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EMERGING TECHNOLOGIES FOR THE RECOVERY OF BIOACTIVE COMPOUNDS FROM RICE BRAN AND THEIR FUNCTIONAL IMPLICATIONS

Ayesha Saddiqa[*1], Muhammad Asif[1,2], Sadaf Shakoor[*2], Arawat Fatima[3], Amara Khan[4], Muhammad Ashfaq[5], Anas Shakoor[2], Nadia Rehan[2], Iqra Aslam[6]

[1]National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan.
[2]Department of Food Science and Technology, UAF-Constituent College, Burewala, Pakistan.
[3]Department of Food Science, Government College University, Faisalabad, Pakistan.
[4]Institute of Food & Nutrition, Gomal University, D.I. Khan, Pakistan.
[5]Department of Entomology, University of Agriculture, Faisalabad, Pakistan
[6]Department of Food Science and Technology, UAF-Constituent College, Depalpur, Pakistan.

[*1]ayeshas3260@gmail.com; sadaf.shakoor@uaf.edu.pk

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Corresponding Author: *
Ayesha Saddiqa
Sadaf Shakoor

Abstract

Rice bran, a by-product of rice milling, is a rich source of bioactive compounds such as γ-oryzanol, tocopherols, tocotrienols, phytosterols, ferulic acid, and dietary fiber. However, its utilization is constrained by rapid rancidity and stability issues. Emerging extraction technologies, including subcritical water extraction, ultrasound-assisted extraction, microwave-assisted extraction, and enzymatic treatments, have shown great potential in efficiently recovering these bioactive compounds while preserving their functional integrity. These advanced methods offer advantages, including higher extraction yields, reduced processing time, and minimal solvent use compared to conventional techniques. The extracted compounds possess significant health-promoting properties, including antioxidant, anti-inflammatory, hypocholesterolemic, and anti-diabetic effects. Incorporation of rice bran bioactive compounds into functional foods such as bakery products, beverages, and cereals enhances nutritional quality and supports consumer demand for clean-label products. Additionally, rice bran valorization contributes to sustainable food systems by reducing agro-industrial waste and promoting circular bioeconomy approaches

1. Introduction

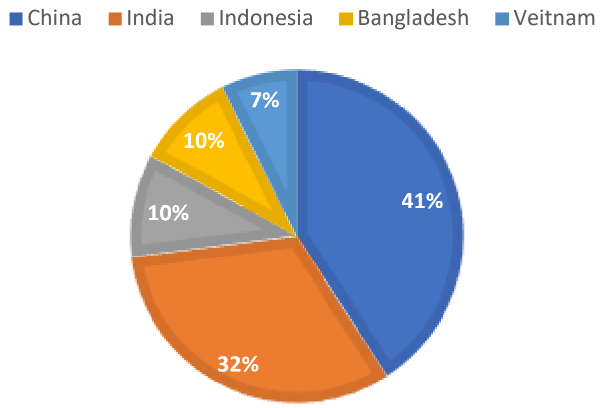
Rice is extensively cultivated and consumed by the majority of the world's population as a staple food. Rice, scientifically known as Oryza sativa, has been a major food staple for humans for centuries. It is valued among cereals as the most valuable nutritional staple food crop because of its versatility, either as human food or as animal feed (Verma and Srivastav, 2020). Rice is well-known as the queen of highly nutritious cereal harvests, which is rich in carbohydrates, fat, fiber, protein, vitamins, food energy, mineral profile, and essential fats. Rice is a balanced carbohydrate medium; it provides a limited amount of protein and fat, as well as riboflavin, niacin, and thiamine (Fresco, 2005). Generally, rice carbohydrate includes starch active in amylose and amylopectin. The rice grain is 14% water, 75% starch, and 8% protein. Its protein, having complex lysine content (5%), is quite digestible (94%), has a high biological value (75.5%), and a protein efficacy ratio (2%) (Ghasemzadeh *et al.*, 2018).

There exist highly nutritional components in addition to these elements existing in various parts of rice known as bioactive compounds (i.e., rice bran, endosperm, and germ portion). In RB, these biologically active compounds are more abundant. These days, owing to the significant relevance of all its dietary qualities, high biological activity, and possible impacts on human wellbeing, rice grains are attracting more interest from their customers as well as nutritionists and health professionals (Verma and Srivastav, 2017).

1.1. Production of Rice

Rice production in 2020 of the various regions of the world is hereby listed (Data estimated by FAO).

