



Rice Bran Oil: Extraction Technologies, Composition, and Applications – A Review

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Abstract

Rice Bran oil (RBO) extraction and uses are increasingly studied due to its unique fatty acid profile, desirable physical properties, and high nutritional value. RBO is a rich source of bioactive compounds, including γ -oryzanol, tocopherols, tocotrienols, and phytosterols, which have strong antioxidant, anti-inflammatory, and hypolipidemic effects that may help prevent or manage chronic diseases such as hypercholesterolemia, hypertension, and diabetes. Historically, however, RBO was produced by thermal solvent extraction. Recently, new "green" technologies, such as ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction, have demonstrated higher extraction efficiencies than traditional methods and better-preserved heat-labile bioactive compounds. Therefore, this review aims to provide a comprehensive synthesis of the current state of knowledge on extraction techniques, compositional profile, functional and phytochemical attributes, multifaceted health benefits, and economic feasibility of RBO. In addition, the review will outline the most recent developments in the applications of RBO in the food, cosmetic, and pharmaceutical industries, while highlighting sustainability and the added value of rice byproducts. This study highlights that hybrid green extraction approaches can achieve 12–25% oil yields while retaining high levels of γ -oryzanol and tocotrienols, and techno-economic analyses suggest that integrated processes combining oil recovery with valorization of rice bran byproducts can enhance commercial viability. Finally, the review demonstrates the potential of RBO as a versatile, bifunctional lipid and outlines avenues for future studies to optimize extraction methods, increase recovery of bioactive compounds, and expand industrial applications.

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Introduction

Rice (*Oryza sativa* L.) is one of the most significant food crops grown worldwide. More than half of the world's population consumes rice as their staple food (Punia et al., 2021). Paddy rice is the final product obtained from the harvesting of rice grains, typically collected with a moisture content of around 20% w/w. To ensure safe storage, it is subsequently dried to approximately 14% w/w moisture. The structure of paddy rice consists of an outer husk layer, the germ, the bran layers, and the endosperm. Different milling processes can remove the outer husk layer, resulting in brown rice kernels. Further milling to eliminate the bran and germ layers produces white rice kernels (Ndindeng et al., 2025). Rice bran is the cuticle between the paddy husk and the rice grain and is obtained as a byproduct of rice

processing. Further, it is an incredible source of vitamins, minerals, amino acids, and essential fatty acids. The composition of rice bran varies with the rice type, climatic conditions, and rice processing methods. Rice bran contains about 18–22% oil and is commercially feasible for oil extraction. However, rice bran is usually not consumed as human food due to its high fiber content and potential hull contamination. Owing to its rapid development of rancidity by activation of lipase enzyme in the bran upon milling, it has limited its application in the food industry. The development of stabilization techniques such as dry heating, ohmic heating, and microwave heating has enabled the use of a small percentage of rice bran as a source for commercial food products. However, rice bran is mostly used either directly as an ingredient in animal feed or as fuel in

boilers. Thus, rice bran is considered an undervalued by-product of the rice milling process (Fabian & Ju, 2011).

Rice Bran oil (RBO) is primarily extracted from rice bran using pressing and extraction techniques due to its higher oil content. As reported by Fortune Business Insights (2024), the global RBO market was valued at USD 7.86 billion in 2023 and is projected to grow to USD 8.55 billion in 2024, with a forecast to reach approximately USD 18.35 billion by 2032, at a Compound Annual Growth Rate (CAGR) of around 10.02% (Introspective Market Research, 2025). Rice bran oil is recognized as one of the healthiest edible oils globally and is a rich source of tocopherols and tocotrienols, as well as gamma-oryzanol (Punia et al., 2021). Gamma-oryzanol is a significant component of RBO, well-known for its antioxidant properties, and is a mixture of ferulic acid and phytosterol esters. Gamma-oryzanol also helps manage cholesterol levels and absorption, lowering low-density lipoprotein (LDL) cholesterol and triglycerides while increasing high-density lipoprotein (HDL) cholesterol in the bloodstream (Juricic et al., 2025). The amount of γ -oryzanol in crude RBO can range from 1.5% to 2.9%, and oil refining may reduce this percentage (Garofalo et al., 2021a). Additionally, the total content and composition of γ -oryzanol in RBO depend on various factors, including rice variety, environmental conditions, cultivation techniques, oil extraction methods, and refining processes.

Rice bran oil is known for its balanced fatty acid profile, containing unsaturated fatty acids such as oleic acid (monounsaturated) and linoleic acid (polyunsaturated). These fatty acids are associated with heart health and a reduced risk of cardiovascular diseases (Mahdavi-Roshan et al., 2021). As reported by Bopitiya and Madhujith (2014), RBO comprises oleic acid (36-38%), linoleic acid (35-38%), and α -linolenic acid (1.8-2.4%) as unsaturated fatty acids, as well as palmitic acid (21-25%) and stearic acid (2.7-3.0%) as saturated fatty acids. This ratio of saturated to monounsaturated to polyunsaturated fatty acids of approximately 1:2.2:1.5 (Jans et al., 2025). This closely aligns with the World Health Organization's recommended ratio of 1:1.5:1 (WHO, 2008), which highlights the nutritional value of RBO. Researchers found that RBO has antihypertensive (Devarajan et al., 2016), antidiabetic (Sivamaruthi et al., 2018), anti-obesity (Yang et al., 2019), and anti-carcinogenic (Rigo et al., 2014) properties due to its significant antioxidant and anti-inflammatory activities.

In food applications, refined rice bran oil is used in a wide range of cuisines worldwide as a mild, versatile cooking oil. Unlike soybean and rapeseed oils, which have stronger flavors that can overpower the natural flavors of dishes, RBO offers a subtle nuttiness that complements a wide range of ingredients without overpowering them. One of the standout features of RBO is its remarkably high ignition point of 350 °C and a smoke point of 232 °C (Lai et al., 2019). These properties significantly reduce the likelihood of oil degradation and polymerization during high-heat cooking methods, such as frying and baking. Consequently, RBO maintains its integrity and nutritional values, making it particularly suitable for processes that require consistent heat

retention, such as stir-frying or deep-frying. Additionally, the high viscosity of RBO not only facilitates its use as a cooking medium but also enhances its role as a dressing for various salads. Its ability to adhere effectively to food surfaces ensures a glossy, appetizing appearance and enriches the overall sensory experience of the meal.

