lertnimitmongkol, 2015
Khao-Mak	Thailand	Fermented sweet rice with Look Pang (starter)	Fermentation	Wongsa et al, 2018
Kimchi	South Korea	Fermentation of vegetables with seasoning components	Fermentation	Baek et al, 2023
Kirimochi, arare, okaki, okowameshi, wagashi	Japan	Rice cakes, rice crackers, steamed rice with red beans, and rice pastries	Hardening, heat gelatinisation	Kobayashi and Nishimura, 2007
Ombus-ombus	Indonesia	Glutinous rice flour dough filled with sugar and coconut	Pasting	Sigalingging et al, 2021
Pulut serunding, tepung gomak, kuih dangai, pulut berinti, badak berendam	Malaysia	Sweet or savoury kuih or cakes	Boiling, steaming, frying, baking	Mahmood et al, 2018
Pyracantha rice wine	China	Glutinous rice fermented with *Pyracantha fortuneana* fruit	Fermentation	Wang et al, 2021
Rice noodle, rice cracker, rice snack	Thailand	Pregelatinised rice flour	Extrusion cooking	Sompong et al, 2011
Tang-yuan	China	Made of glutinous rice shaped into ball	Hardening	Wang et al, 2022
Vinasse	China	Alcoholic beverages fermented with glutinous rice	Fermentation	Situ et al, 2019
Waxy rice flour	South Korea	Thickener for sauces and gravies, tenderising agent in frozen foods	Starch gelatinisation	Kang et al, 2010

carbohydrates, proteins, vitamins, and minerals (Sompong et al, 2011). As a result of the increase in glutinous rice production, the development of novel food products has gained popularity among consumers. Since ancient times, glutinous rice has been extensively used in annual festivals in Japan, representing a fundamental dish in Japanese culture. Rice pastries (wagashi), rice cakes (kirimochi), steamed rice with red beans (okowameshi), and rice crackers (arare and okaki) are among the food products made from glutinous rice (Kobayashi and Nishimura, 2007). Apart from that, glutinous rice has been widely used in producing snacks and festival foods in China such as rice cakes (Mi-gao), dumplings (Tang-yuan), and puddings (Nian-gao) (Wang et al, 2022).

Different processing techniques are required for each food product. For instance, the dough for widely consumed rice cakes and rice crackers is chilled during production for easy cutting. The hardening rate of the rice cakes varies significantly according to the different types of cultivars and the ripening period of the glutinous rice. To broaden the range of uses and consumption rates for glutinous rice, rice cake manufacturers are currently in need of novel glutinous rice cultivars with distinctive processing and grain properties.

Many different types of traditional Asian desserts employ glutinous rice in their preparation. Glutinous rice may be served as ‘sweet rice’ if it has been mildly sweetened during the cooking process. Additionally, it is used to make rice cakes, sushi, rice balls, and rice wine. Glutinous rice flour is also used to thicken sauces and gravies and to tenderize frozen foods among other uses in processed food products (Kang et al, 2010). The genetic concept based on the starch viscosity of glutinous rice was determined using the association analysis approach to establish the starch viscosity profile (Anupapsamosorn and Charoenrein, 2015). The starch viscosity profile of glutinous rice is considered a highly vital indicator of cooking, eating, and processing quality aspects. Although the connection between the starch viscosity profile of glutinous rice and these indicators is limited, knowledge of the genetic mechanism could assist in attempts to improve the quality of glutinous rice. Yan et al (2011) discovered the genotypes of 17 starch synthesis-related genes in 118 glutinous rice accessions using gene-specific molecular markers, which may help enhance the quality of glutinous rice.

The *Hong Qu* glutinous rice wine is a well-known traditional fermented product in Southeast China. It is likely to become one of the most well-known rice wines worldwide due to its bright red color and subtly sweet flavor. In view of its health-promoting functionality, it could lower total cholesterol and total triacylglycerol concentrations while also possessing antioxidant activities (Lv et al, 2012). However, the majority of *Hong Qu* is produced using conventional methods based on empirical knowledge utilizing glutinous rice as the substrate for naturally occurring microbes (Huang et al, 2021). Typically, the conventional methods involved in the open fermentation of *Hong Qu* glutinous wine in pottery jars include steaming, macerating, pressing, saccharification, and storage (Liu et al, 2022). Instead of being produced in sterile and controlled environments, *Hong Qu* is usually made in an open environment. On the other hand, vinasse is a conventional rice-based alcoholic beverage in China, fermented with glutinous rice and leavening agents such as yeasts, molds, and bacteria (Situ et al, 2019).

