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By-products of Rice Processing: An Overview of Health Benefits and Applications

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Abstract

Our study was centred on the increasing literature associated with rice by-products and main components, especially those intended to combat cancer, improve plasma lipid levels or control the blood glucose levels. Rice by-products, such as rice straw, rice husks, rice bran, rice germ and broken rice, are extensively abundant agricultural wastes from the rice industry, and the percentage of their production depends on the milling rate and type of rice. Among all rice by-products, rice bran has been extensively studied.

It contains phytochemicals such as γ-oryzanol, vitamin E, mainly tocotrienols and dietary fibre. This paper reviews the existing literature on the potential role of rice by-products, focusing not only on the role of rice bran but also on the roles of other rice by-products, such as rice germ and rice husk, in the management of the diseases, investigating their various potential uses in the food industry and all possible properties that may contribute to these effects.

Keywords: Rice straw; Husk; Rice bran; Rice germ; Anti-cancer; Lipid profile

Introduction

Rice (*Oryza sativa*) is one of the main cereal crops, as well as staple food for most of the world's population, especially Asian countries [1]. Approximately 600 million tons are harvested worldwide annually [2]. Frequently, rice is eaten in cooked form by humans to obtain various nutrients, as well as to supplement their caloric intake [3]. The milling of paddy rice has nearly a 70% yield of rice (endosperm) as its major product, although there are some unconsumed portions of the rice produced, such as rice husk (20%), rice bran (8%) and rice germ (2%) [4-6].

Most of the rice by-products, including rice husk and rice bran, are used as animal feeds. Brewer's rice, which is a mixture of broken rice, rice bran and rice germ, is also used almost exclusively in the production of beer. In recent years, rice by-products have received increased attention as functional foods due to their phenolic base compounds, in addition to having high amounts of vitamins, minerals and fibre, which can help to lower cholesterol and enact anti-atherogenic activity [7].

This review was performed with the objective of enhancing the understanding of some of the relevant literature on rice production, the milling process and rice by-products, as well as the benefits associated with these by-products. Possible properties in rice by-products that might have positive health effects were discussed, including compounds to improve the lipid profile and blood glucose level and to inhibit the proliferation of cancer cells.

Rice Production and Demand

Rice, a monocotyledon plant, is known as *Oryza*. The genus *Oryza* is composed of two cultivated species, namely *Oryza sativa* and *Oryza glaberrima*, plus 21 wild species [8]. *O. sativa* and *O. glaberrima* are native to Asia and Africa, respectively [9], although they can grow over wide geographical conditions [10]. *O. sativa* has a superior yield and milling quality and is commercially grown in 112 countries across the continents, whereas *O. glaberrima* is grown only in the West Africa region [9].

Rice is one of the most important staple foods for nearly half of the population in the world [11]. The worldwide production area for rice is about 150 million hectares, while the annual production is about 590 million tonnes [12]. The Asian region produces approximately 90% of the total global rice output, to which China and India contribute 28.7% and 19.5% shares of the total output, respectively (Table 1). Rice has become an important crop in specific regions of North and South America, Africa and Europe [13].

Statistics showed that in the year 2009, 196.7 million tons of paddy (unmilled rice) was harvested from 29.8 million ha of planting areas in China, while 41.9 million ha of planting areas harvest approximately 133.7 million tons of paddy in India [14]. The exported quantities of rice from China and India are relatively low due to the high demands of their huge populations, although they are still the largest rice producers in the world [9]. The demand for rice is expected to remain strong over the next few decades due to the economic and population growths forecast in many countries, including African and Asian countries [15]. Therefore, the rice industry will remain sustainable for a long time, and the production of rice by-products will remain high [16].

Rice Processing

Rice grain consists of many components, as shown in Figure 1. Thus, there is a need for rice grains to undergo several processing steps before they can be consumed by humans. Rice processing covers the operations from harvest to the production of graded and polished white rice. From the rice harvesting process, residue-to-product-ratios

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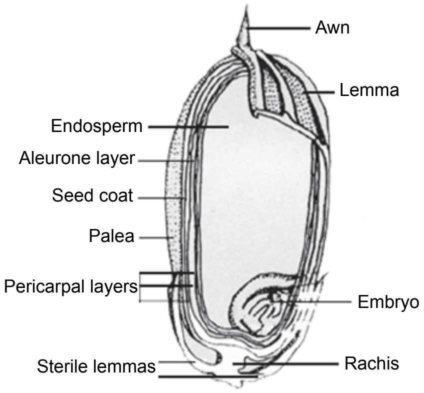

Figure 1: Structure of rice grain [16].

values for rice straw ranging from 0.41 to 3.96 were produced for every kilogram of harvested paddy [17].