In 2020-21, Pakistan cultivated 7.4 million metric tons of rice and is considered the 9th largest producer of rice, of which about 5 million were exported, primarily to neighboring countries of Africa and the Middle East.



2. Milling of Rice

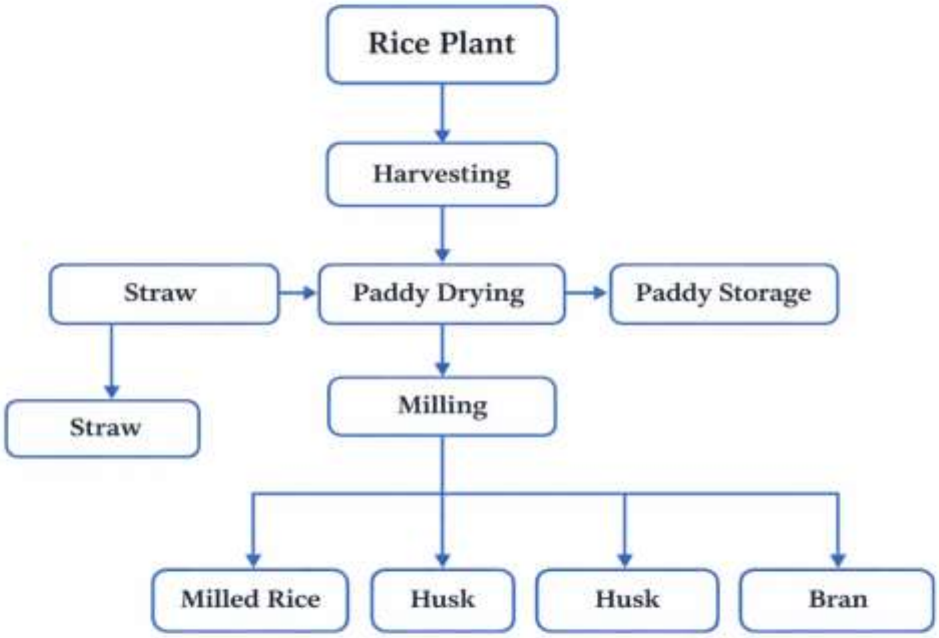


Fig. 2. Commercial rice processing.

Straw, husk, and bran are the primary byproducts produced from rice production and industrial rice processing, as shown in Fig. 2.

One kg of rice crop can yield 2.1 kg of straw, which ensures that about 900 tons of rice straw are collected globally each year from paddy fields. Also, low-value products such as husk (18%) and bran (12%) are generated by commercial rice production (Butsat and Siriamornpun, 2010). Several recent studies suggest that such co-products contain essential bioactive compounds, i.e. fatty acids, total phenolic compounds, antioxidants, and vitamins. E and gamma-oryzanol are likely to benefit human health (Peanparkdee *et al.*, 2018). However, most rice production and rice manufacturing by-products are presently used as animal feed, and there is a substantial quantity that isn't used effectively. Also, the disposal of such co-products has been a significant concern (Daifullah *et al.*, 2003).

2.1. Nutritional Value of Co-products of Rice

In contrast to polished starch, rice co-products have higher levels of essential nutrients. The rice bran (RB), which is extracted from the outermost layer of rice seed, is made up of aleurone film of the kernel, and endosperm, as well as germ, which make up about 10% of the rice grain's weight (Justo *et al.*, 2013). This portion comprises both lipophilic and phenolic antioxidants (tocotrienols, phytosterols, and γ-oryzanol). These compounds guard against chronic coronary diseases and help to reduce free radicals and symptoms of various types of cancer (Rondanelli *et al.*, 2011).

The germ portion of rice is often referred to as the reproductive parts that grow and develop into plants. The vit. E content of a rice germ is 4 times greater than that of rice bran. Alpha-tocopherol is the main vitamin E component of rice germ, while γ-tocopherol is the major vitamin E source of rice bran. Rice grain also includes a large concentration of vitamins (Riboflavin, thiamine, and Niacin), starch, and gamma-aminobutyric acid, which are considered to have multiple therapeutic properties, such as reducing inflammation, increasing concentration, and lowering blood sugar levels (Pawar and Vavia, 2012).