The increasing awareness of the health benefits associated with RBO, including its advantageous fatty acid composition, high antioxidant capacity, and essential nutrient profile, underpins the pressing need to enhance its production. Elevating its market presence and promoting its consumption among health-oriented consumers. Notably, RBO is widely produced and used across various Asian countries, with India, Japan, China, Taiwan, and Indonesia as major contributors. Current annual production figures are approximately 472,000 tons in India, 90,000 tons in China, and 65,000 tons in Japan (Garofalo et al., 2021). The extraction of RBO via hydraulic press techniques was pioneered in Japan and remains in use globally. In recent years, however, the solvent extraction method using nonpolar solvents such as hexane has emerged as the predominant commercial technique for RBO extraction (Punia et al., 2021). Post-extraction, crude RBO typically undergoes a refining process to enhance its quality and marketability. Key steps in this refining process involve dewaxing, degumming, neutralization of free fatty acids, bleaching, and steam deodorization (Garofalo et al., 2021).

Although research on rice bran oil (RBO) has increased significantly, existing reviews remain limited in scope and often focus on isolated aspects such as nutritional composition, health benefits, or conventional processing techniques. These studies generally provide broad overviews and lack a systematic comparison of extraction methods in relation to oil yield, retention of bioactive compounds and physicochemical quality. In particular, comparative evaluations of traditional and emerging extraction techniques are still insufficiently addressed in the literature. Moreover, recent advancements in environmentally friendly extraction technologies, including ultrasound- and enzyme-assisted methods, have not been comprehensively discussed in the context of RBO. At the same time, the growing application of RBO in functional foods, nutraceuticals, and other value-added products has received limited integrated attention in previous reviews. Therefore, a comprehensive and updated synthesis is required to better understand how different extraction and refining approach influence the composition, nutritional value and functional properties of RBO. This review brings together current findings with a particular emphasis on extraction and refining methodologies, compositional characteristics, and emerging applications. Special attention is given to the comparative assessment of conventional and novel extraction techniques and their implications for oil quality and bioactive compound preservation.

Extraction of Rice Bran Oil

Rice bran oil can be extracted through a range of techniques, each offering unique benefits and efficiencies, utilizing both conventional and innovative methods. The most common conventional extraction techniques include solvent extraction and mechanical

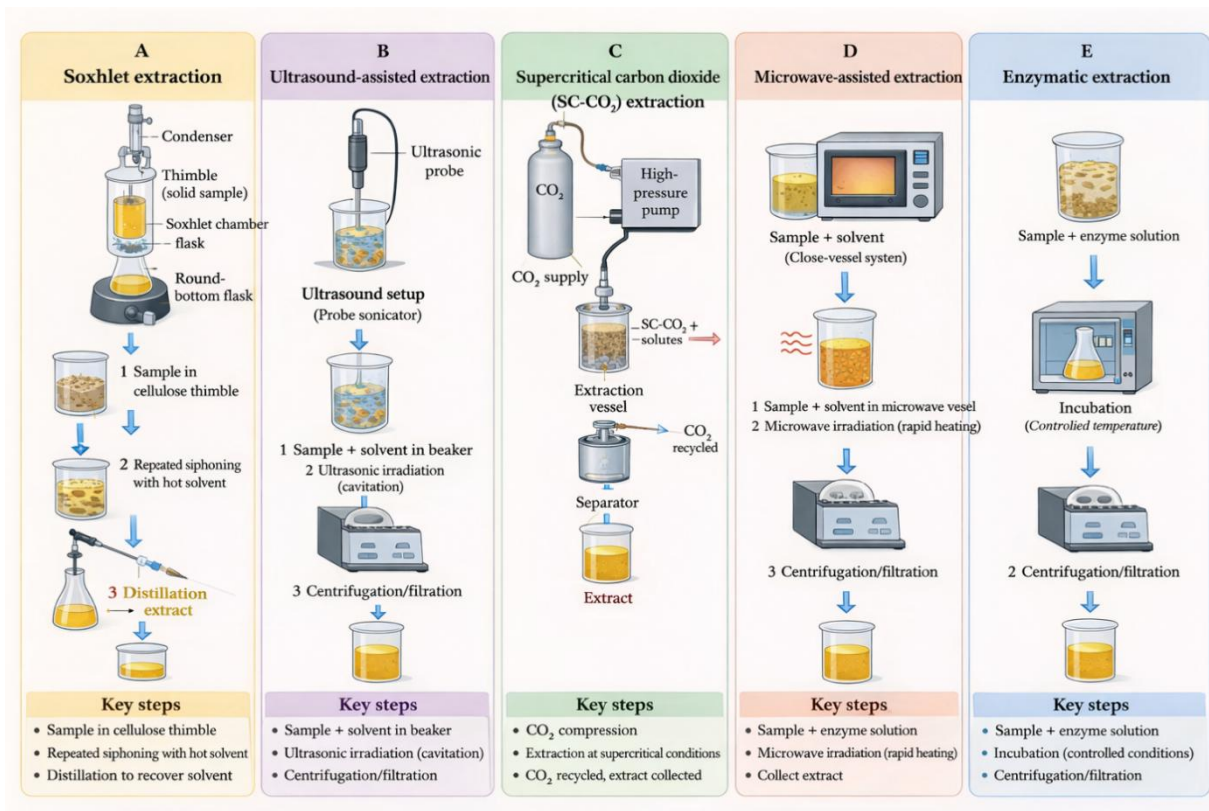


Figure 1. Different main extraction methods and the overall processing of RBO

pressing. Solvent extraction uses organic solvents, such as hexane, to dissolve oil from rice bran, yielding a high yield but requiring further refining to remove solvent residues. Mechanical pressing, on the other hand, uses a screw press to physically squeeze oil from the rice bran, which can produce a more natural oil but may yield lower yields than solvent extraction.

In contrast, novel extraction methods have gained popularity in recent years, leveraging advanced technology to enhance oil recovery while preserving the oil's nutritional and sensory qualities. Supercritical carbon dioxide (CO₂) extraction uses CO₂ under high pressure and temperature to extract oil without leaving harmful residues, making it an environmentally friendly option. Compressed liquefied petroleum gas (LPG) extraction, similar in principle, uses liquefied gas to dissolve and extract oil, offering a quick and effective alternative. Ultrasound-assisted aqueous extraction employs ultrasonic waves to create cavitation bubbles in a solvent, promoting the release of oil from the rice bran and significantly enhancing extraction efficiency. Subcritical water extraction uses water at temperatures and pressures just below its critical point, effectively dissolving polar and nonpolar compounds and extracting oil while eliminating the need for harmful solvents. Enzymatic extraction uses specific enzymes to break down cell walls in rice bran, facilitating the release of oil and yielding high-quality oil with preserved nutrients. Finally, microwave-assisted extraction uses microwave energy to heat the rice bran, causing the oil to be released more readily.