The rice milling process involves cleaning, hulling and post-hulling processing (whitening, polishing and grading), which combined will produce several rice by-products, as described in Table 2. The percentage of rice by-products is dependent upon several factors, such as the milling rate and type of rice. An ideal milling process will yield 20% husk, 8-12% bran depending on the milling degree and 68-72% milled rice or white rice, depending on the variety [18].

Nutritional Values of Rice By-products

Rice by-products actually had higher amount of nutrients when compared to the polished rice. Table 3 shows the proximate composition and major minerals of several rice by-products. Rice bran, which is derived from the outer layer of the rice grain, is composed of an aleurone layer of the rice kernel, with some proportion of the endosperm and germ [35] accounting for approximately 10% of the weight of the rice grain [36]. This part is composed of both lipophilic antioxidants (tocopherols, tocotrienols and γ-oryzanol) and phenolics [37]. These substances protect against chronic diseases of the cardiovascular system and help to quench the free radicals and anti-cancer effects [38,39].

Rice germ is also known as the embryo or reproductive parts, which germinate and grow into plants [40]. The content of vitamin E in rice germ is 5 times higher than that in rice bran. The major vitamin E component in rice germ is α-tocopherol, which is the most active form of vitamin E, whereas for rice bran, the major vitamin E component is γ-tocopherol. In addition to these, rice germ also contains a substantial concentration of vitamins (B_1, B_2 and B_6), fibre and neurotransmitter γ–aminobutyric acid (GABA), which is believed to have many beneficial health effects, such as lowering the blood pressure, improving cognition and lowering blood glucose levels. The level of γ-oryzanol in rice germ, however, was 5 times lower than the level in rice bran [41]. This is in accordance with Butsat and Siriamornpun [42], who also reported that the bran has the highest oryzanol content compared to other parts of rice.

The components of dietary fibre in rice by-products include cellulose, hemicellulose, pectins, hydrocolloids and lignin. These can be classified into two types, depends on their solubility in water. The structural or matrix fibres, such as lignins, cellulose and some hemicelluloses, are insoluble, while the natural gel-forming fibres (pectins, gums, mucilages and the remainder of the hemicelluloses) are soluble. Generally, soluble fibre forms a gelatin-like substance in the intestine and increases the water content in the stool. It has also been demonstrated to possess the ability to decrease the blood cholesterol and sugar after meals in diabetics [43]. Insoluble fibre plays a key role in adding bulk or softening stool, which helps to reduce constipation and haemorrhoids and is also effective in creating a feeling of fullness.

The fibres found in rice husks are mainly lignin, hemicellulose, cellulose and hydrated silica [44]. These components are similar to those in ground rice husk made from defatted concentrated rice bran (Table 4). They are not digested by human pancreatic or brush border enzymes and therefore are not expected to be fully absorbed. However, their consumption does help to control blood glucose levels and lipid concentrations by enhancing the viscosity of the gastrointestinal contents [46].

Antioxidant Properties of Rice By-products

Antioxidants play an important role in preventing damage to the cellular components caused by chemical reactions involving free

Regions	Harvested quantity (million tons)	Estimated rice straw[a] (million tons)	Estimated rice husk[b] (million tons)
Africa	24.51	24.51	4.90
Americas	38.10	38.10	7.62
Asia	618.24	618.24	123.65
China	196.68		
India	133.70		
Indonesia	64.40		
Bangladesh	47.72		
Vietnam	38.90		
Europe	4.10	4.10	0.82
Oceania	0.29	0.29	0.06
World	685.24	685.24	685.24

[a]With residue ratio of 1.
[b]With residue ratio of 0.20.

Table 1: Production quantity of paddy, rice straw and rice husk [13].

Step	Process	Description	By-products
1	Pre-cleaning	Remove all impurities and unfilled grains from the paddy	
2	Husking	Remove the husk from the paddy	
3	Husk aspiration	Separate the husk from the brown rice/ unhusked paddy	Husk
4	Paddy separation	Separate the unhusked paddy from the brown rice	
5	De-stoning	Separate small stones from the brown rice	
6	Whitening	Remove all or part of the bran layer and germ from the brown rice	Rice germ and rice bran
7	Polishing	Improve the appearance of milled rice by removing remaining bran particles and by polishing the exterior of the milled kernel	
8	Sifting	Separate small impurities or chips from the milled rice	Separate small impurities or chips from the milled rice
9	Length grading	Separate small and large brokens from the head rice	Broken rice
10	Blending	Mix head rice with predetermined amount of brokens, as required by the customer	
11	Weighing and bagging	Prepare milled rice for transport to the customer	

Table 2: Rice milling process [18].