The amount of γ-oryzanol in the germ portion of rice is 4 times less than that in RB. Collagen, hemicellulose, glycerol, hydrocolloids, and cellulose are the sources of fiber in rice co-products. Structural fibers, including certain lignocellulosic materials and xylose, are insoluble, whereas certain wax fibers, like pectin, gums, and glucans, are soluble (Saisavoey *et al.*, 2016). The fibers present in the husk portion of rice are cellulosic fiber, lignin, hydrated silica, and hemicellulose. They remain undigested by human pancreatic secretion but their ingestion can help to regulate blood sugar levels, hypertension, and lipid profile (Sankam *et al.*, 2013).

3. Rice Bran

Rice bran (RB), a by-product of rice milling, is derived from the outer coat of the grain that is an excellent source of many nutritional and bioactive compounds. To process RB, various methods i.e. stabilization, liquefaction, enzymatic therapy, fractionation, and fermentation are mostly employed (Alauddina *et al.*, 2017). Studies have shown that rice bran (6% of the diet for seven weeks), enzymatically extracted, raises blood pressure, insulin sensitivity, and glycogen synthesis. In particular, adenosine injection (7.9 mg/kg), an active RB ingredient, enhances metabolic syndrome in hypertensive stroke-resistant rats (Shirakawa *et al.*, 2009). Kaempferol supplementation (8 mg/kg body mass), rice bran active compound releases endorphins and regulates lipid profile (Ohsaki *et al.*, 2008).

3.1. Compositional distinctiveness of rice bran

The composition of RB varies with rice cultivars, geographical factors, and methodological approaches for processing and production. Rice bran, accounts for 7.9-8.9% of the total grains per spike, carbohydrates (36-58%), lipids (15-18%), dietary fiber (7.9-9.8%) ash (7.2-8.9%) as well as protein (12.9-15.2%). In general, rice oils and bioactive components are plentiful in rice bran. RB is abundant in lipids i.e. linoleic acid (31.2-32.9%), palmitic acid (19.9-.26.2%), and linolenic acid (31.2-32.2%). Due to the high Polyunsaturated fatty acids amount, rice bran is often known as a healthier meal (dos Santos Oliveira *et al.*, 2011). Health statistics show that 90 calories are provided by one bowl of crude RB, and that proportion of RB contains 6.2g fat (2.1g saturated fat and 4.4g unsaturated FA). Moreover, one bowl of RB offers 124 g of carbs and 4.1 g protein, and vitamins B includes thiamine, biotin and pantothenic acid are provided by a single cup of RB (Alauddina *et al.*, 2017).

3.2. Bioactive compounds in rice bran

The material that serves as a secondary metabolite against some environmental threat is phytochemicals (Zhang *et al.*, 2010). Natural bioactive compounds have been reported as flavonoids, alkaloids, terpenoids, nitrogenous compounds, carotenoids, and organophosphate groups. Many phenolics have a high propensity to contribute to the activity of antioxidants in the human metabolism. This chemical is capable of fighting against free radicals that may damage lipids, DNA, and other larger molecules (Liu, 2007). A great source of biologically active phytochemicals is RB, derived from various species of dyed rice. Different research on bioactive compounds in rice bran species has been performed, such as the therapeutic properties of some pigmented RB (Laokuldilok *et al.*, 2011). Rice bran formulations differ based on the source of it, the machining processes, and the strategies of stability. These substances, though, are susceptible and easily destroyed by high thermal treatments (Thanonkaew *et al.*, 2012). Patel and Naik observed that Japan, a successful manufacturer of nutraceuticals and other value-added commodities from bran and paddy derivatives, supplies 3% to the world's overall rice cultivation. Researchers used the food bran portion from colored rice varieties to stimulate the antioxidants in the blood of rabbits, and findings revealed a substantial decrease in endothelial dysfunction (Nagendra Prasad *et al.*, 2011). As a result of this approach in nutritional content and bioactive phytochemicals in rice bran, RB has now been used in various food items due to excellent nutritional benefits (Issara and Rawdkuen, 2016).

