

Original Research

View Article online



Received 01 March 2025

Revised 22 March 2025

Accepted 23 April 2025

Available Online 07 July 2025

Edited by Prathapan Ayyappan

KEYWORDS:

Nutraceuticals
Bioavailability
Extrusion
Food chemistry
Rice bran oil

Natr Resour Human Health 2025; 5 (3): 484–498

<https://doi.org/10.53365/nrhh/204287>

eISSN: 2583-1194

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Exploring the Potential of Nutraceutical Foods Prepared from Rice Bran Oil, Flaxseed, and Barley Combination through Extrusion Technology: An Updated Review

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ABSTRACT: Nutraceuticals and their various characteristics, according to a common definition defined as food components undergoing health benefits beyond basic nutrition, is gaining more and more attention as it supports wellness and prevention of diseases. Extrusion technology is one of the most widely used food processing techniques known to increase the bioavailability of nutrients while improving their digestibility, and develop novel foods with desirable flavor and texture profiles. The unique health properties associated with each ingredient include high antioxidant content from rice bran oil, omega-3 fatty acids and lignans from flaxseeds, and soluble fiber from barley, which aids in cholesterol regulation. Food formulations utilizing the developed combinations and processing methods have great potential in the functional food sector to cater a growing number of consumers looking for a multi-pronged approach to health and nutrition while responding to an increasing demand of health-promoting food products. This review highlights the significance of nutraceutical foods in enhancing human health.

1. INTRODUCTION

The increase in chronic diseases and the shift toward preventive health in the 21st century have created a great deal of interest in nutraceuticals that provide a fascinating intersection between nutrition and pharmaceuticals (Almada, 2014). Nutraceutical production has now turned into one of the global planetary food industries for enhancing longevity of life and ameliorating health concerns among humans. Advancement in the nutraceutical market is observed due to interest of researchers for applying advanced techniques

for testing different qualitative and quantitative features as well as for providing a healthy life. The term nutraceutical encompasses numerous categories and subcategories, such as traditional nontraditional, fortified, recombinant, and potential nutraceuticals, phytochemicals, herbals, functional foods, dietary supplements, probiotics, and prebiotics (Bommakanti et al., 2023). Nutraceuticals include a wide range of options, including isolated nutrients, genetically engineered “designer” foods, dietary supplements, botanical products, and processed products, such as stews and cereals (Bagchi & Nair, 2016).

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The word “nutraceutical” is a portmanteau of the words “nutrition” and “pharmaceutical,” meaning foods that may have health benefits in addition to their basic nutritional functions. These advantages often involve the prevention of disease, effects on health as well as beneficial impacts on diverse biological processes (Nasri et al., 2014). Although most of these nutraceuticals are generally based on food or food components, they often capitulate under the category of complementary and alternative medicine because of their therapeutic effects. The word “nutraceutical” was introduced as a food or part of a food that provides medical or health benefits, involving the prevention and/or treatment of a disease (Agrawal et al., 2020). This definition is sufficiently broad to include isolated nutrients, dietary supplements, herbal products, processed foods, and genetically engineered designer foods. Nutraceuticals are not classified as drugs, and are regulated to some extent as food products (Kumar & Kumar, 2015).

1.1. Nutraceuticals

Nutraceuticals are natural food products that have health benefits, such as improving physiological function and treating a variety of illnesses. Products made from isolated nutrients, dietary supplements, genetically modified designer foods, herbal items, processed foods, and drinks are included in the category of nutraceuticals. Functional foods with probiotic benefits include fresh foods, such as fruits, vegetables, and fermented meals containing living organisms, as well as “vitamin-enriched” health-promoting products. Nutraceuticals offer a proactive healthcare approach with significant therapeutic effects on the human body. With pharmaceutical dosage forms (pills, powders, capsules, etc.) that contain food bioactive substances as active ingredients, nutraceuticals are a major development in healthcare medicine linked to food science. They include a variety of products derived from isolated nutrients, dietary supplements, and genetically engineered designer foods, herbal products, processed foods, and beverages. Among them, “vitamin-enriched” health-promoting products and also fresh foods, such as vegetables, fruits, and fermented foods populated with live cultures, are considered to be functional foods with probiotic benefits. Thus, nutraceuticals provide a proactive healthcare approach with tremendous therapeutic impact on the human body (Bagchi et al., 2015; Das et al., 2012).

1.2. Malnutrition

Malnutrition is a serious global health issue and a major cause of death in low-income and developing nations.

In particular, malnutrition and undernutrition (mostly of proteins and micronutrients) are recognized as major public health concerns in a number of regions of the world (Million et al., 2017). In this context, methods for preventing and treating malnutrition have been identified, including food diversification, food fortification, biofortification, and food supplementation. Food supplementation and fortification have been employed for a long period as economical means to combat malnutrition, particularly in Third World nations (Ohanenye et al., 2021).