Nutrients	Broken[a]	Husk[b]	Bran[c]	Polishings[d]	Straw[e]
Dry matter	87.0-89.0	87.0-92.5	89-94	90	90.9
Protein[f]	6.7-9.8	2.1-4.3	10.6-16.9	11.2-13.4	1.2-7.5
Crude fat	0.5-1.9	0.30-0.93	5.1-19.7	10.1-13.9	0.8-2.1
Crude fibre	0.6	30.0-53.4	7.0-18.9	2.3-3.6	33.5-68.9
Ash	5.0	13.2-24.4	8.8-28.8	5.2-8.3	12.2-21.4
Carbohydrate		22.4-35.3	90	51.1-55.0	39.1-47.3
Calcium	0.09-0.19	0.04-0.21	0.08-1.4	0.05	0.30-0.71
Phosphorus	0.03-0.04	0.07-0.08	1.3-2.9	1.48	0.06-0.16

[a][19-23]
[b][19,20,24-29]
[c][19-29]
[d][22,23,29]
[e][25,26,30-33]
[f]Animal scientists commonly use a conversion factor of N x 6.25 for crude protein [34].

Table 3: Proximate composition and minerals content (% of dry matter) of rice by-products.

	Rice husk[a]	Rice bran fiber[a]	Rice straw[b]
Cellulose (%)	38	30	32.0
Hemicellulose (%)	20	20	35.7
Lignin (%)	22	20	22.3

[a][40]
[b][45]

Table 4: Composition of rice husk, rice bran fiber and rice straw.

Author(s)	Year	Components	Findings
Kawabata et al. [67]	1999	Rice germ	Inhibit ACF formation and reduced incidence of colonic adenocarcinoma.
Mori et al. [68]	1999	Rice germ	Numbers of ACF/colon, ACF/cm^2 and aberrant crypts/colon in the group treated with AOM + gamma-aminobutyric acid (GABA)-enriched defatted rice germ (2.5% in diet) and the group with AOM + rice germ (2.5% in diet) were smaller than those of the group with AOM alone ($P < 0.005$). Decreased incidences of AOM-induced large bowel neoplasms ($p < 0.05$).
Park et al. [69]	2003	Chungkookjangs (fermented with rice straw and B. *licheniformis*)	Strongly inhibited the growth of AGS human gastric cancer cells.
Huang et al.[70]	2005	Isovitexin (rice husk)	Inhibit release of TNF-α, a proinflammatory cytokine and cyclooxygenase-2 (COX-2) expression Reduced lipopolysaccharide-stimulated prostaglandin E2.
Jeon et al. [53]	2006	Methanol extracts (rice husk)	Possess significant reactive oxygen activity scavenging and metal chelating activities and protective against oxidative DNA damage using human lymphocytes
Kim et al. [71]	2007	Methanol extracts (rice husk)	Highly cytotoxic, with IC_{50} values of 0.5 µg/ml *in vitro* Reduced colonic pre-neoplastic ACF formation by 35%.
Joung et al. [72]	2008	Momilactone B (rice husk)	Suppressed hypoxia-induced increases in phospho- STAT5, STAT5b, cyclin D1, and cdk4 protein levels in human breast cancer cells.
Boateng et al. [73]	2009	Rice bran	5% and 10% rice bran significantly ($p < 0.05$) reduced the incidence of AOM induced colon tumors in male Fisher 344 rats after 44 weeks feeding.
Roschek et al. [74]	2009	Stabilized rice bran extracts	
Kannan et al. [75]	2010	Peptides (rice bran)	Inhibit 84% of colon cancer cells (Caco-2 and HCT-116) growth, 80% for breast cancer cells (MCF-7, MDA-MB-231) growth and 84% for liver cancer cells (HepG-2) growth.
Norazalina et al. [76]	2010	Phytic acid (rice bran)	Suppressed the number of ACF in the distal, middle and proximal colon compared to AOM.
Nurul-Husna et al. [77]	2010	Phytic acid (rice bran)	Inhibit growth of human colorectal cancer cell line HT HT-29).
Kim et al. [78]	2011	70% ethanol extract	*Seolgaeng* rice husk extract showed anti-proliferative activity against breast cancer (MCF7) and lung (NCI-H460) cell lines; *Hongjinju* rice husk extract significantly exhibited mitogenic activity.
Kim et al. [79]	2011	Smoke extract (rice husk)	Reduced tumor necrosis factor-R (TNF-R), IL-1β, interleukin-1β (IL-1β), interleukin-6 (IL-6), leukotriene B4 (LTB4), prostaglandin E2 (PGE2) and myeloperoxidase (MPO).
Li et al.	2011	Rice bran	Reduced the number of ACF and COX-2 expression of the middle colon.
Shih et al. [80]	2011	Rice bran oil	Colon tumor formation, mucin-depleted foci and ACF especially sialomucin-producing ACF were significantly reduced in 1,2-dimethylhydrazine/dextran sodium sulphate induced colitis-related colon carcinogenesis after 13 weeks feeding.
Norazalina et al. [81]	2011	Phytic acid (rice bran).	Inhibition the growth in hepatocellular cell lines ($HepG_2$).
Revilla et al. [82]	2013	Enzymatic extract (rice bran)	Induce cellular death in human T cell acute lymphoblastic leukemic (MOLT-4) cells.