3.3. Dietary Fiber of Rice Bran

Dietary fiber (DF) is an edible portion of crops or similar carbohydrates resilient to digestion and reabsorption in the colon of humans by partial fermentation in the large intestine. There are plant-based components that aren't even digested by the metabolites produced by the gastrointestinal tract of humans, but can be hydrolyzed in the colon by intestinal flora. Non-starch polysaccharides such as lignocellulosic materials, certain hemicelluloses, pectin, and lignins comprise these organic food products (DeVries *et al.*, 2001). Polysaccharides, lignocellulose, pectin, hydrogels, and lignin are constituents of DF. Based on their absorbency, they can be divided into two main groups. Structural fibers i.e., cellulose, lignins, and some lignocellulose, are insoluble by the human gastrointestinal tract, while normal gel-forming fibers i.e., pectin, mucilage, gums, and other hemicelluloses, are soluble in mammals. Like a gel, soluble fiber works, and insoluble fiber adds bulk or dampens stool (Sharif *et al.*, 2014). Fiber enrichment is now concentrating on biscuits, pretzels, snacks, drinks, sweets, synthetic cheese, and cereals. The WHO recommendation for DF intake is 23g/day (Organization, 2003). Depending on the commodity, the DF content in the stabilized rice bran ranges from 20 to 35 %. A comparatively limited proportion of soluble fiber (8-12%) is the fiber of rice bran, while the remainder is insoluble fiber (Anderson et al., 1990).

3.4. Oryzanol: Bioactive component of rice bran

A study on the phytoconstituents of RB has recently shown that it comprises hundreds of compounds that are bioactive. Phenols, tocopherol, and oryzanole are the most common. These constituents have a potent antioxidant activity relative to several other minor RB components, and in addition to their therapeutic benefits as bioactive components, they are also used to enhance the stability of various foods in storage. It has been found that the cholesterol-lowering potential of rice bran oil (RBO) is greater than predicted from its FA profile. This indicates that other constituents present in the oil are also responsible for the hypolipidemic effect of

RBO, along with fatty acids (Ghatak and Panchal, 2012).

Rice bran (RB) is an excellent source of bioactive components among agricultural co-product that have uses in clinical, grooming, and food. In specific, γ-oryzanol, phytosterols, and tocotrienols are the unsaponifiable constituents of RBO. Carotenoids, lecithin, and long-chain alcohols such as 2-octacosanol, sitosterol, and flavonoids are other molecules that are present in lower amounts (Danielski *et al.*, 2005). The amount of γ-oryzanol varies from 1.2-3.2% and relies largely on genetic and environmental factors variables (Lloyd *et al.*, 2000). The powerful antioxidant ability has been shown by RB oryzanol, which prevents cells from the detrimental consequences of very-low-density lipoprotein (Friedman, 2013). As it was first extracted from RBO, it is called oryzanol. Like vitamin E, γ-oryzanol has a similar impact on growth stimulation, the circulatory system, and cellular secretions. RB is the most accessible natural source of γ-oryzanol. It consists of around 10.3 g/kg (Fang *et al.*, 2003). The concentration of γ-oryzanol is 15–25 times greater than that of RB phytosterols and tocotrienols (Bergman and Xu, 2003). It has been documented that about 18% oryzanol with a high melting point (129.2-137.9 ° C) is an unsaponifiable fraction of RBO, leading to high photocatalytic activity (Friedman, 2013).

4. Extraction of Bioactive Compounds from Rice Bran

Some of the methods that are employed for the extraction of bioactive compounds from rice bran are discussed below;

Various methods have been used to extract bioactive compounds from rice by-products, including conventional solvent extraction, Soxhlet extraction, and new technologies (such as microwave-assisted extraction, ultrasound-assisted extraction, and supercritical fluid extraction). Additionally, the type and polarity of solvents are also important, since they influence the solubility of bioactive compounds (Wasi et al., 2022; Talha et al., 2024). The advantages and limitations of each technique are mentioned in Table 1.

Table 1. Different extraction techniques: their advantages and limitations

Technique	**Advantage**	**Limitation**
Soxhlet	Broadly used as a classical technique Basic model for the comparison of other techniques	Time consuming High quantity of solvent requires Not environmentally friendly
Super critical fluid extraction	Environment-friendly Time saving Lower viscosity and higher diffusion Minimum wastage Suitable for volatile compounds and performed at room temperature	Polar compounds cannot dissolve Too much costly a system Not suitable for drug and pharmaceutical samples
Microwave Assisted Extraction	Good quality of extract High selectivity of the extract High yield Less time Cost-Effective than Soxhlet	Apparatus is costly Operation is more difficult than ultrasound-assisted extraction Poor extraction yield for non-polar compounds Unfit for heat liable biomolecules
Ultrasound Assisted Extraction	Less energy and power used Higher yield Short processing time	Optimization of ultrasound frequency and power, propagation of cycle, input power, system geometry is required for maximum yield