1.3. Role of Nutraceuticals in prevention of disease

Nutraceuticals are used to enhance health, delay the aging process and lengthen life expectancy, prevent chronic diseases, and simply sustain the body's integrity and functions. These products are regarded as a beneficial resource for preventing illnesses, such as diabetes, kidney and gastrointestinal problems, and various infections. Numerous nutraceuticals have important roles in immune functioning and vulnerability to specific diseased states. Additionally, oxidative stress-related disease-modifying indications for nutraceuticals include cancer, Alzheimer's disease, cardiovascular diseases, allergies, eye disorders, Parkinson's disease, and obesity.

2. BIOACTIVE COMPOUNDS

Phytoestrogens, terpenoids, limonoids, glucosinolates, phytosterols, polyphenols, carotenoid, flavonoids, isoflavonoids, and anthocyanidins are a few examples of the wide range of phytochemicals that the nutraceutical industry has taken advantage of. These phytochemicals have specific pharmacological effects on human health, such as the following: antiinflammatory, antibacterial, antiallergic, antifungal, chemopreventive, hepatoprotective,

hypolipidemic, neuroprotective, hypotensive, anti-aging, antidiabetic, in osteoporosis, carminative, antispasmodic, in heart disease, to induce apoptosis, DNA damage, anticancer, diuretic, CNS stimulant, analgesic, and immunomodulator (Gupta & Prakash, 2014; Karwande & Borade, 2015).

2.1. Antioxidants

Functional foods that are high in antioxidants, such fruits, vegetables, and nuts, are essential for reducing the negative effects of dangerous free radicals in the human body (Stephen et al., 2023). Antioxidants play a key role in scavenging these free radicals, a procedure that has serious health consequences.

Antioxidants are widely acknowledged for their capacity to reduce inflammation and oxidative stress, and play a significant role in preventing chronic illnesses (Vignesh et al., 2022). Antioxidants have the ability to counteract the variables that contribute to cardiovascular diseases; thus their significance in cardiovascular health is particularly notable (Wang & Kang, 2020). These substances support the preservation of vascular health and general cardiovascular well-being by lowering oxidative stress.

2.2. Omega-3 fatty acid

Omega-3 fatty acids are essential components of functional foods known for their dual effects on cardiovascular and cognitive health. They are found in large quantities in foods such as walnuts, flaxseeds, and fatty fish (Fekete et al., 2023). Alpha-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) are the three main constituents of omega-3 fatty acids. Only diet can provide ALA, the parent omega-3 fatty acid family, which subsequently is transformed into EPA and DHA. This conversion mechanism, however, is insufficiently effective in humans to meet the requirement of EPA and DHA, both involved in positive health effects (Siriwardhana et al., 2012).

2.3. Lignan and soluble fiber

Lignans are phytoestrogens abundantly available in fiber-rich plants, cereals (wheat, barley, and oats), legumes (bean, lentil, and soybean), vegetables (broccoli, garlic, asparagus, and carrot) fruits, berries, tea, and alcoholic beverages. Flaxseeds contain about 75–800 times more lignans than cereal grains, legumes, fruits, and vegetables (Meagher & Beecher, 2000). Flaxseeds serve as a good source of both soluble and insoluble dietary fiber. Flaxseed mucilage has gained momentum due to its superb health benefits and potential functional properties (Susheelamma, 1987).

Nutraceuticals are the products that primarily aim to grant health benefits much more than what is achieved by normal foods and diets. Nutraceuticals available in the market today are classified into numerous broad categories based on their origin, function, and regulatory standards. These mainly consist of functional foods, dietary supplements, and medical foods (AlAli et al., 2021). Each category offers different functions, that is, adding specific nutrition for curing a particular ailment. Table 1 summarizes few sources of nutraceutical products along with their health benefits.

3. CLASSIFICATION OF NUTRACEUTICAL FOODS

3.1. Functional Foods

Functional foods are the food products that, in addition to providing essential nutrients, have specific compounds or components beneficial to health and conducive to the reduction of disease(s). This may consist of vitamins, minerals, dietary fibers, probiotics, antioxidants, and different bioactive compounds. Functional foods are usually whole or minimally processed, but they can also be fortified with additional nutrients (Obayomi et al., 2024). Functional foods can be distinguished from conventional food by its specific health target(s) with scientific evidence to support it. Functional foods were first introduced in Japan in the 1980s, as an element of “Foods for Specified Health Use” (FOSHU) and defined as foods with health benefits beyond basic nutrition. Since the daisy chain effect in functional foods started, it is now routinely employed globally but with country-based definitions and regulations (Sun-Waterhouse, 2011).

Functional foods have shown a number of health benefits. Their regular consumption reduces the risk of chronic diseases, cardiovascular diseases, diabetes, and some cancers. Functional foods are rich in antioxidants, including vitamin C, polyphenols and beta-carotene, that reduce oxidative stress involved in aging and the development of a disease. Healthy fats, such as omega-3 fatty acids from fish and flaxseeds, contribute to a healthy body by reducing inflammation that helps both heart and brain (Essa et al., 2023). Probiotics in fermented food balance gut microbiome, boost immunity, help with digestive issues, and even help in proper functioning of the gut–brain axis (Hemarajata & Versalovic, 2013).