Table 5: Summary of anti-cancer effect of rice by-products.

radicals [47]. The outer layers of plants, including their peels, shells and husks, can protect the seeds from oxidative damage due to the large amounts of strong antioxidants present, such as flavonoids, hydrocinnamic acid derivatives, isovitexin, phytic acid, anisole, vanillin and syringaldehyde [48-50]. They are good sources of natural antioxidants. However, these by-products, such as rice husk, are mostly

Author (year)	Rice bran derived products	Number of animals or subjects	Study design (Study duration)	Pharmacological effect
Wilson et al. (2002) [119]	20% defatted rice bran 20% whole fat rice bran	60 male Golden Syrian hamsters	10 weeks period	↓ TC, VLDL-C and aortic fatty streak formation.
Zhao (2004)	7% oryzanol (RBO)	47 Sprague-Dawley retired female rats	11 weeks	↑ Fecal cholesterol and total bile acid excretion.
Ausman et al. (2005) [120]	Physically refined RBO	30 hamsters	8 weeks	↓ TC and LDL-C.
				↓15-17% in cholesterol absorption.
				↑30% in neutral sterol excretion.
				↑300-500% in intestinal HMG-CoA reductase.
				↓ > 25% in hepatic HMG-CoA reductase activity.
				No effect on bile acid excretion.
Ha et al. (2005) [121]	BRBO	30 Sprague-Dawley rats	4 weeks rats	↓Liver cholesterol, triacylglycerol and hepatic thiobarbituric acid.
				↑HDL-C.
Minhajuddin et al. (2005) [122]	Tocotrienol rich fraction (RBO)	24 Hyperlipidemic rats	1 week	↓Thiobarbituric acid reactive substances and conjugated dienes.
Wilson et al. (2007) [123]	RBO	48 F_1B Golden Syrian hamster	10 weeks	↓TC, VLDL-C, LDL-C, TG and aortic ester accumulation.
Kennedy et al. (2010) [124]	Rice bran and sunflower oil blend (80:20 ratio with minimum of 5000 ppm of oryzanol)	48 hyperlipidemic and normolipidemic	30 days	↓TC, LDL-C, VLDL-C and TG
Ghatak and Panchal (2012) [125]	Oryzanol (Crude RBO)	36 adult Wistar rats	21 days	↓TC, TG, LDL and VLDL.
				↑HDL-C.

Abbreviations: BRBO: Bioactive components from rice bran oil; HMG-CoA: 3-hydroxy-3-methylglutaryl coenzyme A; LDL-C: low-density lipoprotein cholesterol; TC: Total cholesterol; TG: Triglycerides; VLDL: very low-density lipoprotein cholesterol; HDL-C: high-density lipoprotein cholesterol.

Table 6: Summary of anti-hyperlipidaemic of rice bran derived products.

wasted and are usually used as a feedstock due to their low digestibility, peculiar size, low bulk density, high ash/silica contents and abrasive characteristics [51].

Rice husk contains an antioxidant defence system, including polyphenolic compounds, to protect the inner materials from oxidative stress [49,52]. Phenolic compounds from methanol extracts of rice husks have been shown to exert high antioxidant activities against scavengers of singlet oxygen and to inhibit high hydrogen peroxide-induced damage to DNA in human lymphocytes [53]. These data are also supported by the findings of Kim et al. [54], who showed that *Nokmi* rice husk extracts have effective antioxidant activities.