(Garcia-Salas *et al.*, 2010; Azmir *et al.*, 2013; Abbas *et al.*, 2008; Mendiola *et al.*, 2007; Wang and Weller, 2006; Zhang *et al.*, 2009; Zhang *et al.*, 2011; Barba *et al.*, 2015; Sticher, 2008; Chen *et al.*, 2007; Coman *et al.*, 2020)

4.2. Supercritical Fluid Extraction (SFE)

Specific compounds from liquid or solid food matrix can be extracted using supercritical fluids (CO_2 and N_2) as solvent in supercritical fluid extraction. Supercritical fluid is formed at the highest temperature and pressure above the vapor-liquid equilibrium. It can be used on an industrial scale to extract the targeted bioactive compounds (Lima *et al.*, 2019). In this extraction technique, bioactive compounds are extracted in 2 steps. Firstly, the specific compounds, like flavors, pigments, and bioactive compounds, are extracted. Secondly, unwanted compounds from the matrix, like pesticides, toxins, and pollutants, are removed (Rubio-Rodríguez *et al.*, 2012; Zia *et al.*, 2022).

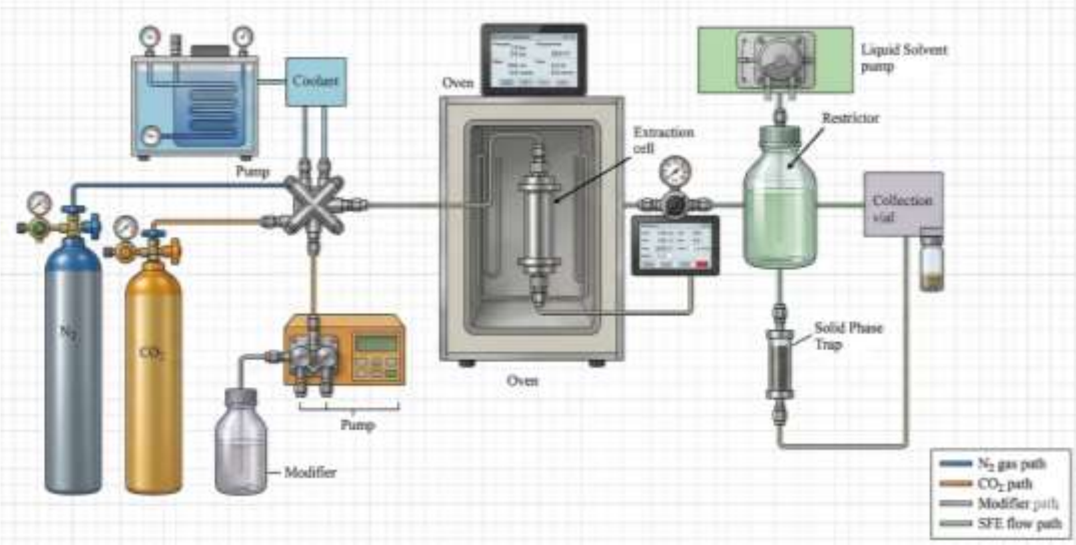


Figure 2. Pictorial representation of supercritical fluid extraction

The traditional method of extraction is the retrieval of biological compounds from plant materials i.e. RB, using solvents. Combustible and sometimes highly hazardous solvents i.e. propanol, heptane, hexane, as well as petroleum ether, are often used in this practice. As there are issues involved with their treatment, the use of such solvents is not environmentally safe. These issues caused scientists and technologists to pursue alternative extraction methods that are non-hazardous and environmentally safe. SFE is a popular tool for this function. This is a promising strategy for meeting the growing market for food and other biological materials for green, edible, and organic fractions. Compared to traditional approaches such as enzymatic extraction and solvent extraction for the isolation and purification of bioactive compounds, the use of the SFE process is ecologically friendly and helpful (Herrero *et al.*, 2010).

As a solvent, SFE uses a supercritical fluid. Each supercritical fluid is characterized by a particular perilous point that depends on the gas/ liquid's pressure and critical temperature. A gas cannot be converted into a liquid above its optimal temperature, irrespective of the pressure applied, but can reach a state similar to a fluid. A material is said to be a supercritical fluid directly above the critical pressure and temperature. The major properties of an SF are viscosity, density, thermal conductivity, and diffusivity. Low viscosity allows movement and penetration into the material without pressure, while greater dissolving strength is given by high densities (Lang and Wai, 2001).