Demand of functional foods has increased due to consumer interest and ability of the food industry to innovate more functional food products for desired health action. One avenue of development is the incorporation of bioactive compounds, such as curcumin, resveratrol, and plant sterols into functional foods. High performance in bioactivity of such natural compounds is commonly limited by their stability, bioavailability, and efficacy because of food processing conditions and changes during storage (Obayomi et al., 2024). Functional foods assert scientific verification to avoid exaggeration to customers.

Countries have different regulations about governing functional food norms, being stricter in the European Union and Japan and more relaxed in other areas. In the United States, functional foods are classified as dietary supplements under the jurisdiction of the US Food and Drug Administration (US FDA), but not requiring the same regulatory scrutiny as expected for pharmaceuticals (Farid et al., 2019).

Table 1

List of few sources of nutraceutical foods with their bioactive compounds and health benefits.

Source of nutraceuticals	Bioactive compounds	Mechanism of action	Health benefits	References
Turmeric (<i>Curcuma longa</i>)	Curcumin	Anti-inflammatory and antioxidant by inhibiting NF- κ B and scavenging free radicals	Reduces inflammation, improves joint health, and supports immune function	Memarzia et al., 2021
Garlic (<i>Allium sativum</i>)	Allicin, S-allyl cysteine	Reduces blood pressure and cholesterol through inhibition of angiotensin-converting enzyme (ACE) and antioxidant properties	Cardiovascular health, improved lipid profile	Batiha et al., 2020
Green tea (<i>Camellia sinensis</i>)	Epigallocatechin gallate (EGCG), catechins	Antioxidant and anti-carcinogenic by modulating cell signaling pathways, such as mitogen-activated protein kinase (MAPK) and inhibiting angiogenesis	Supports weight management, reduces cancer risk, enhances metabolic health	Farhan, 2022
Tomatoes	Lycopene	Antioxidant effect through singlet oxygen quenching, preventing lipid peroxidation	Cardiovascular protection, reduced cancer risk	Agarwal & Rao, 2000
Blueberries	Anthocyanins	Antioxidant and anti-inflammatory; enhances brain-signaling pathways and supports neurogenesis	Cognitive health, reduced inflammation, anti-aging benefits	Kalt et al., 2020
Flaxseeds	Omega-3 fatty acids, lignans	Anti-inflammatory via modulation of lipid metabolism and reduction of pro-inflammatory cytokines	Heart health, improved digestion, hormonal balance	Rodriguez-Leyva et al., 2010
Broccoli	Sulforaphane	Activates antioxidant response element (ARE) pathways, detoxifying enzymes, and anti-carcinogenic properties	Cancer prevention, detoxification	Kaiser et al., 2021
Soybeans	Isoflavones (genistein, daidzein)	Modulates estrogen receptors, antioxidant, and anti-inflammatory effects	Bone health, cardiovascular support, menopausal symptom relief	Kim, 2021
Ginger (<i>Zingiber officinale</i>)	Gingerols, shogaols	Anti-inflammatory by inhibiting cyclooxygenase (COX) and lipoxygenase (LOX) enzymes; digestive support by promoting gastrointestinal motility	Anti-inflammatory, digestive health, nausea relief	Aregawi et al., 2024
Grapes	Resveratrol	Antioxidant and anti-aging effects by activating SIRT1 and modulating inflammatory pathways	Cardiovascular protection, anti-aging	Sarubbo et al., 2018
Pomegranate	Punicalagins, ellagic acid	Antioxidant and anti-inflammatory, modulates NF- κ B pathway, promotes apoptosis in cancer cells	Cardiovascular health, reduced cancer risk	Xu et al., 2021
Spinach	Lutein, zeaxanthin	Antioxidant effect protecting eyes from UV-induced damage and inhibiting age-related macular degeneration (AMD)	Eye health, reduced risk of macular degeneration	Kumar et al., 2024
Chia seeds	Omega-3 fatty acids, fiber	Anti-inflammatory; promotes satiety, and modulates blood glucose levels	Heart health, digestive health, weight management	Chen et al., 2024
Barley	Beta-glucans, tocotrienols	Reduces blood cholesterol and enhances immune response by modulating lipid metabolism and supporting gut health	Heart health, immune support, blood sugar regulation	Raj et al., 2023
Rice bran oil (RBO)	Gamma-oryzanol, phytosterols, tocotrienols	Antioxidant and cholesterol-lowering effect by modulating lipid metabolism and inhibiting low-density lipoprotein (LDL) oxidation	Cardiovascular health, improved lipid profile	Perez-Ternero et al., 2017
Flaxseed	Alpha-linolenic acid (ALA), lignans	Anti-inflammatory, improves blood lipid levels, and modulates hormonal balance	Heart health, hormonal balance, and antioxidant support	Noreen et al., 2023
Oats	Beta-glucan	Lowers cholesterol by forming a viscous gel in the gut, reducing cholesterol absorption	Heart health, cholesterol reduction	Joyce et al., 2019
Honey	Flavonoids, phenolic acids	Antioxidant activity by scavenging free radicals; antimicrobial action by inhibiting bacterial growth	Immune support and wound healing	Almasaudi et al., 2021

3.2. Dietary Supplements

Dietary supplements are the preparations that supply nutrients or other bioactive compounds that may be missing in daily diet. These are vitamins, minerals, amino acids,

enzymes, probiotics, antioxidants, and botanicals designed to help the body to maintain health or assist with a specific nutritional requirement. While supplements may benefit the overall well-being, most are designed to prevent nutrient deficits; improve immunity; promote exercise performance and

recovery; and provide routine functions for physiological processes in both military and nonmilitary populations identified as being at increased risk of nutritional deficits or requiring specific medical requirements (Shao et al., 2021).