Numerous primary nutraceutical compounds extracted from rice bran also contain high levels of phytochemicals, which exert antioxidant activities [55]. These phytochemicals are α, β, γ, δ-tocopherol, tocotrienols (vitamin E) [56,57] and γ-oryzanol [56,58]. Vitamin E protects the cell membrane by preventing the oxidation of unsaturated fatty acids and by scavenging free radicals [59,60]. Gamma-oryzanol, however, has been shown to have higher antioxidant activity than tocopherols or tocotrienols [61].

In addition to the rice husk and rice bran, the study by Moongngrm et al. [62] also showed that rice germ contain highest amounts of α-tocopherol and γ–tocopherol, further supporting the earlier finding by Yu et al. [41]. Rice germ has also been demonstrated to have the strongest antioxidant activity, compared to rice bran (containing a bran layer and rice germ) and the rice bran layer (without the germ) [62]. The rice germ extract exhibited electron-donating abilities and hence may play a key role in radical chain terminators by transforming the reactive free radical species into more stable, non-reactive products [63]. For brewer's rice, data from Tan et al. [64] showed that the content of phenolics, vitamin E and γ-oryzanol was significantly lower than in rice bran. It is expected, as indicated by Zhou et al. [65], that the phenolic acids and γ-oryzanol contents of rice are chiefly concentrated in the bran; brewer's rice mostly consists of broken rice, with only small percentage of rice bran and rice germ.

Anti-cancer Effect of Rice By-products

The consumption of whole grains has been reported to protect against colorectal cancer in human interventions [66]. The chemopreventive properties of whole grain consumption have been attributed both to fibres and to other phytochemicals [67] that are mostly present in the bran layer. The data in Table 5 summarise several previous findings on the effect of rice by-products on cancer. Water-soluble rice bran hemicelluloses prevent against 1,2-dimethylhydrazine (DMH)-induced colonic tumours in rats. Rice germ prevents azoxymethane (AOM)-induced colonic aberrant crypt foci (ACF), a preneoplastic lesion in colon cancer, as well as tumours in rats [68,83,84].

Rice bran inhibits the growth of human colon cancer cells [85], and rice bran consumption reduces the number of intestinal adenomas in APC^{Min} mice, an animal model of human familial adenomatous polyposis (FAP) [86]. Finally, DMH- and AOM-induced preneoplastic lesions are inhibited by rice bran-derived sphingolipids in the colons of rats [87,88]. Several phenolic compounds have been recognised in the ethyl acetate extracts of rice bran, such as caffeic acid, cycloartenyl ferulate, ferulic acid, methoxycinnamic acid, p-coumaric acid, protocatechuic acid, sinapic acid, tricin and vanillic acid.

Some of these phenolic compounds have been reported to inhibit the growth of human breast and colon cancer cells [85]. There is no evidence to indicate that rice husk is carcinogenic or mutagenic. Nevertheless, rice husk has shown anticarcinogenic and antimutagenic activities in vitro and in vivo. The in vitro study of water extract from brewer's rice by Tan et al. [64] also demonstrated the cytotoxic effects of the extract against ovary cancer (Caov-3) and colon cancer (HT-29) cell lines with IC_{50} 36.67 µg/ml and 38.33 µg/ml respectively [85-87].

Anti-cancer Mechanism by Rice By-products

Dietary fibre

Epidemiological data has suggested that the consumption of dietary fibre, especially the mixture of soluble and insoluble fibres, is inversely associated with the risk of cancers, such as colon cancer [88,89]. Therefore, the presence of dietary fibre in high amounts in rice by-products might partly explain its effects on the reduction of cancer. The dietary fibre in rice bran that ferments slowly may exert its protective effects through the physical dilution of the contents of the gut through its potential for dilution and faecal bulking capacity [90,91].

This property may shorten the transit time, hence leading to alterations in the mutagenicity of the intestinal contents, altered mucosal cytokinetics and subsequent effects in the excretion of putative carcinogens [90]. It has also been suggested that the production of butyrate from these fibres could protect against the initial stages of colon carcinogenesis [92]. Butyrate, as suggested, is able to arrest the growth of neoplastic colonocytes and inhibit the preneoplastic hyperproliferation induced by the several tumour initiators and promoters [93,94]. This type of fibre also has been suggested to be paramount to carcinogenesis by changing from propionate to butyrate, as observed in animals fed hydrolysed guar [95].