A traditional Chinese dish called sweet fermented glutinous rice (Jiu-niang) is made by fermenting steamed glutinous rice with a starter made of molds (Huang et al, 2017). Jiu-niang is one of the most well-known traditional solid-state fermentation foods in China due to its sweet flavor and rich nutritional content. For this reason, Jiu-niang has been utilized as a quality enhancer in the production of steamed bread, primarily to improve sensory and textural properties. The dough used in Jiu-niang produces a unique taste and imparts sweet flavors to steamed bread. Moreover, the discovery of the potential of dandelion to be incorporated with glutinous rice has therapeutic effects on high-fat diet induced hepatic steatosis and diuretic activity. Dandelion root powder has been combined with glutinous rice and schisandra fruit to improve the processing technologies of fermented compound wine (Wu et al, 2016). In addition, glutinous rice has been fermented with *Pyracantha fortuneana*, a type of wild plant resource with significant nutritional and medicinal benefits to enhance the functional quality of wine (Wang et al, 2021). It is anticipated that creating a nutrient-rich and healthful pyracantha glutinous rice wine would offer an efficient method for the entire utilization of *P. fortuneana* resources.

It was revealed that glutinous rice flour can replace some of the high-priced Hom-Mali flour often used in bakery products (Chueamchaitrakun et al, 2011). To determine the market potential of the food product, more research into consumer acceptance of cakes and pastries manufactured from mixed flour is required. Cereal products created from glutinous rice flour have been employed in a meat emulsion to retain water, bind meat particles, improve texture, and aid in the gel formation and structure of the food product (Pereira et al, 2019). Glutinous rice flour may offer good nutritional content and enable the manufacturing of healthier, as well as gluten-free, meat products. Hemicelluloses from glutinous rice bran show enormous promise in the food industry, particularly for functional and nutritional purposes, such as bread, cookies, pizza, and beverages (Gul et al, 2015). The protein extractability and solubility of glutinous rice bran have shown potential improvements in thickening, emulsifying, as well as stabilizing properties in food products. A high-fiber meal such as rice bran can give certain food texture, gelling, thickening, emulsifying, and stabilizing qualities in addition to the physiological advantages it offers. The small amount of fat present in glutinous rice bran fiber naturally can act as a flavor enhancer, whereas food products coated with stabilized glutinous rice bran tend to absorb less fat during frying (Surin et al, 2020).

Khao-Mak is a sweetened glutinous rice that has lactic acid and alcohol added for a unique flavor which is made with Look-Pang (a fermentation starter) (Mongkontanawat and Lertnimitmongkol, 2015). Look-Pang is a semi-circular starch ball that consists of mold, yeast, and antibacterial herbs, including galangal, garlic, and pepper (Wongsa et al, 2018). In the future, Khao-Mak made from germinated black glutinous rice could be a new nutritious product employed for its medicinal benefits. Traditional cakes or kuih from Malaysia are passed down from one generation to another and could be differentiated by state and location. The texture and nutritional properties of Malay kuih vary according to the natural ingredients used, including sweet potato, tapioca flour, sago flour, and glutinous rice flour (Mahmood et al, 2018). Some Malay kuih made from glutinous rice, such as pulut serunding, tepung gomak, kuih dangai, pulut berinti, and badak berendam, have a sweet or savory flavor and are frequently consumed for breakfast or tea. Glutinous rice has also been incorporated with honey due to its stickiness and enticing natural sweetness. It is typically utilized in Asian traditional snacks or sweets such as mochi, hangwa, injeolmi, dodol, and Bhoja chaul, which could improve the quality of these food products by softening the texture and delaying the hardening process (Seow et al, 2019). Khao Mao is another well-known Thai dish produced from young and green glutinous rice (Sattaka, 2019).