The most widespread dietary supplements are vitamins (e.g., vitamins A, C, D, E, and K as well as the vitamin B complex) and minerals (e.g., calcium, magnesium, iron, and zinc). These include important nutrients for energy, immunity, bone health and production of red blood cells (RBCs) (Mishra et al., 2021). For example, vitamin D and calcium are commonly recommended as nutritional supplements in the treatment/prevention of osteoporosis, particularly in the older population. Iron is involved with oxygen transport and prescribed to prevent anemia in menstruating women and to those with low bioavailable iron dietary intake (Godswill et al., 2020).

Herbal supplements are the concentrated forms of specially selected beneficial compounds derived from plants, including herbs, roots, and flowers. Some common examples are echinacea to support the immune system, ginseng to provide energy, and turmeric (curcumin) for anti-inflammatory effects. Such supplements are used in traditional medicine and studied for their therapeutic effects (Mercola, 2021). Amino acids form protein and are essential for muscle recovery, activity of neurotransmitters, and metabolic health. Branched-chain amino acids (BCAAs) work well for recovery and performance of muscles and are therefore commonly used by athletes; specific amino acids, such as glutamine, support immune function and cell division; and lysine provides structural support to connective tissues (Rajendram et al., 2015).

Omega-3 fatty acids found in fish oil and in plants, such as flaxseeds, are essential for normal cardiovascular, cognitive, and inflammatory physiology. Eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) supplements are commonly used for reducing triglycerides and supporting mental health, especially in those who do not consume enough of fatty fish (Laye et al., 2018). On the other hand, probiotics are live beneficial bacteria or yeast that help to improve the microbiome and thus support gut health. They are essential for those with digestive problems, such as irritable bowel syndrome, and for general immune support, given the importance of gut microbiome in immune homeostasis (Sánchez et al., 2017).

Dietary supplements work differently in the body depending on the compounds included. Vitamins and minerals in common act as cofactors to enzymatic reactions demanded for cellular processes (Mishra et al., 2021). The bioactivity of herbal supplements is associated with antioxidant, anti-inflammatory, or adaptogenic effects by modulating several biological pathways. Amino acids are the foundational building blocks of proteins and thus assist in the repair and maintenance of the cells, while probiotics function by balancing gut

microflora composition and improving gut barrier integrity (Mercola, 2021).

3.3. Medical Foods

Medical foods are governed by the US FDA under the Orphan Drug Act. They are structured to have either enteral ingestion or enteral application under the guidance of a clinician (Holmes et al., 2021). Medical foods differ from traditional foods, as the former are designed and prescribed for specific nutritional needs of patients with distinctive metabolic or physiological requirements because of a disease. They are not ordinary foods that contribute to the overall nutrition, or drugs designed to cure or treat a disease (Mozaffarian et al., 2024).

Medical foods are prescribed for treating various chronic and acute conditions, including metabolic disorders, neurologic condition, gastrointestinal disorders, and malnutrition. To illustrate, people with phenylketonuria (PKU), a genetic condition that restricts how the body metabolizes phenylalanine, (an amino acid found in high-protein foods), will frequently need medical food which are free of phenylalanine (McWhorter et al., 2022). In a similar context, for patients with Alzheimer's disease it is suggested that ketone-precursor-enriched medical food can supply an alternative brain fuel source to ameliorate cognitive deficits linked to impaired glucose metabolism (Taylor et al., 2019).

3.4. Probiotics and Prebiotics

Prebiotics and probiotics are the functional foods or supplements that are beneficial for gut health components that add to microbiome balance and optimal health via the gut-brain axis (Dahiya & Nigam, 2022).

Probiotics are live bacteria or yeast that may provide health benefits if prescribed in adequate quantity. *Lactobacillus*, *Bifidobacterium*, and *Saccharomyces boulardii* are some of the common probiotic strains. These good microbes are present in different fermented foods, such as yogurt, kefir, sauerkraut, kimchi, and some supplements. They colonize the gastrointestinal tract, combat pathogenic bacteria, and provide protection to gut barrier, thus preventing infections and related diseases (Ansari et al., 2023). Probiotics are effective when they colonize in the gut with suppressing effect through competition against others. They also generate short-chain fatty acids (SCFAs), including acetate, butyrate, and propionate, which nourish colon cells, suppress inflammation, and help to ensure that gut barrier stays intact. Moreover, probiotics also regulate immune response through their interaction with

immune cells in gut-associated lymphoid tissue (GALT), enhance immune tolerance, and suppress chronic inflammation (Ballini et al., 2023).