Phytic acid

Phytic acid (inositol hexaphosphate, IP_6), which is a component of rice bran, most cereals, nuts, oilseeds and legumes, has been shown to reduce the incidence of carcinogen-induced large bowel cancer [96] and to inhibit the growth of transplanted tumours [97]; further, it has been shown to have cytotoxic effects against hepatocellular cell lines ($HEPG_2$) [82]. The modifying effects of phytic acid on carcinogenesis have been investigated in several studies [77,90,98].

The phytic acid in rice bran is a negatively charged molecule that is able to bind proteins and starch. Thus, it contributes to the reduction of absorption and increases faecal bulk [99]. Several other mechanisms by which the phytic acid exerts its anti-cancer and chemopreventive properties include gene alteration, cell cycle inhibition, increased natural killer cell activity and antioxidant function [100,101]. Phytic acid enacts effects at the genetic level by affecting signal transduction pathways, cell cycle regulatory genes and tumour suppressor genes [102]. Hence, phytic acid may cause greater differentiation among malignant cells and complete reversions to normal phenotypes [103]. Phytic acid has also been demonstrated to block phosphatidyl inositol-3-kinase (PI-3 K) through its activity and has been found to influence the activity of neoplastic cell transformation in a dose-dependent manner [104].

Furthermore, several colon cancer studies have supported the ability of phytic acid to favourably influence colon morphology by increasing both cell apoptosis and differentiation [105]. These data show that phytic acid may affect the cell cycle by decreasing the S phase of mitosis and arresting cells in the G_0/G_1 phase, thereby enacting an anti-proliferative effect on tumour cells [106]. Phytic acid can be absorbed by cells rapidly (in vitro and in vivo) and metabolised to cause phosphates and inositol levels to become lower. The conversion of phytic acid to its lower forms, IP_{1-5}, by dephosphorylation may contribute to phytic acid's anti-cancer properties. Hence, IP_3 plays a major role in cellular signal transduction and intracellular function [100].

Tricin

Tricin is an O-methylated flavone, a type of flavonoid that can be found in rice bran, and it has been shown to inhibit colon cancer cell growth. Cai et al. [107] reported that feeding on a diet containing 0.2% tricin decreased the size and number of intestinal adenomas formed in *Apc*$^{Min/+}$ mice through the inhibition of cyclooxygenase (COX)-2 [108]. Tricin consumption decreased PGE2 levels in the murine plasma and reduced the number of adenomas, particularly in the proximal small intestine. In addition to these properties, tricin has also long been credited for health beneficial effects due to its antioxidant potential, which can inhibit lipoperoxidation, and its sparing effect on vitamin E in erythrocyte membrane [109,110].

Vitamin E

Various studies have shown the effects of tocotrienol as an anti-cancer agent. For example, rice bran-derived tocotrienol inhibited tumour cell-induced angiogenesis in the mouse dorsal air sac (DOS) assay [111] and could promote tumour necrosis factor-related apoptosis-inducing ligand (TRAIL) through the up regulation of death receptors in leukemic, kidney and pancreatic cells [112].

Oryzanol

A study by Kim et al. [113] suggested that γ-oryzanol in rice bran inhibits tumour growth in tumour-bearing mice by the induction of natural killer (NK) activity, the activation of macrophages and the inhibition of angiogenesis (reduction of vascular endothelial growth factor VEGF, cyclooxygenase-2 COX-2 and 5-lipoxygenases 5-LOX).

Hypocholesterolaemic Effects of Rice By-products

Numerous data on the hypocholesterolaemic effects of rice bran have been produced, especially regarding the oil. Studies have been conducted on rats [114], rabbits [115], hamsters [116], monkeys [117] and humans [118]. In addition to those preliminary studies, other research has shown that there is a significant effect of these rice bran-derived products on improving the lipid profile (Table 6). However, black rice bran extracts reduce the progression of dietary cholesterol-induced atherosclerotic plaque development and cholesterol plasma levels in rabbits [125,126] while decreasing the levels of serum triglycerides and total cholesterol in mice [127].

Some components of rice bran oil that is mainly responsible for the cholesterol-lowering effects in rice bran oil's unsaponifiable fraction (4.2%) [128] include tocols (tocopherols and tocotrienols), β-sitosterol, γ-oryzanol and unsaturated fatty acids [11,129-132].