Together, these advanced extraction techniques are transforming the landscape of rice bran oil production, offering enhanced efficiency, improved oil quality, and sustainability, catering to the evolving needs

of consumers and the food industry (Huang et al., 2024). The common steps involved in all the extraction methods are shown in Figure 1.

Conventional Methods of RBO Extraction

Solvent extraction is the widely used method to recover oil from any materials with low oil content, or for pre-pressed oil cakes in order to obtain high oil content (Bakhshabadi et al., 2025). Hexane is the most used solvent for extracting oils because it is relatively cheap and possesses excellent oil-extraction properties, such as easy oil recovery, a narrow boiling point (63–69 °C), and exceptional solubility. The study conducted by Lakkakula et al. (2014) showed that 92% oil can be recovered using hexane as a solvent with the support of the ohmic heating method. Even though hexane is widely used for the extraction of RBO, it has some undesirable features such as being highly flammable, volatile, toxic, and polluting the environment (Wang, 2019). Therefore, short-chain-alcohols such as ethanol and isopropanol have been proposed as alternative solvents to extract RBO. For instance, Oliveira et al., (2012) reported that 42.7% - 99.9% oil yields can be extracted using ethanol as an extraction solvent by changing the ethanol to rice bran ratio into 2.5:1 and 4.5:1 and temperature into 60–90 °C. After extraction, the crude RBO is further subjected to chemical or physical refining to meet the specifications of food-grade edible oil.

In addition, the Soxhlet-based solvent extraction method can be used in RBO extraction. Al-Okbi et al. (2014) reported that the use of heptane and petroleum ether at 40–60 °C yields 15–20% and 18.4% RBO yield by weight of rice bran, respectively. Further, Liu and Mamidipally (2005) obtained an RBO yield of about 67.73% from Soxhlet extraction with hexane. However,

there was no sufficient research indicating the use of the Soxhlet method for the extraction of RBO in higher quantities in the industry level, where it is mainly being used in laboratory extraction processes (Garba et al., 2019). Mechanical pressing is the most used conventional method for extracting oil from oilseeds (Garba et al., 2019). It has been used especially by small and medium-scale oil extraction industries for commercial RBO extraction in some countries such as Thailand, India, Vietnam, and China. Compared with other solvent extraction techniques, mechanical pressing is less expensive and less labor-intensive (Sayasoonthorn et al., 2012), and the process's safety and simplicity are additional advantages. Since this method does not involve any heat or chemical treatment, it has become an interesting alternative for conventional practices as consumers prefer natural and safe products. Screw and hydraulic presses are the widely used mechanical pressing techniques in RBO extraction (Das et al., 2025). However, the extraction yield of RBO using the screw method is only about 9-10% of the bran weight (Garba et al., 2019). Different methods used for RBO extraction are shown in Table 1.

Extraction methods for RBO differ greatly in terms of yield, preservation of bioactive compounds, and suitability for industrial use (Table 2). Traditional solvent extraction produces higher amounts of oil. However, it can degrade heat-sensitive bioactive such as γ -oryzanol, tocopherols, and tocotrienols. Newer green extraction techniques, such as ultrasound, microwave, supercritical CO₂, and enzymatic extraction, offer relatively higher yields and better retention of bioactive compounds, but their industrial scalability is limited by equipment costs and process complexity. Solvent extraction currently dominates commercial production with a 90% market share, while supercritical CO₂ and enzymatic methods are aimed at the premium functional oil market (Zhang et al., 2026)

Novel Methods of RBO Extraction

Many researchers have investigated the use of water as a medium for extraction of oil from different oil seeds such as corn germ, soybean, peanut, sunflower and rice bran. However, it was found to be ineffective due to low oil yield and solubility. Therefore, recent development involves the use of enzymes to assist the extraction, thus resulting in more oil yield (Punia et al., 2021). The enzymatic process helps hydrolyze and degrade the structural polysaccharides that make up the cell wall, thereby releasing both oil and protein into the aqueous system (Gao et al., 2024). Moreover, enzyme-assisted extraction technology for RBO has been regarded as an eco-friendly process for producing high-quality oil. Huang et al. (2013) stated that a yield of 92.63% RBO was obtained by combining enzymatic extraction and ultrasonic treatments using an enzyme combination such as cellulase (1.2%, w/w), protease (0.6%, w/w), and amylase (0.3%, w/w) at 55 °C, 4.5 pH, and a hydrolysis time of 5.5 h. The enzyme-assisted extraction of RBO from full-fat rice bran has been reported by many researchers using different combinations of enzymes, including protease, α -amylase, cellulase, and neurase (Sahini & Mutegoa, 2023). In contrast, when these enzymes were used

alone, the process did not result in reasonable oil extraction yields (Butter & Cbe, 2011). This method is superior to the traditional process because it yields oil of good quality attributes such as color, phosphorus contents, free fatty acids value, and peroxide value as well as less chemical contamination (Sivakanthan et al., 2023), low energy consumption, and good retention of protein, polysaccharide, and other components (Sharma et al., 2001). The effect of enzyme concentration was the most important factor for determining oil and protein extraction yields, whereas incubation time and the temperature had no significant influence on oil yield (Hanmoungjai et al., 2002).

Use of Super-critical Carbon Dioxide (SC-CO₂) is another emerging technique of extracting RBO. Supercritical fluid extraction allows for an extract free of toxic residues which can be used directly without further treatment. The extract also contains excellent features such as absence of degradation products as off flavors, and presence of ultra-pure composition (Nozari and Kander, 2025). This method also gives higher oil yield compared to that of conventional solvent extraction (Balachandran et al., 2008). When supercritical fluids are used for oil extraction, there is no risk of solvent contamination, thermolability and chemical modification problems, that may exist in conventional methods. The SC-CO₂ is an alternative to organic solvent extraction and has been shown to be ideal for extraction of many oils including RBO (Punia et al., 2021). Balachandran et al. (2008) reported a yield of 20% (w/w) RBO from the SC-CO₂ extraction at 60 °C, 50 MPa, for 1.5 h using a CO₂ flow rate of 40 g/min. The oil yield can be increased by increasing the temperature up to 70 °C, pressure above 50 MPa and extraction time. In other study, RBO yield of 22.2% (w/w) obtained by SC-CO₂ extraction at 45 °C and pressure of 35 MPa (Sparks et al., 2006). However, this technology has some limitation because of its high cost of equipment.