Prebiotics (as opposed to probiotics, which are live organisms) are selectively fermentable fibers—fructooligosaccharides (FOS), inulin, and galacto-oligosaccharides (GOS)—as well as other non-bacterial food molecules that preferentially expand the growth of beneficial bacterial species, including *Bifidobacterium* and *Lactobacillus*. Prebiotics indirectly promote gut health, immune function, and metabolic health by encouraging the growth of healthy bacteria (Wu et al., 2017). Prebiotics also stimulate SCFA production, which facilitates acidic gut environment that limits pathogenic growth. In addition, such SCFAs help with mineral absorption, blood sugar control, and maintaining healthy levels of cholesterol. According to a research, prebiotics help bolster digest biological defence and cognition via modulation of gut microbiota composition (Peng & Biswas, 2017).

Combination of probiotics and prebiotics creates “synbiotics,” which are specific type of formulations that provide a survival advantage to beneficial bacteria when they enter the gut. Synbiotics are increasingly studied to promote favorable gut microbiome as well as metabolic and immune health. The literature shows how synbiotics improve probiotic efficacy by providing resources that support the growth of probiotics. The synergistic relationship between synbiotics and probiotic is fundamental for a healthy microbiome, and as such both in combination are integral for the overall health (Khan et al., 2020).

3.5. Fortified and functional beverages

The nutraceutical food sector is spotting growth in the fortified and functional beverage category, targeting a shift from basic hydration to health benefits. These drinks are fortified with nutrients, bioactive compounds, and functional ingredients to promote targeted health results, including immune support, cognitive enhancement, gut health, and energy metabolism (Puri et al., 2022). Owing to the development of food technology and consumer interest in health and wellness, these drinks are convenient products to make consumers healthier.

Fortified beverages are the drinks having additional vitamins, minerals, and other nutrients that may not be supplied in good quantity through diet. Some examples are immediate juices fortified with calcium or vitamin C, plant-based milk with vitamins D and B12, and electrolyte drinks with potassium and magnesium (Gupta et al., 2023). These fortified drinks help to fulfil nutrient deficiencies in the deficient population, such as vitamin D-fortified milk for people having low sun exposure, or iron-enriched juices to prevent anemia in high-risk populations.

Micronutrient-fortified beverages are designed to match the dietary needs of different population groups, such as children (i.e., healthy growth), athletes (i.e., recovery), and elderly individuals (i.e., nutritional boost), allowing them to receive micronutrients lacking in normal diet, without requiring substantial changes in food intake composition. They are infused with bioactive ingredients, such as antioxidants, probiotics, prebiotics, adaptogens, herbal extracts, and Omega-3 fatty acids, thus targeting the areas, such as immunity, mental alertness, and gut health. Some popular functional beverages are probiotic-packed kombucha, green tea with infused antioxidants, and turmeric lattes with anti-inflammatory properties (Ward, 2017). Fortified beverages emphasize on preventing deficiency whereas functional beverages are mostly concerned with encouraging well-being and helping the body's natural functions (Dini, 2019).

4. SOURCES OF NUTRACEUTICAL FOODFOODS

4.1. Barley

Barley (*Hordeum vulgare*), one of the world's oldest cultivated grains, is increasingly recognized as a nutraceutical food because of its diverse range of phytochemicals and bioactive compounds, which provide health benefits beyond basic nutrition. With its impressive nutritional profile and an array of health-promoting properties, barley is a rich source of dietary fiber, vitamins, minerals, and a variety of phytochemicals, making it a valuable addition to nutraceuticals and functional foods.

Barley is one of the cereal grains that contains a lot of soluble and insoluble dietary fibers and other bioactive ingredients, including tocotrienols (form of vitamin E), vitamin B-complex, minerals, and phenolic compounds. Important phytochemicals found in barley and their health benefits are explained in Table 2. Antioxidant activity of phenolic compounds is widely studied and is thought as partly, if not entirely, due to their phenolic hydroxyl groups, including the classes such as phenolic acids, tannins, flavonoids, pro-anthocyanidins, and amino phenolic compounds. Consumption of whole grain barley and its hydroalcoholic extracts reduces the onset of chronic diseases because of phytochemicals such as β -glucan, phenolic acids, flavonoids, lignans, phytosterol, and folate.

4.2. Flax Seed

Flaxseed or linseed (*Linum usitatissimum*), in India also known as *alsi*, *jawas*, or *aksebija*, belonging to the family *Linaceae*. It has a glossy and smooth appearance seed coat,

Table 2

List of phytochemicals present in barley and their health benefits and mechanism of action.