Ombus-ombus is a conventional container for wet cakes, normally eaten at special events for the Batak communities in Indonesia (Sigalingging et al, 2021). The major ingredients used for making ombus-ombus are glutinous rice flour dough filled with coconut and sugar. Flaked glutinous rice is a type of flake rice created from pre-roasted and flattened glutinous rice grains. It is often made from glutinous rice grains in pigmented or non-pigmented forms (Amrinola et al, 2022). Due to its distinctive stickiness and opaque characteristics, glutinous rice is regarded as a great substance for thickening soups, staple dishes, and sweets. Dumplings are often produced from glutinous rice flour with a soft and sticky texture as a unique dish for the Chinese Lantern Festival (Shi et al, 2021). Particularly, dumplings are produced from glutinous rice flour mixed with water to be formed into various shapes and sizes (Wang et al, 2019). Over the past few years, glutinous rice has been widely used in Chinese delicacies and festival foods such as Tang-yuan (sweet rice balls), rice cakes (Nian-gao), and pudding (Mi-gao) (Wang et al, 2022). The most popular traditional Korean fermented food is kimchi, often served with other side dishes in practically every meal. In order to make kimchi, vegetables like cabbage, radish, and green onions are fermented together with other key spice ingredients including red pepper flakes, leek, garlic, and ginger (Baek et al, 2023). Numerous sub-ingredients, including glutinous rice paste, pine nuts, and fish sauce, are frequently added to enhance the taste and flavor of kimchi.

Challenges and future perspectives

The concerns regarding glutinous rice encompass vast potential across several indicators, including processing, production, location, facilities, culture and tradition, management of natural resources, community involvement, community administration, promotion, and services. To ensure a sustainable quality of life for glutinous rice farmers and their communities, incorporating glutinous rice cultivation and cultural activities into the overall community development program is anticipated to raise awareness regarding food, employment, and cultural security. Establishing specifications for glutinous rice quality that can be globally adopted is imperative due to its international trade. Labelling, packaging, and branding are several strategies that could promote glutinous rice, particularly in markets where consumers are accustomed to buying packaged products. The utilization of ultrasonic processing has been proposed to develop rapid cooking times and the soft texture of glutinous rice on an industrial scale (Surin et al, 2020). Employing advanced processing and cooking technologies can enhance the quality and overall acceptability of glutinous rice. Other challenges concerning glutinous rice include packaging type, storage temperature, and pre-treatment, all of which impact glutinous rice quality during storage. Therefore, effective and affordable processing and packaging methods are also required to increase the shelf-life and stability of glutinous rice during storage.

Glutinous rice starch characteristics have received significant attention in genetic research as they are essential for modifying glutinous rice to suit consumer preferences. Glutinous rice starch is a crucial component in the production of nanofilms, mucoadhesive, and pharmacological adjuvants. It is expected that glutinous rice bran and its biomolecules will be developed into medications to treat various human disorders, including inflammatory disorders, metabolic diseases, and oxidative stress-related carcinogenesis. However, the development of specific breeding trait targets is hindered by the lack of understanding of the genetic factors affecting texture complexity and grain filling rate. Linking genetic data with quality phenotypes in different environments is necessary, as the physicochemical properties of glutinous rice vary depending on environmental conditions and gene interactions (Custodio et al, 2019). Commercializing glutinous rice as future functional foods presents opportunities due to the vast genetic variation in different glutinous rice colors. To ensure bioavailability and food safety, it is crucial to assess the final concentrations of bioactive compounds in pigmented glutinous rice-based food products after cooking or baking (Kasote et al, 2021). Identifying the best postharvest processing methods to generate more polyphenolic compounds via conventional cooking and baking operations is advisable to maintain the health benefits. Moreover, the nutty flavor and astringent taste of glutinous rice, derived from volatiles and phenolic compounds, can limit its consumption.

Depending on the desired quality, postharvest and processing steps of glutinous rice must be coordinated with different cultivars, environmental factors, and types of fertilizers (Müller et al, 2022). Monitoring postharvest handling based on the chemical compositions of the crop can assist in decision-making related to glutinous rice production. Further research should explore microwave drying with controlled air temperatures and intermittent or fixed-layer processes linked to freeze-drying technologies for industrial-scale purposes. Additionally, promising directions for glutinous rice storage include modified environments and artificial refrigeration. Developing new technologies using sensors and software to continuously monitor risks and hazards in glutinous rice storage and processing facilities is essential.

However, despite successful applications of supplementing of glutinous rice-based food products with natural sources in research studies, the application of processing technologies in the food industry is facing some technological challenges. Upcoming studies should address health concerns, safety, and cost-effectiveness for the supplementation of glutinous rice-based food products with natural sources. Various by-products of glutinous rice, including husk, straw, and bran, are beneficial for further applications in processing bioactive compounds. These compounds can potentially be transformed into food preservatives, colorants, additives, as well as anti-cancer and anti-inflammatory agents. However, the cost of extracting bioactive compounds and the toxicity of the extracting solvents are significant considerations for the industry. Current research has investigated the extraction and processing of bioactive compounds based on different cultivars of glutinous rice. Greater attention should be paid to producing glutinous rice-based food products to prevent environmental pollution and alleviate farmer poverty.