The sub-critical fluid extraction is a continuous counter-current process in which the solvent is removed after extraction using a vacuum at low temperature (Marcus, 2019). The sub-critical fluid is referred to as hot liquid solvent or pressurized/accelerated liquid solvents (Gbashi et al., 2017), which are compressed below their critical temperatures and still maintain in the liquid state and used above their boiling point by increasing pressure. The sub-critical fluid extraction has the advantage of lower pressure and temperature as compared to supercritical fluids extraction which may be expensive due to the high pressure and temperature requirement. Solvents such as hexane, propane and butane can be used for sub-critical fluids extraction due to their low critical temperature and pressure, colorless nature and leaving no toxic residues in the product. Although this method gives high yield and good quality oil with high concentration of the health components (Liu et al., 2015), its application is yet not popular and the data concerning its use for extraction of RBO is not widely available.

Refining Process of Rice Bran Oil

The main aim of edible oil refining is to make the oil suitable for human consumption. This involves improving the colour, minimize off-flavor, change in the

Table 1. Different extraction techniques used to recover RBO from rice bran

Extraction technique	Solvents/ chemicals/ gas used	Extraction yield	Reference
Solvent extraction	Hexane	16.72 g/100 g of bran	Pandey and Shrivastava (2018)
	Isopropanol	20.12 g/100 g of dry rice bran	Zigoneanu et al., (2008)
	Isopropanol, Ethanol with 6% (v/v) of water	10.00 g/100 g of fresh rice bran	Capellini et al., (2017)
	Ethanol with Isopropanol	16.00 g/100 g of dry rice bran	Shukla and Pratap (2017)
	D-Limonene	17.09 g/ 100 g of dry rice bran	Liu and Mamidipally (2005b)
Ultrasound-assisted extraction	Water	21.00 g/100 g of dry rice bran	Kuriakose (2015)
	Water	20.00 g/100 g of dry rice bran	Khoei and Chekin (2015)
	Ethanol 87%	19.83 g/100 g of dry rice bran	Tabaraki and Nateghi (2011)
	Methanol	0.15 g/100 g rice bran	(Kumar et al., 2016)
	Hexane	6.74 g/100 g rice bran	
Supercritical carbon dioxide (SC-CO ₂) extraction	CO ₂	7.11 g/ 100 g dry rice bran	Garcia et al., (1996)
		5.39 g/ 100 g of fresh rice bran	Sookwong and Mahatheeranont (2017)
Microwave-assisted extraction	Isopropanol (120 °C, 3:1 w/w, 15 min)	15.00 g/ 100 g of fresh rice bran	Zigoneanu et al., (2008)
	Isopropanol (82 °C, 2.1 bar, 95 W, 3:1 w/w, 30 min)	2.36 g/ 100 g of dry rice bran	Shukla and Pratap (2017)
	Methanol (38 °C, 800 W, 3:1 w/w, 1h)	96 g/ 100 g of dry rice bran	Kumar et al., (2016)
	Ethanol (120 °C, 3:1 w/w, 20 min)	1.72 g/ 100 g of dry rice bran	Kanitkar et al., (2011)
	Ethanol (Continuous flow 100 ml/min, 73 °C, 3:1 w/w, 21 min)	8.23 g/ 100 g of dry rice bran	Terigar et al., (2011)
Enzymatic extraction	Water (60 °C, pH 4.5, water/bran 3:1 w/w, hexane/bran 1.5:1 v/w, Pectinase, Cellulase)	20.6 g/100 g of dry rice bran	Sengupta and Bhattacharyya (1996)
	Water (65 °C, pH 7, 80 rpm, 18 h, Protease, Pectinase)	78 g/100 g of recoverable RBO	Sharma et al., (2001)
	Water (50 °C, pH 9, Alcalase, 2h)	79 g/100 g of recoverable RBO	Hanmoungjai et .,(2001)

crystal habit, rearrangement of their molecular structure and to make the extracted or mechanically pressed oil suitable as per our requirements. The crude RBO is dark greenish brown to light yellow colour due to the presence of different pigments such as carotenoid, chlorophyll and

products of Millard browning. Further, colour of the crude oil depends on the extraction method, composition and condition of the bran (Jans et al., 2025).

Physical refining and chemical refining are the two major types of oil refining processes currently used

in oil industry (Gharby, 2022). Physical refining of RBO includes degumming, neutralization, bleaching, dewaxing, deodorization, and winterization. Degumming is the initial step where it is necessary to remove the phospholipids, mucilage and gums present in the crude oil. This includes the use of acid or enzyme at moderate temperatures followed by filtration or settling to remove the unwanted materials. Neutralization process helps to remove the free fatty acids present in the crude RBO with the help of alkali such as caustic soda. After neutralization, oil is subjected to bleaching or decolorization to remove any pigments, trace metals, polycyclic aromatic compounds and impurities either by physical or chemicals means. Generally, decolorization gives oils with 2-3 red units in lovibond colors, which is an acceptable level for high grade cooking oil and salad oils (Fengxia et al., 2001). De-waxing of oil is a process of eliminating higher melting point constituents like waxes or triglycerides from oil by gradually cooling oils and separating saturated glycerides from the oil. This step is really important as waxes like substances have low solubility and result turbidity when they crystallize.

Final step of refining process involves the removing of oxidative breakdown products such as aldehydes and ketones which is responsible to create undesirable odors and taste. This can be carried out by heating the oil at 200 – 250 °C under high vacuum condition and all the undesirable volatiles, as well as free fatty acids, peroxides and some amount of natural tocopherol also removed in this process. In the winterization step, waxes and saturated triglycerides which are fairly visible at low temperatures are removed to keep the appearance of oil clean. Manjula and Subramanian (2009) noticed that Maillard reaction products are responsible for the color of RBO rather than β -carotene and chlorophyll. Furthermore, they reported that the removal of phosphorus-containing components is essential to avoid color fixation in the oil during physical refining. Therefore, in physical refining process, proper pretreatment is crucial to remove phospholipids as well as waxes and metals (Ghosh, 2007).

Chemical refining of RBO is a traditional method used in past centuries. The main purpose of chemical refining is to remove FFA by an alkaline solution and at the same time remove other impurities. Chemical refining of crude RBO yields better product with acceptable colour and without cloudy appearance. However, this process also causes high refining losses in the form of wax sludge, gum sludge, and soap stock. These residues, produced in the RBO refining industry, are a rich source of many nutraceuticals like, oryzanols, tocopherols, vitamin E, ferulic acid, phytic acid, lecithin, inositol and wax (Patel, 2014; Gharby, 2022).