Phytochemicals	Mechanism of action	Health benefits	Additional insights	References
Beta-glucans	Forms a viscous gel in the intestine, slows down glucose absorption, binds bile acids, reduces cholesterol, and promotes satiety	Lowers cholesterol, stabilizes blood glucose, aids in weight management, and improves gut health	Key soluble fiber known for its cholesterol-lowering effects; recommended dosage for efficacy is 3 g/day. Commonly used in functional foods for cardiovascular and metabolic health	Ahmad & Ahmed, 2021
Tocotrienols	Inhibits HMG-CoA reductase, antioxidant effects that protect cell membranes from oxidative damage	Reduces LDL cholesterol, protects cardiovascular health, has anti-inflammatory properties	Part of vitamin E complex; tocotrienols are particularly effective in lipid-lowering, compared to tocopherols. They offer potential protection against neurodegenerative diseases and certain cancers	Pang & Chin, 2019
Phytosterols	Competes with cholesterol for absorption in the intestine, leading to lower blood cholesterol levels	Supports heart health, reduces risk of cardiovascular diseases	Known for their lipid-lowering capabilities; consuming ~2 g/day of phytosterols can effectively reduce LDL cholesterol. Often used in foods marketed for cholesterol reduction, such as fortified margarine	Poli et al., 2021
Phenolic acid	Scavenges free radicals, anti-inflammatory, and inhibits lipid peroxidation	Protects against oxidative stress, reduces inflammation, supports cellular health	Includes ferulic acid, caffeic acid, and p-coumaric acid; phenolic acids contribute to the preservation of food quality by reducing lipid oxidation in processed foods	Rudrapal et al., 2022
Flavonoids	Antioxidant action by scavenging free radicals, modulates immune responses, and may inhibit cancer cell proliferation	Reduces risk of chronic diseases, supports immune health, has anti-aging properties	Flavonoids in barley include catechins and quercetin; known to play a role in cancer prevention and anti-inflammatory responses. Regular intake associated with reduced risk of cardiovascular disease	Obrenovich et al., 2011
Lignans	Mimics estrogenic activity, modulates hormone metabolism, and exhibits antioxidant properties	Reduces risk of hormone-related cancers (e.g., breast, prostate), supports cardiovascular health	Phytoestrogens with cancer-protective properties; lignans are metabolized by gut bacteria to produce enterolactone and enterodiols, which have health benefits, particularly for hormonal balance in post-menopausal women	Chavda et al., 2024
Saponins	Forms complexes with cholesterol in the gut, reducing absorption, and exhibits anti-inflammatory properties	Supports lipid management, may improve immune function, has anti-cancer properties	Saponins are less abundant in barley, compared to other grains; they play a role in reducing cholesterol and modulating the immune system	Timilsena et al., 2023
Proanthocyanidins	Antioxidant and anti-inflammatory effects; inhibits bacterial adhesion, particularly beneficial in urinary health and inflammation reduction	May reduce risk of infections, improves urinary tract health, supports anti-inflammatory responses	Polymeric flavonoids that contribute to anti-inflammatory and cardiovascular benefits. These compounds are also involved in reducing oxidative stress markers in the body	Cádiz-Gurrea, et al., 2017
Selenium	Integral part of antioxidant enzymes, particularly glutathione peroxidase, and supports immune function	Antioxidant activity, immune system support, cancer prevention	Selenium is an essential trace mineral; barley grown in selenium-rich soil is an excellent source. Selenium-enriched barley is considered as a valuable ingredient in nutraceuticals targeting immune and antioxidant benefits	Battin & Brumaghim, 2009
Melatonin	Regulates sleep-wake cycles and acts as an antioxidant	Improves sleep quality, supports immune function, has anti-aging properties	Melatonin levels in barley are relatively low but may be enhanced through processing techniques; its presence adds value for nutraceuticals targeting sleep health	Xia et al., 2023
Glutathione	Acts as a powerful intracellular antioxidant, neutralizing reactive oxygen species and supporting detoxification pathways	Detoxification support, protects cellular health, and improves skin health	Glutathione is a key antioxidant that plays a role in cellular health and detoxification, with emerging applications in nutraceuticals for anti-aging and immune support	Lushchak, 2012

which is hard in nature with desirable flavor, and a range of color from dark brown to yellow. It looks like a tiny nut (3–5 mm), which is slightly more pointed at the top than at the base. Since pre-historic period, flaxseed cultivation is widely prevalent in India, Europe, and Egypt. Presently, flaxseeds are used as a food and are also known for their medicinal properties. Although flaxseed is an underutilized oilseed, it has gained popularity over the past few decades because of its favorable nutritional profile and other functional properties.

Flaxseeds through times have evolved as one of the leading ingredients of functional food products because of nutritive and functional properties (Ganorkar & Jain, 2013). Flaxseed is a good source of omega-3 fatty acid among non-fish consumers. Owing to its high nutritional value, it is a potent functional beauty ingredient. As a functional food, it has become an emerging powerhouse of global food supply. Numerous studies have shown that the consumption of flaxseed aids in the lowering of high blood pressure and cholesterol levels, the two major reasons for cardiovascular diseases.

Being a good source of alpha-linolenic acid, lignans, proteins, phenolics, flaxseed is one of the most promising functional foods (Table 3). It has acquired herbal history since antiquity because of its therapeutic properties against many diseases, such as diabetes mellitus, arthritis, osteoporosis, cardiovascular diseases, and cancer. Compared to other plants, flaxseeds contain a high amount of lignans (600 mg kg⁻¹).

4.3. Rice Bran Oil (RBO)

Rice is a staple for a large portion of Asia's population. Rice bran is the brown layer of rice obtained after removing the outer husk during paddy milling. Rice bran oil is among the richest sources of bioactive phytochemicals and has great commercial significance. Although not new, RBO is a less popular cooking medium used in Asian countries, such as India, Japan, and China.