Supercritical CO_2 is a broadly used SF in the food industry. In addition to the non-combustible and non-toxic aspect of carbon dioxide, supercritical CO_2, under differing conditions such as temperature, flow rate, and pressure, often has the benefit of versatility in its extraction capacity. Carbon dioxide is converted above 7.4 MPa and 31 °C to its supercritical state, rendering it the perfect solvent for recovering heat-labile compounds from food media. Furthermore, it also provides improved extraction of fat-soluble compounds with fast recovery rates (Dunford *et al.*, 2003).

The researchers performed a study using the SFE method for the extraction of oryzanol from RB. The effect of procedure parameters on the extraction effectiveness of RBO from rice bran samples using CO_2 as a supercritical solvent was investigated using column partition purification to monitor the isolation and concentration of γ-oryzanol. SFE extracted 17.5 percent oil with 85% extraction performance at 315-kelvin temperature and 330-bar pressure, absorbing 2 kg of CO_2 over 5 h. For the extraction of RBO and γ-oryzanol mainly based on RSM, temperatures of about 330–333 kelvin and pressures of about 255–345 bar were recorded to be optimal (Chen *et al.*, 2008).

Later, experiments were performed to equate the SFE method with the Soxhlet procedure for the efficiency of RB extraction of γ-oryzanol. The effect of various process parameters on the SFE method was assessed by associating the γ-oryzanol recovery rate, γ-oryzanol concentration, and fatty acid profile of the obtained fraction. Mathematical simulation has also examined the average extraction curve. At 28-MPa pressure and 290-K temperature, the highest rate of γ-oryzanol recovery (32.1%), overall global yield (35±5%), moderately high γ-oryzanol content (3.5 %), and the presence of large quantities of MUFA and PUFA are noted (Jesus *et al.*, 2010).

4.3. Microwave-Assisted Extraction (MAE)

Microwave-assisted extraction (MAE) has gained a lot of attention in recent years. It is one of the best green extraction techniques due to high productivity, less extraction time, and low overall cost (Moreira *et al.*, 2017). The main principle of MAE is that energy during microwaves is passed through a medium and transformed into thermal energy, which enhances the extraction process (Iqbal *et al.*, 2021). Disruption of H bonds occurs due to the microwave heating, which causes dipole rotation of molecules. Migration of ions results in dissolution of the component and solvent diffusion. Another mechanism is due to the vaporization of moisture content in the cells, which produces high pressure on the cell wall and changes the physical characteristics and porosity of materials (Datta *et al.*, 2014). It also enhances the solvent penetration, which improves the extraction yield (Datta *et al.*, 2014; Skenderidis *et al.*, 2020).

Figure 3. Pictorial representation of MAE

The antioxidant amalgams in RBO extracted by MAE were analyzed by some authors and reported the strong antioxidant potential of the resulting rice bran oil as shown by the DPPH assay (57.60 μmol). No major variations in the oil produced and overall vitamin E content of RBO extracted by traditional methods and MAE were noted by the authors (Zigoneanu *et al.*, 2008). Microwave-assisted extraction of RBO has been contrasted with traditional methods of extraction by some researchers. They explained how microwave extraction provides improved extraction yield of oil and can therefore be used commercially for efficient recovery of high-quality oil (Terigar *et al.*, 2011).

The researchers observed increased recovery of phenolic resin compounds in different experiments by pretreating the defatted RB with microwaves before subcritical water removal. For the pretreated rice bran, less extraction time was needed. In contrast to the untreated one, microwave pretreatment brings about 65% supplementary overall phenolic withdrawal (Wataniyakul *et al.*, 2012).

Similarly, several chemists performed an analysis to remove antioxidants from rice bran using MAE. The antioxidant potential was higher for pretreated trials. The findings concluded that one of the superior extraction approaches for the extraction of phenols and tocotrienols from RB is microwave-assisted extraction (Duvernay *et al.*, 2005).

4.4. Ultrasonic Assisted Extraction (UAE)

Ultrasound-assisted extraction (UAE) technique uses sound energy, which can be produced by ultrasonic waves having a frequency ranging from 20-100kHz. UAE basically works on the cavitation process, which produces compression and expansion of the food matrix, producing the permeabilization of the cell wall and enhanced extraction of specific compounds. Higher amplitude increases the compression and refraction cycle, assisting the extraction (Al-Dhabi *et al.*, 2017). It is an environment friendly technique and thermo-sensitive compound can be extracted through this technique (Drevelegka and Goula, 2020). Extraction which carried on more than 20kHz could negatively effect on the physicochemical properties of bioactive compounds due to the formation of free radicals (Kentish and Feng, 2014; Shen *et al.*, 2017).