Conventionally, chemical refining is preferred over physical refining. The RBO has a variety of minor components such as gamma oryzanol, tocopherols, tocotrienols and phytosterols, which differ in their composition and render RBO refining more complicated when compared with the refining of other oils (Patel, 2014). Some stages in the chemical refining of RBO cause significant losses or changes in the composition of these minor components (Liu et al., 2019). For instance, the oryzanol content for physically refined RBO was found to be 1.1%-1.74%, whereas that of chemically

refined oil was a considerably lower amount i.e. 0.19%-0.20 % (Krishna et al., 2001). When the effect of chemical refining was examined on the micronutrients, it showed that alkali treatment results in significant loss of gamma oryzanol and modifies the composition of phytosterols. Bleaching shows formation of some isomers of 24-methylenecycloartanol (a gamma oryzanol component). During deodorization, the highly volatile compounds like phytosterols and tocotrienols are stripped off while the nonvolatile gamma oryzanol is retained that leads to formation of less than 1% Trans FA. The entire process of chemical refining removes 99.5% of the free fatty acid component (Greyt et al., 2006).

Composition and Physicochemical Properties of RBO

RBO mainly consists of fatty acids, phytochemicals and vitamins. The health benefits are mainly attributable to the balanced fatty acid (FA) composition of RBO, which contains approximately 22% saturated (SFA), 41% monounsaturated (MUFA) and 37% polyunsaturated fatty acids (PUFA). Unsaturated fatty acids make up the majority of RBO's fatty acids (55–87 %). Chemical composition of bran is widely affected by rice variety, grain pretreatment before milling, milling technique, degree of milling, and downstream bran processing, such as fractionation. Therefore, the oil content of rice bran typically ranges between 10% and 25% w/w (Dunford, 2019). Oleic acid (38–48%) is the most abundant unsaturated fatty acid, followed by polyunsaturated fatty acid linoleic acid (16–36%) while palmitic acid is the most abundant saturated fatty acid, accounting for 19%–35% total (He and Liu, 2019). The amount of FFA in RBO varies substantially depending on the type of bran utilized to extract the oil. The FFA content of RBO is typically between 2% and 5%. The comparison of fatty acid composition of RBO with other common oils are shown in Table 3.

In addition to that, RBO is rich in active enzymes such as lipase, lipoxygenase and peroxidase (Bansal et al., 2023). These enzymes are important in commercial RBO as they determine the physical condition and shelf-life of the product. The breakdown of the oil in the bran into glycerol and free fatty acids (FFA) is aided by lipase. The lipase enzyme and substrate are brought together during grinding. The rate at which FFA is formed is significantly influenced by environmental factors. Lipase activity has long been linked to the instability of rice bran. The accepted amount of FFA in the RBO is less than 5% (Kwon, 2005) and the FFA concentration of rice bran grew to 5% in a day and 79.2% after a month of storage under 80% humidity.

The unsaponifiable fraction of RBO contains bioactive compounds such as 43% phytosterols, 10% steryl esters, and 1% tocopherol. Most of these micronutrients are often lost or reduced to a large degree during oil refining processes. They become concentrated in several byproducts or residues such as gum and soap stock from chemical refining steps, deodorizer distillate, and wax from both physical and chemical refining. For example, 90% of tocopherols and tocotrienols are lost during the deodorization process and 83-89% of γ -oryzanol is lost in chemical refining.

Table 2. Comparison evaluation of RBO extraction methods; yields, process characteristics, bioactive preservation and industrial applicability

Extraction Technique	Yield Range (%)	Mechanism	Bioactive Retention	Process Conditions	Economics scalability	References
Solvent extraction	15-22%	Solvent diffuses into the bran matrix, solubilizes non-polar lipids via partitioning; exhaustive multi-stage washing	Moderate: Gamma-oryzanol (\downarrow 15-25% with prolonged heat), tocotrienols (\downarrow 10%), and phytosterols remain stable; risk of solvent residues.	60-70 °C 6-8 hrs 1:5 (bran: solvent)	High at the traditional industrial level but lacking in sustainability. It exhibits low selectivity and demands large solvent volumes, which result in elevated purification costs and environmental concerns. Cost Factors - Although equipment costs are low, ongoing expenses for solvent purchase and hazardous waste disposal are significant.	Wongwaiwech et al. (2023); Pandey and Shrivastava (2018)
Ultrasound-assisted extraction (UAE)	12-20%	Acoustic cavitation creates microjets/shear forces (20 -40 kHz); cell wall rupture enhances solvent diffusion	Good: Gamma-oryzanol (10-20% compared to solvent), phenolics increase, tocotrienols preserved; minimal thermal degradation.	50-60 °C 15-30 min 100-500W 20 – 40 kHz	It offers high scalability with low to moderate initial and operating costs. Its efficiency minimizes solvent use and shortens extraction time, making it more practical for industrial use.	Kuriakose (2015); Khoei and Chekin (2015) Nayak et al. (2026)
Microwave-assisted extraction (MAE)	15-22%	Dielectric heating generates internal pressure (2.45 GHz); rapid cell rupture releases oil bodies	Variable: Gamma-oryzanol decreases by 10-30% at hotspots; tocopherols experience moderate loss; phenolics increase; thermolabile risk is present.	3-10 min, 300-800 W	Highly scalable, this method offers rapid heating and efficient extraction, cutting energy use by up to 100 times compared to conventional techniques. However, at larger scales, there is a risk of uneven heating, and it requires a higher initial investment than traditional methods.	Reis et al. (2020); Zigoneanu et al. (2008) Nayak et al. (2026)
Supercritical Fluid Extraction SC-CO ₂	9-13%	Supercritical CO ₂ (300-400 bar) acts as tunable non-polar solvent; selective lipid extraction	Excellent: Gamma-oryzanol 1.8-2.2%, tocotrienols 800-1100 mg/kg, phytosterols highest; no	40-60 °C, 5-10% ethanol co-solvent	High operational investment and energy consumption are significant concerns. Nevertheless, this method provides superior selectivity and purity, reducing	Baixinho et al. (2025); Sookwong and Mahatheerant (2017)

			thermal or solvent damage.		organic solvent disposal costs and being cost-effective for high-value products. The need for expensive high-pressure equipment restricts its use mainly to high-value applications markets.
Enzymatic extraction	15-20%	Common enzymes used include cellulase, pectinase, and protease. Improves oil yield and quality by breaking down cell walls and liberating oil, acting as an eco-friendly alternative to chemical solvent extraction.	Excellent: Gamma-oryzanol and tocotrienols fully preserved; phenolics increased by 30%; no heat or solvent degradation.	40-54°C, pH 4.5-5.5, 12-24h	The high cost of enzymes and the possibility of prolonged, complicated processing can limit economic viability at very large scales.
					Punia et al. (2021); Sharma et al. (2001)