Conventional methods for assessing glutinous rice are challenging even for skilled individuals due to the tedious nature of these tasks. One drawback is the time required to complete these tasks, which can hinder large-scale evaluation and decision-making processes. Moreover, the classification task is computationally challenging and rigorous due to the inherent variability of the crop. Further studies are needed to assess the effectiveness and practical applications of emerging processing technologies in creating healthier glutinous rice-based food products with enhanced sensory and gastronomic qualities. Future research should also focus on evaluating the effects of glutinous rice consumption on human health to generate high-quality scientific data regarding its potential health benefits. A major obstacle to the commercialization of glutinous rice is the lack of consumer awareness regarding its health benefits. Therefore, educating consumers about the relationship between glutinous rice consumption and well-being is crucial to promote its utilization as a food product.

Conclusions

The promising potential of glutinous rice has garnered renewed interest, particularly in its applications in the food industry. This review has elucidated the nutritional compositions, volatile compounds, health benefits, emerging processing technologies, and the development of glutinous rice-based food products. Glutinous rice is rich in nutrients and minerals beneficial to human health, including carbohydrates, proteins, anthocyanins, vitamin E, and flavonoids. Its distinctive volatile compounds and nutritional values have made glutinous rice a profitable crop with potential applications in the pharmaceutical and biomedical industries. Numerous studies have demonstrated the antioxidant, anti-inflammatory, anti-diabetic, and cholesterol-lowering effects of glutinous rice. The functionalities of glutinous rice significantly impact its chemical compositions, necessitating research into the relationship between chemical compositions and functionalities to develop diverse glutinous rice-based products tailored for commercial markets.

Apart from that, attention should also be given to developing emerging processing technologies rather than focusing exclusively on the distinctive qualities and properties of glutinous rice. To pique the interest of the private sector and growers in expanding glutinous rice production, particularly in rural areas, the related parties should offer more facilities and appropriate services. It is important to conduct extensive research and development of glutinous rice in numerous areas such as agronomy, pest and disease control, automation, as well as postharvest handling and storage. New exploitations need to be discovered to increase the market and niche for glutinous rice-based products. Since glutinous rice is available year round, there are many opportunities for commercial value to be realized. Future investigations could provide new perspectives related to the enhancement of glutinous rice productivity. For this reason, it is advantageous to identify the main issues surrounding glutinous rice to maximize the exploitation of the crop. However, there are several challenges and limitations with the commercialization and consumption of glutinous rice in terms of sensory characteristics and shelf life. There is a need for cutting-edge processing technologies to create nutritious glutinous rice-based food products with high edible and sensory properties. Thus, emerging processing technologies must be developed that are easy to use, inexpensive, practical, and efficient to increase the utilization of glutinous rice in the field of food and pharmaceutical industries.

Exploring the relationships among these elements involves understanding the intersection of nutritional contents, health benefits, potential food products, challenges, and future perspectives in the context of glutinous rice. Glutinous rice serves as a staple food in many cultures. Leveraging these nutritional aspects, the potential for producing diverse food products from glutinous rice expands. However, challenges such as maintaining consistency in nutritional content across varieties, addressing the high glycemic index associated with its carbohydrate content, and meeting evolving consumer demands for healthier alternatives pose hurdles. Future perspectives revolve around innovative processing methods and formulations that balance tradition and health, aligning with changing dietary preferences and health-conscious markets.

Emerging processing technologies significantly impact the nutritional content of glutinous rice-based products. Understanding the influence of these compounds on sensory attributes becomes pivotal in developing food products that align with consumer preferences while utilizing innovative processing techniques. Volatile compounds contribute significantly to the aroma and flavor of food products derived from glutinous rice. Leveraging emerging processing technologies to manipulate volatile compounds can enhance aroma profiles but poses challenges in retaining traditional tastes or creating consistent sensory experiences. The interconnectedness among nutritional contents, health benefits, potential food products, challenges, and future perspectives of glutinous rice underscores the intricate relationship between technology, nutrition, sensory attributes, and consumer preferences. Balancing these elements while leveraging emerging processing technologies forms the cornerstone for the evolution of glutinous rice-based food products in response to changing market demands and health considerations.

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