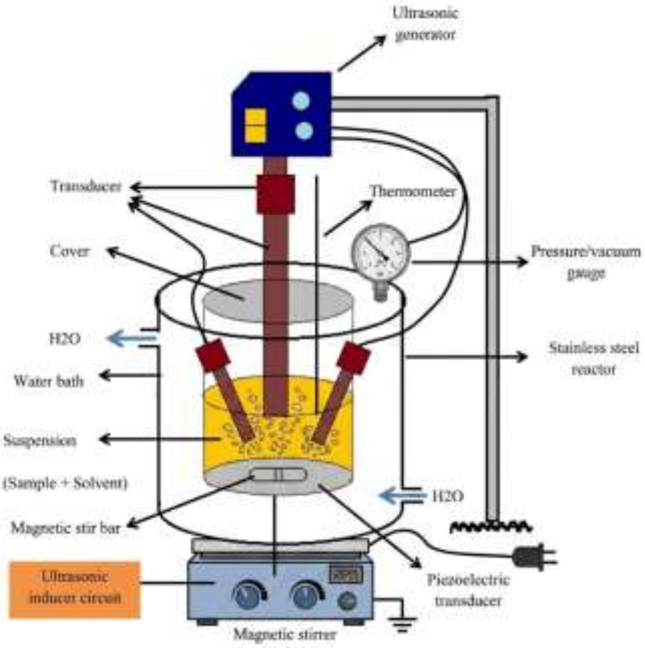


Figure 4. Pictorial representation of UAE

The extraction of organically active fractions using ultrasound practices (15–105 kHz) is being explored as an additional promising practice (Chemat *et al.*, 2008). This method comprises ephemeral sound waves of about 18-22 kHz from a diluent having the raw factual. The sound waves move from the media of extraction and yield substitute expansion and compression sets.

While expansion due to bubble creation, a negative pressure gradient is formed. Bubbles develop, vary in volume, and burst gradually.

This results in increased liquid fluid motors, which, when encountered with solid material, have a powerful effect (Luque-García and de Castro, 2004). High extraction rate, short period, low cost, less retention time, low pressure, and reduced fuel input are major advantages involved in this extraction process (Chemat *et al.*, 2008). The mechanical strength of ultrasonic waves results in significant penetration of diluents into cellular structures, thus enhancing the transfer of mass. To promote the release of cellular components, these forces interrupt the cytoplasmic membrane and primary cell wall, thus increasing extraction efficiency (Wang and Weller, 2006).

Although determining the impact of ultrasound treatment on RBO yield, it was confirmed that RBO yield was greatly affected by the exposure to ultrasound radiation (Khoei and Chekin, 2016). Some findings revealed that the yield of rice bran oil by UAE was like the yield of solvent extraction by using the Soxhlet apparatus. Moreover, relative to the extraction from Soxhlet. RBO obtained using ultrasonic treatment has lower coloring polymers and FFE. Some researchers have investigated the extraction of RB antioxidants and phenolic compounds using USE and ethanol as extraction media. Their findings revealed that USE is an efficient strategy for obtaining high antioxidant potential and better yields of bioactive compounds from RB. In addition, they claimed that the extraction of polyphenols by using ultrasound from RB is a sustainable and ecologically healthy method to acquire compounds rich in antioxidants (Tabaraki and Nateghi, 2011).

5. Health benefits of rice bran

Organic products derived from plants are used as a significant basis of prophylaxis agents for animal and human disease prevention and control (Bagchi, 2006). Nutraceuticals are known to provide several best prospects for improving human health, including bioactive compounds (Camire, 2003). In the recent past, phytochemicals of dietary and non-dietary origin have become the subject of researchers due to their ability to fight different diseases. Rice bran includes phytochemicals that have good health effects (Jabeen *et al.*, 2015). RBO, rich in antioxidants, may play a key role in minimizing the risk of CVD (Thanonkaew *et al.*, 2012). Sterols occur both in the free and esterified arrangements in plants; phytosterol ferulic esters are generally termed as oryzanol (Mariod *et al.*, 2010). Different reports show that rice bran is abundant in γ-oryzanol, a combination of triterpenoid alcohol and sterol ferulic acid esters. The richness of rice bran oil owes to oryzanol and sitosterol (Gul *et al.*, 2015).