Table 3. Fatty acid composition of RBO with other common oils

Type of Fatty Acid	Percentage (%)				
	Rice bran Oil	Sunflower Oil	Mustard Oil	Palm Oil	Coconut Oil
Caprylic	-	-	-	-	6.21 ± 0.34
Capric	-	-	-	-	6.15 ± 0.21
Lauric	-	-	-	-	51.02 ± 0.71
Myristic	0.4–1.0	-	-	1.23 ± 0.28	18.94 ± 0.63
Palmitic	17.0–21.5	6.52 ± 1.75	4.51±3.83	41.78 ± 1.27	8.62 ± 0.50
Stearic	1.0–3.0	1.98 ± 1.44	2.78±0.59	3.39± 0.65	1.94 ± 0.17
Oleic	38.4–42.3	45.39 ± 18.77	38.21±21.=88	41.90 ± 1.20	5.84 ± 0.50
Linoleic	33.1–37.0	46.02 ± 16.75	25.31±5.74	11.03 ± .02	1.28 ± 0.18
Linolenic	0.5–2.2	0.12 ± 0.09	11.30±6.09	-	-
SFA	18.4–25.5	8.51 ± 1.91	15.94±2.58	46.34 ± 0.40	92.92 ± 0.56
MUFA	38.4–42.3	45.5 ± 16.89	49.57±8.56	41.46 ± 0.56	5.84 ± 0.46
PUFA	33.6–39.2	46.10 ± 14.92	36.62±6.42	11.84 ± 0.92	1.28 ± 0.17

SFA – saturated fatty acids, MUFA – monounsaturated fatty acids, PUFA – polyunsaturated fatty acids (Sources: Chowdhury et al. (1970); Yeasmin et al. (2024))

Singanusong and Garba (2019) stated that during alkali treatment of crude RBO, up to about 93-94.6% of oryzanol can be removed while only 1.1% and 5.9% oryzanol was lost during degumming and dewaxing of crude RBO, respectively. The deodorization distillate typically contains squalene (8.5%), phytosterols (3.5%), sitosterol (2.05%), stigmasterol (0.69%), and campesterol (0.76%), tocopherol (1.6%), triacylglycerol (58.0%), and diacylglycerol plus fatty acids (26.5%).

The comparison of physicochemical properties of RBO and some other common oils are shown in Table 4. Color is regarded as a critical indicator of edible oil quality. Due to pigments such as carotenoids, xanthophyll, and gums, crude RBO is greenish-yellow, dark brown, and yellowish-green in color with a hazy appearance. A particular device, such as a Lovibond

tintometer, was used to determine the color value of the oils. The color of refined RBO lightens during refining, and unlike other vegetable oils, the color of refined RBO cannot be fully erased. RBO, like most vegetable oils, is susceptible to oxidation, resulting in the generation of nonvolatile hazardous chemicals during storage or processing.

Health Benefits of Rice Bran Oil

Rice bran oil (RBO) is characterized by a unique profile of bioactive compounds that contribute to its nutritional and functional properties. It contains significant amounts of γ -oryzanol (approximately 1-2%), a mixture of ferulic acid ester of phytosterols and triterpene alcohols, which has been widely associated with cholesterol-lowering and antioxidant effects

Table 4. Comparison of physicochemical properties of RBO with other common oils

Properties	Rice Bran Oil	Sunflower Oil	Mustard Oil	Coconut Oil
Moisture content (%)	0.03±0.001	8-9	0.05±0.002	0.1
Density at 25°C	0.8933±0.3	0.8985	0.8867±0.3	0.908-0.921
Specific gravity at 25°C	0.9017±0.05	0.915	0.9021±0.01	0.915±0.005
Refractive index at 25°C	1.4672±0.021	1.4600	1.4652±0.001	1.448-1.450
Viscosity	59.06±0.03	37.05	61.30±0.02	48.4-52.5
Free Fatty Acid (as oleic %)	0.10 ±0.004	0.43	0.15 ±0.006	0.3±0.08
Peroxide value (meq/kg)	1.46±0.21	4.19	2.84±0.13	0.41±0.002
Iodine value (g/100 g)	120±0.41	102.02	121.3±0.32	6.3-10.6
Acid value (%)	0.5±0.01	0.953	0.4±0.02	0.3-0.5
Unsaponifiable matter	1.8±0.11	0.81	1.5±0.10	1.5

Sources: Guinda et al. (2003); Krishna et al. (2010); Martins et al. (2020); Fraterrigo et al. (2021); Jans et al. (2025)

(Jans et al., 2025). In addition, RBO is a rich source of tocopherols and tocotrienols (vitamin E homologues), typically ranging from 50-150 mg/100 g oil, which play a critical role in reducing oxidative stress. Phytosterols present at levels of approximately 1-2% are known to inhibit intestinal cholesterol absorption. These bioactive compounds not only enhance the oxidative stability of the oil but also contribute to its physiological functions through distinct and complementary mechanisms. For instance, γ -oryzanol and phytosterols are primarily involved in cholesterol regulation, while tocopherols and tocotrienols act as potent antioxidants, collectively supporting metabolic health.

Plant-based foods have been shown to be highly effective in slowing the progression of various non-communicable diseases, including coronary heart disease (CHD), diabetes mellitus, certain cancers, and strokes (Manickavasagan et al., 2017). One significant factor influencing plasma cholesterol levels is dietary fat, with its intake directly linked to the onset of CHD and stroke mortality (Pal and Pratap, 2017). Research has demonstrated that the consumption of rice bran oil (RBO) can lead to reductions in blood cholesterol (Lai et al., 2012), blood pressure (Devarajan et al., 2016), and blood glucose levels (Son et al., 2011). These reductions can potentially alleviate inflammation and the symptoms associated with metabolic syndrome (Manickavasagan et al., 2017). These benefits are primarily achieved through mechanisms such as inhibiting cholesterol absorption, exhibiting antioxidant properties, and modulating inflammatory responses. Together, these aspects highlight that incorporating RBO into the diet may play a role in preventing and managing metabolic syndrome and related conditions. The next section of this review will summarize both *in vitro* and *in vivo* studies concerning RBO consumption.

In-vitro and In-vivo Studies on Health Benefits of Rice Bran Oil

A substantial body of evidence from *in vitro*, animal, and human studies collectively demonstrates that rice bran oil (RBO) exerts significant hypolipidemic, antioxidant, anti-inflammatory, and metabolic regulatory effects. These biological activities are largely attributed to its rich content of bioactive compounds, particularly γ -oryzanol, tocotrienols, and phytosterols.