With a paddy production of 150 million tons, RBO is one of the promising functional edible oils in India. This policosanol is extracted from RBO, which can be isolated by various extraction methods, including solvent or n-hexane-based extraction, Ohmic heating, and supercritical fluid extraction. Known as "heart oil," RBO is extremely popular in Japan for being a preferred cooking medium. RBO is a known functional food or health food in Western countries (Nayik et al. 2015).

As per the standards of "Codex Alimentarius," RBO must have a relative density of 0.910–0.929, refractive index of 1.467–1.470, and an iodine value of 136–148. RBO is extracted from the germ and inner husk of rice and mainly consists of gamma-oryzanol, vitamin E complex, tocotrienols,

and β -sitosterol (Chotimakorn et al., 2008). The major unsaturated fatty acids in RBO are oleic acid (38.4%), linoleic acid (34.4%), and α -linolenic acid (2.2%), and the main saturated fatty acids are palmitate 54 (cetyl palmitate; 21.5%) and stearate 52 (double-pressed stearic acid with a specific composition; 2.9%). In crude RBO, content of gamma oryzanol ranges from 1.5% to 2.9% (w/w) (Pauca-Menacho et al., 2007). The crude or unrefined RBO is subjected to physical (Arumughan et al., 2003) or chemical refining (Gopala Krishna et al., 2006) to meet the standards of other edible vegetable oils.

5. OVERVIEW OF EXTRUSION TECHNOLOGY

5.1. Definition and Process

Extrusion technology is a well-established and widely used process for the preparation of food products. It impels food constituents through a combination of mechanical and thermal treatments to obtain desirable textures, shapes, and functionalities (Prabha et al., 2021).

Extrusion process drives food ingredients through a cylindrical barrel containing one or two rotating screws. The material is heated, pressured, and exposed to mechanical shear as it flows through barrel (Bordoloi & Ganguly, 2014). Following steps are involved in the Extrusion process:

Temperature: For all food products and texture requirements, extrusion barrel's temperature is maintained at 90–200°C. These high temperatures maintained for extended periods gelatinize starches and denature proteins while also inactivating many pathogens and spoilage organisms that may affect product safety and desired textural characteristics (Yacu, 2020). Temperature must be controlled very precisely, as it influences the texture and nutritional quality of the finished product (Alam et al., 2016).

Pressure: As screw rotates, the die at the exit of the extrusion barrel builds up high pressure inside. With a high pressure of up to 100–150 bar, it is easy to curl and squeeze in the ingredients (Shelar & Gaikwad, 2019). Using a combination of heat and pressure, the moisture content is decreased, thus resulting in a dry and expanded product discharged from the die (Bouvier & Campanella, 2014).

Mechanical shearing: The mechanical shearing force applied to food material by rotating screw(s) helps in mixing, kneading, and/or extrusion of the material. This mechanical shearing destroys the structure of food matrix, resulting in homogeneous mixing of ingredients and changes in texture (Sule et al., 2024). The shearing force influences protein alignment and starch gelatinization,

Table 3

List of phytochemicals present in flaxseeds and their nutraceutical applications.