6. Supplementation of Rice bran in Functional foods

In livestock feed, RB has a fine history of perceived usefulness. The use of RB dates to the early 1920s in livestock feeds. This shows that earlier RB, obtained through polishing, was mostly used as animal feed, but because of the beneficial, nourishing, and health effects, it is becoming important commercially. To boost nutritional consistency, several types of research have been conducted to test RB as a functional component in different diets. RB is rich in dietary fiber and its inclusion will lead to the production of nutraceuticals or functional foods that are highly in demand nowadays, given its medicinal potential.

In the food industry, RB hemicellulose and degraded RB preparations have excellent potential, particularly to produce functional foods i.e. bakery products. For practical and dietary purposes, stabilized RB or its components have been used as additives in different food mediums, such as biscuits (Bhanger *et al.*, 2008), bread (Hu *et al.*, 2009), drinks (Faccin *et al.*, 2009), cod liver oil (Chotimarkorn *et al.*, 2008), pizza (de Delahaye *et al.*, 2005), powdered milk (Nanua *et al.*, 2000) and mutton mince (HIH and Daigle, 2003). Rice bran can be used to manufacture bread items with low fat and high fiber. RB is also added in batter mixtures and meat emulsions mechanically (Tuncel *et al.*, 2014).

Improvements have been seen in the color, taste, protein extraction of bran, as well as other characteristics, i.e. fluid and fat absorption, foaming, and emulsifying ability, which inform us on the possible use of bran in foods. Utilizing a high fiber food, RB can provide consistency, forming, thickening, creaming, and stabilizing characteristics to some foods. Stabilized RB-coated foods appear to consume less fat during cooking, although the small amount of fat existing naturally in RB fiber will function as a taste enhancer (Fabian and Ju, 2011).

7. Industrial Applications

The ability of RB to act as a scavenger of harmful material and as a raw ingredient to manufacture biodiesel and bioethanol fuels will be briefly discussed here. An analysis of the ability of RB to extract the highly harmful fabric dyes Malachitea Red and Methylene Blue taken from polluted water showed that the captivation of dyes by RB was a physical mechanism that was affected by pH and accelerated with interaction time. Using rice rinsing, drainage and RB extracted from a rinse-free rice engineering technique, scientists have achieved bioethanol production. Ultrasonic pretreatment and the addition of 32 mg per 100 mL of proteases enzyme and 4 mg per 100 mL of lipases enzyme to the rice-based products produced with the maximum ethanol yield (3.1—3.5 %). A mechanism for biodiesel amalgamation from RB fatty acids (FA) was developed by some researchers. Around 80% of the FA is processed into biodiesel under optimal conditions. The researchers found that phosphoric acids are effective catalysts of solid acids for the amalgamation of biodiesel from high FA content in rice brans (Srilatha *et al.*, 2012).

The system was optimized as a two-step process for the manufacturing of biodiesel from RBO (El Boulifi *et al.*, 2013). The microbial fuel cell method for the production of electricity from RB was created by (Moqsud *et al.*, 2013). The studies cited indicate that RB's and bran-derived foodstuffs can enhance the quality and nourishment of food and function as raw constituents for the manufacture of industrial co-products (Friedman, 2013).

Figure 5. Applications of rice bran

Conclusion

Rice bran, a nutrient-dense by-product of rice milling, holds immense potential for the development of value-added functional foods due to its rich content of bioactive compounds such as γ-oryzanol, tocopherols, tocotrienols, phytosterols, and phenolic acids. The extraction of these compounds using environmentally friendly techniques, such as subcritical water extraction, enzymatic hydrolysis, or supercritical fluid extraction, enhances their recovery while maintaining their bioactivity. Utilization of rice bran-derived compounds can improve the nutritional and functional profile of food products, offering antioxidant, anti-inflammatory, cholesterol-lowering, and anticancer properties. Incorporating these bioactives into snacks, beverages, bakery items, and dietary supplements aligns with the growing consumer demand for clean-label and health-oriented products. Moreover, valorizing rice bran supports sustainable food systems by reducing agro-industrial waste. Future research should focus on optimizing extraction methods and product formulations to maximize bioavailability and consumer acceptability, thereby transforming rice bran from a by-product into a valuable nutritional resource.

Conflict of Interest

All authors declare no conflict of interest.

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