In vitro studies consistently indicate that γ -oryzanol plays a key role in modulating lipid metabolism and oxidative stress. For instance, studies using Caco-2

and HepG2 cell lines have shown that γ -oryzanol reduces cholesterol uptake and downregulates lipogenesis-related gene expression (Wang et al., 2015; Sultana et al., 2021). Furthermore, its antioxidant potential has been demonstrated through activation of the Nrf2 signaling pathway under oxidative stress conditions, suggesting a protective role against cellular damage and age-related diseases (Rungratanawanich et al., 2018).

Animal studies provide strong supporting evidence for these effects. Across multiple models, including rats, hamsters, and non-human primates, dietary intake of RBO consistently results in reductions in total cholesterol (TC), low-density lipoprotein cholesterol (LDL-C), and triglycerides, while either maintaining or increasing high-density lipoprotein cholesterol (HDL-C) levels (Sharma and Rukmani, 1986; Rukmini, 1988; Nicolosi et al., 1991; Kahlon et al., 1992; Purushothama et al., 1995; Rong et al., 1997). In addition, improvements in antioxidant status, such as reduced lipid peroxidation and increased glutathione levels, have been observed (Araghi et al., 2016). These findings highlight the dual role of RBO in lipid regulation and oxidative stress mitigation.

Evidence from human studies further supports these beneficial effects. Clinical and dietary intervention studies have demonstrated that RBO consumption leads to moderate but significant improvements in lipid profiles, including reductions in total cholesterol, LDL-C, triglycerides, and in some cases blood pressure and blood glucose levels (Berger et al., 2004; Most et al., 2005; Kuriyan et al., 2005; Wang, 2019). Additionally, supplementation with γ -oryzanol has been shown to improve lipid metabolism and endocrine parameters, including thyroid-stimulating hormone levels and menopausal symptoms (Sasaki et al., 1990; Shimomura et al., 1980; Sultana et al., 2021).

Beyond lipid-lowering effects, emerging evidence indicates that RBO may contribute to broader metabolic health. Studies suggest that RBO can reduce body fat accumulation through increased adiponectin secretion, enhance insulin secretion and glucose utilization, and alleviate oxidative stress in pancreatic β -cells (Sultana et al., 2021; Zhang et al., 2021). Furthermore, its bioactive components have been associated with immune-modulating effects, potentially enhancing host defense mechanisms (Sharma et al., 2015).

Overall, the collective evidence strongly

supports the role of RBO as a functional edible oil with multiple health-promoting properties. The consistency of findings across in vitro, animal, and human studies indicates that RBO can contribute to the prevention and management of metabolic disorders, including hyperlipidemia, hypertension, and insulin resistance. These effects are primarily mediated through its antioxidant activity, inhibition of cholesterol absorption, and regulation of key metabolic pathways.

Applications of Rice Bran Oil in Food and Other Industries

The unique properties of RBO make it useful in various industries such as food, pharmaceutical, and cosmetic. A summary of the application of RBO in different industries is shown in Table 5.

RBO has a mild flavor and can be utilized in a variety of cuisines around the world. The smoke point (>200 °C) and ignition point (350 °C) of RBO are also extremely

high (Nayik et al., 2015). As a result of high smoke point and ignition point, it is extremely stable while cooking at higher temperatures, with very little degradation and polymerization. RBO has the highest viscosity compared to the other oils, even surpassing extra virgin olive oil, with an oryzanol level of >10,000 mg/kg where the oryzanol content may influence viscosity. This implies that RBO has a strong dressing performance, particularly in Chinese cuisine. RBO can readily be held on the surface of food due to its high viscosity, making the food glossy and appealing (Wang, 2019).

In deep-frying applications, the oxidative stability of RBO is comparable to that of peanut and cottonseed oils. The presence of natural antioxidants in RBO, including as tocopherols and -oryzanol, can help to reduce the rate of oil oxidation during frying (Fan et al., 2013). Further, RBO improves the taste and flavor of food while lowering the amount of oil absorbed while

Table 5. Use of Rice Bran Oil on Pharmaceutical, Cosmetic, and Nutraceutical Formulations

Type of Formulation	RBO/ Bioactive Compound	Use	Results	References
Gel-creams containing benzophenone	Rice bran oil at 3% or 5% (w/w)	Sunscreen	Enhancement of spread ability and no alteration of the sun protection factor	Rigo et al., 2014
Nano emulsions	Rice bran oil at 10% (w/w)	Treatment of skin disorders	Improvement of skin moisture in a model of skin psoriasis	Bernardi et al., 2011
Solid lipid nanoparticles	γ -Oryzanol	Platform for the development of formulations	Particle sizes between 220 and 280 nm, and entrapment efficiency from 15% to 66%	Ruktanonchai et al., 2008
Liposomes	γ -Oryzanol	Natural preservative	<i>In vitro</i> inhibition of free radical generation in pharmaceutical oils	Juliano et al., 2005
Gels or creams containing liposomes	Ferulic acid, γ -oryzanol, and phytic acid	Anti-aging in cosmetics	High transdermal accumulation of the compounds in dermis and epidermis	Manosroi et al., 2012
Emulsions containing nano-sponges	γ -Oryzanol at 0.06%	Dermal application	Skin retention of γ -oryzanol using a porcine ear skin model	Sapino et al., 2013
Lipid-core nano-capsules	Rice bran oil at 3%	Nano carrier platform for medicines of cosmetics	Suitability to prepare polymeric nano-capsules to control drug release	Rigo et al., 2014
Hydrogels containing lipid-core nano-capsules	Rice bran oil at 3%	Raw material for sunscreen or skin care formulation	Prevention of edema formation and anti-inflammatory effect in skin damage induced by UV-B radiation	Rigo et al., 2014
Chitosan-coated micro particles	γ -Oryzanol at 2.72%	Gastrointestinal drug delivery system	Control of γ -oryzanol either in simulated gastric fluid or in intestinal fluid	Lee et al., 2009; Rohman, 2014
Chitosan-coated micro particles	γ -Oryzanol	Oral administration	Improvement of γ -oryzanol bioavailability after oral administration	Kim et al., 2010; Rohman, 2014

frying (Choudhary and Grover, 2013). According to the study done by Sharif et al., (2014), snacks cooked with RBO absorbed 12% to 25% less oil compared to ground nut oil. During frying or baking, RBO gives unique organoleptic and sensory characteristics including flavour, texture and appearance, which could be due to the presence of vanillin (Wang, 2019).