Cholesterol-lowering Properties

Gamma-oryzanol

Gamma-oryzanol, is present at 13 to 20 times (w/w) higher content in rice bran compared to total tocopherols and tocotrienols [133] and has been shown to decrease animal serum-cholesterol levels and anti-inflammatory activities while inhibiting cholesterol oxidation in vitro [134,58,61].

The effects of γ-oryzanol on biliary secretion and faecal excretion of cholesterol, phospholipids and bile acid were investigated in male albino rats. Bile flow and composition did not cause any changes by feeding gamma-oryzanol at 0.5% level with the control diet. However, the bile flow and total bile acid output were increased by 12% and 18%, respectively. An earlier study by Seetharamaiah et al. [135] showed that there is a significant increase in the faecal excretion of cholesterol

(28%) and bile acids (29%) after feeding gamma-oryzanol with a high cholesterol diet, while cholesterol absorption was lowered by 20%.

Gamma-oryzanol's antihypercholesterolaemic effect also might be due to the sterol moiety, which is split off from the part of the ferulic acid in the small intestine by cholesterol esterase [132,136]. Sakamoto et al. [137] reported that gamma-oryzanol and cycloartenol ferulate have an anti-hyperlipidaemic action and identified that intravenous administration creates more remarkable effects than oral administration due to a direct inhibition of the lipid metabolism. Furthermore, ferulic acid that has been absorbed and metabolised demonstrated an intrinsic hypolipidaemic effect in several studies [138, 139]. Another suggestion from Makynen et al. [140] was that the hypocholesterolaemic activity of γ-oryzanol is due in part to the impaired apical uptake of cholesterol into enterocytes and perhaps a decrease in HMG-CoA reductase activity.

Phytosterols

There are three groups of phytosterols that are usually found in the crude rice bran oil. These include 4, 4'-dimethylsterols (1.2%), 4-monomethyl-sterols (0.4%) and 4-desmethylsterols (1.8%) [141]. Several mechanisms by which plant sterols affect the concentration of cholesterol in the body, such as the formation of non-absorbable complexes with cholesterol, alterations of the size and/or stability of the micelles, interferences with the cholesterol esterification in the mucosal cell and interactions with the protein receptors that are required in the absorption of cholesterol [134].

In addition, the cholesterol-lowering effects of the rice bran oil could also be due to the bile acids and total plasma cholesterol complexes in the intestinal lumen (anion exchange resin-like action) [142]. This hypothesis has been confirmed by a study conducted by Shinomiya et al. [143]. Another study by Wang and Ng [144] on human subjects also reported the anti-hypercholesterolaemic effects of phytosterol.

Vitamin E

Corn, wheat and soybeans contain major tocopherols, while barley, oats, palm, commercial rice bran and rice bran oil contain up to 70% tocotrienols [145]. The hypocholesterolaemic activity of vitamin E in rice bran oil has been clearly shown in several animal species [146,147] and in humans [148,149]. There are several mechanisms that demonstrate how vitamin E can lower cholesterol levels. This includes the role of vitamin E as an antioxidant that inhibits the oxidation of cholesterol [61] and the activity of liver enzyme, 3-hydroxy-3-methylglutaryl-coenzyme A reductase (HMG-CoA-R) [150], which is critical in the cholesterol synthesis rate [151].

Vitamin E also increased the controlled degradation of the reductase protein and decreased the efficiency of the translation of HMG-CoA-R messenger RNA [152,153]. By inhibiting the activity of HMG-CoA-R, the serum total and LDL cholesterol could be reduced; hence, the levels of cholesterol will be lowered [154]. Data from a study by Cicero and Derosa [155] also showed that tocotrienols act as a main mediator of the antihypercholesterolaemic effect in rice bran oil.

Hypoglycaemic Effect of Rice By-products

The effects of rice by-products on the reduction of diabetic risk have been shown by many studies. The diabetes mellitus Type 2 subjects fed with rice bran water-soluble and rice bran fibre concentrates plus AHA Step-1 diet had decreased glycosylated haemoglobin levels (15% and 11%) and fasting glucose (33% and 22%), respectively [154]. The levels of serum insulin were also increased (4%) in both types of diabetes.

The properties of the rice by-products that might contribute to this effect include tocotrienol, γ-oryzanol and fibre. The tocotrienol-rich fraction from palm oil and rice bran oil has been reported to lower the blood glucose levels of patients and preclinical animal models [156-159]. Siddiqui et al. [160] outlined the fact that treatment with the palm oil-tocotrienol rich fraction and the rice bran oil-tocotrienol rich fraction in hyperglycaemia induced nephropathy in Type 1 diabetic rats, significantly improving the glycaemic status and renal functions of the rats.