Rice Bran Oil is also utilized in the production of foods like mayonnaise and salad dressings due to its emulsification ability (Sharma and Das, 2013). Salad dressing and mayonnaise can be made with winterized RBO. In margarine and shortening, the hard fraction of RBO could be utilized to substitute plastic fats. Furthermore, RBO can be used to produce high quality emulsion filled gel (EFG) or fat replacer to substitute or mimic the properties of fats in foods. However, Mehrnia et al., (2017), reported that RBO bears a distasteful flavor and strong odor which could limit its application. These undesirable characteristics of RBO can be eliminated by preparing the RBO as oil-in-water (O/W) emulsions. The emulsions are easy and low cost in terms of production and provide better sensory properties, i.e. less or no oily mouth feel, unpalatable taste and unpleasant odor. RBO O/W emulsions are applied in a variety of products such as foods, paints, cosmetics and pharmaceutical products.

Other than that, many byproducts can be obtained during the processing of RBO, including oryzanol, lecithin, rice bran wax, rice bran stearin, rice bran meal, fatty acid, and sterols. Oryzanol is a substance manufactured from RBO soap stock produced during the neutralization of RBO refining process, is nearly the sole source of oryzanol in the industry (Wang, 2019). The emerging application of oryzanol in cosmetic preparations includes its usefulness in treatment of skin related disorders like melanin related disorder and minimizing the wrinkles in aged women (Venkatadri and Sreesaila, 2005). In food application, oryzanol proves its usefulness as an antioxidant (Kaewboonnum et al., 2010). All these beneficial effects of oryzanol in health care generated interest in developing viable separation method for oryzanol from the rice bran oil soap stock. Since RBO is particularly resistant against rancidity and oxidative deterioration, RBO-based products have a longer shelf-life, thereby aids in the preservation of snack items. Despite its high monounsaturated fatty acids concentration, RBO is still underutilized oil in many nations (Tufail et al., 2024).

Apart from the food application, topical applications of RBO improve skin tone, prevent wrinkle formation, aids hair protection against premature greying, and strengthen hair roots. The presence of squalene and tocotrienols in rice bran oil helps in skin softening and skin repair. The RBO also protects against harmful UV rays, hence are used in sun screens (Rigo et al., 2014; Nayik et al., 2015). Further, nano emulsions of rice bran oil at 10% (w/w) level was used to improve the skin moisture level (Bernardi et al., 2011). As a result, RBO is becoming more popular as a specialty component in cosmetics and personal care products.

Limitations and Constraints in Using RBO

A significant concern surrounding the utilization of RBO for application is the critical time gap between

the production of rice bran and the oil extraction process. To preserve the oil's quality and prevent spoilage, it is essential to extract the oil immediately after the bran is produced. If extraction is delayed, the lipase enzymes naturally contained within the rice bran initiate a hydrolytic reaction, leading to the conversion of the oil into free fatty acids (FFAs) and glycerol. Under conditions that are warm and humid, the rate of oil degradation and the formation of FFAs can accelerate dramatically, as noted by (Emebu et al., 2022).

Furthermore, the subsequent oxidation of these free fatty acids results in the production of various undesirable and aromatic compounds, including aldehydes and ketones, which significantly detract from the oil's flavor profile and aroma (Ali et al., 2019). Generally, RBO that contains more than 10% FFAs is considered unfit for human consumption, as it can lead to adverse health effects. Additionally, rice bran that contains more than 5% FFAs poses complications for chemical refining methods, as these elevated levels contribute to heightened refining losses and reduce the overall yield of the desirable edible oil (Japir et al., 2017).

Furthermore, it is vital to implement advanced extraction techniques and explore effective methodologies for protein separation, ensuring the production of a healthy and high-quality rice bran oil. By adopting optimized processing strategies and minimizing delays, we can safeguard the integrity of the oil and deliver a safe, flavorful product that meets consumer standards (Chakrabarti and Jala, 2019).

Future Research Directions and Technological Challenges

Emerging studies are essential to address the rapid hydrolytic rancidity of rice bran (FFA >8% within 24 hours post-milling). There is an urgent need for the development and implementation of future research focused on rice bran oil (RBO) to create scalable and sustainable extraction technologies that mitigate the inherent volatility of fresh rice bran. Lipase activity can surge to high levels (FFA >5-10% within hours after milling) soon after processing. Green and hybrid techniques, such as ultrasound-assisted supercritical CO₂ extraction using ethanol co-solvents, have demonstrated the ability to achieve extraction yields of 12-25% while retaining γ -oryzanol (1.8-2.2%) and tocotrienols (800-1100 mg/kg). However, this method is currently limited to pilot-scale operations due to its high capital costs, estimated at \$5-10 per kilogram of oil. Aqueous extraction employing enzyme cocktails of cellulase and pectinase under mild conditions (40-50°C, pH 4.5) can provide similar yields (15-20%), with the added benefit of eliminating hexane residues, although the costs associated with enzyme usage may approach 20-30% of the potential oil value. Utilizing computational modeling, artificial intelligence (AI), and machine learning can significantly expedite the optimization of extraction conditions, predict the stability of bioactive, and support techno-economic feasibility assessments. This can be accomplished through approaches such as virtual screening of process parameters, scaling strategies, and cost-effective experiments, ultimately enhancing reproducibility.

The technological challenges remain consistent,

focusing on the need to balance preservation, bioactivity, and mass production. Thermal stabilization at temperatures between 120-140 °C effectively inactivates lipases; however, this process may result in a 15-25% decrease in heat-sensitive gamma-oryzanol levels. In contrast, physical refining must contend with elevated levels of wax (2-5%) and phospholipids, which require specialized dewaxing and degumming techniques. Emerging solvent recovery methods, such as membrane-based systems and limonene/CO₂-expanded acetone, are addressing these issues and are now regarded as environmentally sustainable. Nevertheless, they face challenges with scaling up and consume two to three times as much energy as conventional hexane extraction. Future research should also include clinical trials to validate the health benefits of RBO bioactive, particularly in cardiovascular and metabolic contexts, by examining the relationship between molecular composition and functional outcomes. Using integrated biorefinery models, RBO can achieve both economic feasibility and nutraceutical superiority by transforming defatted rice bran to recover over 90% of the oil while preserving high levels of dietary fiber (60%) and protein (15%).

Conclusion

RBO is a healthy oil with a combination of saturated fatty acids, monounsaturated fatty acids and polyunsaturated fatty acids which is in the range described by the WHO. It can be extracted using traditional methods such as solvent extraction; soxhlet based solvent extraction, mechanical pressing; and novel techniques such as enzymatic extraction, supercritical carbon dioxide extraction and subclinical fluid extraction. Both In-vitro and In-vivo studies confirmed that RBO is a good source in retarding the development of many non-communicable diseases such as coronary heart disease, diabetes, cholesterol problems and hypertension conditions. RBO is a valuable alternative to cooking oil at the domestic level as well as industrial level. In addition, it is a good source of bioactive compounds compared to the other common oils used in the food industry. Thus, it has become a good alternative in food, pharmaceutical and food industries.

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