A study by Fang et al. [158] further showed that δ-tocotrienol within the tocotrienol-rich fraction functioned as a peroxisome proliferator-activated receptor (PPAR) modulator and may improve the utilisation of whole body glucose and insulin sensitivity in diabetic Db/Db mice by selectively regulating its PPAR target genes. Gamma-oryzanol that is present in high amount of rice bran also tends to increase the insulin sensitivity in rats with streptozotocin-/nicotinamide-induced type 2 diabetes [161]. Its activity as a potent antioxidant can suppress the reactive oxygen species generated under a high blood glucose concentration. The high fibre content in rice by-products could also slow down the absorption of the glucose, while the colonic fermentation products of fibre may also enhance glucose utilisation [162].

In addition to tocotrienol, fibre and γ-oryzanol, the phenolic acid fraction of rice bran also may be beneficial for the treatment of type 2 diabetes mellitus because it regulates blood glucose levels by elevating glucokinase activity and the production of glycogen in the liver [163]. Furthermore, GABA also might be beneficial in the reducing the risk of diabetes due to it potentiation of insulin secretion from the pancreas [164].

Applications in Food Products

Currently, people are concerned about personal health and nutrition. Rice bran is highly nutritious and thus is used as a food additive [165]. The primarily use of rice bran as an additive in food is due to its high fibre content, which mildly promotes stool regularity [166-168]. From a marketing view point, the most commonly available rice bran-derived product is the oil [169]. Rice bran oil has an impressive nutritional quality that makes it suitable for nutraceutical products.

It also has the potential to be used as an additive to improve the storage stability in food due to its antioxidants properties [170,171]. Rice bran oil has industrial potential, especially in the preparation of snack food due to the great stability of frying [172], whereas rice bran fibre can be used as both a nutritional and functional ingredient. Chicken coated with stabilised rice bran fibre tends to absorb less fat during frying, and the small amount of fat present naturally in rice bran fibre can act as a carrier of flavours [173].

The nutritional and functional properties of rice bran are suitable for baked products, namely cookies, muffins, breads, crackers, pastries and pancakes [174]. The addition of rice bran into the wheat flour further increased the protein, lysine and dietary fibre contents in bread and cookies. The colour, flavour, protein extractability and solubility of bran, as well as other properties, such as water and fat absorption, emulsifying and foaming capacity, have demonstrated improvements that further enlighten us on the potential use of bran in foods [175]. Due to its naturally occurring enzymatic activity (lipases) and subsequent hydrolytic rancidity, rice bran need to be stabilised to control these undesirable reactions [176].

The process also destroys the fungi, bacteria and insect infestations, hence enhancing the shelf life of rice bran. The stabilised rice bran was successfully incorporated in up to 20% of the production of yeast bread because the hygroscopicity of the rice bran may improve its moisture retention in the baked products, while its ability to foam improved the air incorporation and leavening processes [177]. Defatted rice bran can be used to substitute for up to 10 to 20% of the wheat flour used for making cookies without adversely affecting the quality [178]. Biscuits prepared with broken rice powder were highly acceptable in terms of taste and feel in the mouth [179].

Beside oil, rice bran also has a 10-15% protein content, consisting of 37% water-soluble, 31% salt-soluble, 2% alcohol-soluble and 27% alkali-soluble storage proteins. Rice bran proteins have been found to be of high quality and application in food and pharmaceutical industries. Its unique properties, hypoallergenicity [180] and anti-cancer effects make it a superior cereal protein with a wide range of possible applications. However, as of now, commercial rice bran protein is still unavailable on the market [181].

Rice husks can be formulated and optimised to meet the particle sizes. Its use is technically feasible for about 5% in dry mix applications and about 35% as an adsorbent in liquids [182]. Furthermore, brewer's rice can also be utilised as a brewing adjunct [183]. The brewing industry favours the use of adjuncts because of economic reasons. Shortages of barley and malt and demographic growth will lead to a substantial increase in the use of brewing adjuncts [184].

Conclusions

Rice straw, rice husk, rice bran, rice germ and broken rice are the main rice by-products in the rice industry. Rice by-products may serve as important sources of raw material that could be used as ingredients of functional food and nutraceuticals. They have great potential to be converted into human food to improve food security in the country.

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