Phytochemicals	Mechanism of action	Health benefits	Nutraceutical application	References
Alpha-linolenic acid (ALA)	Anti-inflammatory omega-3 fatty acid, reduces cholesterol and triglycerides, inhibits pro-inflammatory eicosanoids	Supports cardiovascular health, reduces inflammation, and aids in weight management	Used in heart-healthy products, anti-inflammatory supplements, and weight management formulas. ALA is a plant-based omega-3 ideal for vegetarians and vegans	Shibabaw, 2021
Lignans (secoisolariciresinol diglucoside [SDG])	Phytoestrogen activity, antioxidant properties, modulates hormone metabolism, and may reduce cancer cell proliferation	Reduces risk of hormone-related cancers, supports heart health, and has antioxidant effects	Lignans in flaxseed are linked to hormone balance and are commonly used in women's health supplements for menopausal support and cancer prevention, particularly for breast and prostate health	Truan, 2010
Dietary fiber	Soluble fiber forms a viscous gel in the gut, slowing glucose absorption and binding cholesterol; insoluble fiber supports digestive health	Stabilizes blood glucose, reduces cholesterol, improves digestion.	Used in formulations targeting cholesterol management, blood sugar regulation, and gut health. Known for its ability to improve stool bulk and prevent constipation.	Mudgil & Barak, 2013
Phenolic acids	Antioxidant action by neutralizing free radicals, anti-inflammatory, may prevent lipid peroxidation	Reduces risk of chronic diseases, and supports cellular health	Includes ferulic acid and p-coumaric acid; phenolic acids contribute to anti-inflammatory and anti-carcinogenic properties, widely used in antioxidant-rich nutraceuticals for chronic disease prevention	Rahman et al., 2021
Protein (rich in arginine)	Provides essential amino acids, arginine aids nitric oxide production, supports vascular health, and is anti-inflammatory	Muscle repair, heart health, and reduces inflammation	Flaxseed protein is often used in vegan protein supplements and muscle recovery products. Arginine supports vascular health and is used in nutraceuticals for athletes and active individuals	Oyovwi & Atere, 2024
Phytosterols	Competes with cholesterol for absorption, lowering blood cholesterol levels	Supports cardiovascular health, and reduces cholesterol levels	Phytosterol-rich flaxseed products are often included in nutraceuticals focused on heart health and cholesterol management, such as fortified foods and dietary supplements	Poli et al., 2021
Flavonoids	Antioxidant and anti-inflammatory, may inhibit cancer cell proliferation, and improve vascular function	Reduces risk of cancer, supports heart health, and is anti-aging	Flaxseed flavonoids are included in nutraceuticals for cardiovascular and cancer prevention because of their potent anti-inflammatory and anti-carcinogenic properties	García-Lafuente et al., 2009
Saponins	Forms complexes with cholesterol in the gut, reducing absorption; has anti-inflammatory and anti-cancer properties	Supports lipid management, may reduce cancer risk	Saponins are included in cholesterol-lowering supplements and nutraceuticals for cancer prevention, providing a natural means to improve lipid profiles and protect against cellular damage	Marrelli et al., 2016
Mucilage (soluble fiber)	Forms a gel in the gut, slows digestion, improves satiety, and aids in weight management, supports gut microbiome	Promotes fullness, regulates blood sugar, and improves digestion	Commonly used in weight management and gut health products; mucilage helps to control appetite, promotes satiety, and supports the growth of beneficial gut bacteria	Meldrum & Yakubov, 2024
Tannins	Antioxidant and antimicrobial, binds to proteins and metals, potentially reducing digestive enzyme activity in pathogens	Antimicrobial, antioxidant, and supports immune health	Tannins are utilized in immune-support nutraceuticals for their antimicrobial effects, offering a natural way to protect against pathogens and oxidative damage	Liu et al., 2020
Glutathione	Acts as an antioxidant, supports detoxification pathways, and neutralizes reactive oxygen species	Cellular detoxification, skin health, and improves immune functions	Glutathione is a major antioxidant used in detox and anti-aging supplements for its role in cellular health and immune support. Its presence in germinated flaxseed enhances its nutraceutical value	Lushchak, 2012

thereby providing specific structure functionality and texture to extruded foods ([Arêas, 1992](#)).

When the pressurized food material exits barrel through inside die, it decompresses and then rapidly expands and

cools to produce end products that are porous and crispy (e.g., snack foods). The effect depends on the formulation, water content, and preparation conditions ([Schmid et al., 2022](#)).

5.2. Advantages of Extrusion Technology for Nutraceuticals

The key features of extrusion technology are its versatile and efficient processing, stability, and long shelf life, thus making it very favorable for the food sector.

5.3. Nutrient Retention and Bioavailability

Extrusion technology while producing nutraceuticals is able to keep the stability and bioavailability of key nutrients. The process of extrusion minimizes nutrient loss because of favorable conditions of high temperature and pressure (Camire et al., 1990). Although some vitamins and sensitive bioactive constituents might be prone to heat, extremely short extrusion time (generally from seconds to minutes) minimizes the exposure and helps to maintain the relative potency of antioxidants and other micronutrients, such as minerals and vitamins (Gulati et al., 2020). This is important for bioavailability of nutraceuticals with health benefits, such as immune support and cardiovascular health (Choron et al., 2020).

6. SYNERGISTIC EFFECT OF HEALTH CLAIMS ASSOCIATED WITH RICE BRAN OIL, FLAXSEED, AND BARLEY

Alpha-linolenic acid, a type of omega-3 fatty acid, is abundant in flaxseed oil, extracted from the seeds of flax plant; this is considered to be a very nutrient-dense oil (Thomas et al., 2015). ALA in flaxseed oil lowers blood pressure and helps to prevent heart disease (Guasch-Ferré et al., 2020). Flaxseed oil has the potential to improve blood flow and heart health by promoting blood vessel relaxation and lowering arterial stiffness. In addition to cardiovascular health, flaxseed oil may help with the digestive process (Venkatakrishnan et al., 2020).

Barley contains smaller amounts of vanillic acid, syringic acid, 2,4-dihydroxybenzoic acid, and sinapic acid along with ferulic acid, which accounts for the majority (68%) of phenolic acids. Phenolic acids are composed of ferulic acid and coumaric acid. It also has a variety of phytochemicals, which are often controlled by genotypic or environmental factors, or by their interactions. Numerous phytochemicals found in barley are categorized into different types, such as lignans, tocopherols, flavonoids, phenolic acids, and folates.

Phenolic acids, such as ferulic acid, flavonoids, anthocyanins, such as cyanidin glucoside, and steroidal chemicals, such as gamma-oryzanol and gamma aminobutyric acid (GABA), are among the bioactive substances found in rice bran. Policosanol is one of the aliphatic alcohols and wax

esters found in rice bran wax. Rice bran contains bioactive substances that have anti-inflammatory, anti-diabetic, and antioxidant properties.

7. MARKET GROWTH AND POTENTIAL OF NUTRACEUTICALS

In 2023, the global nutraceutical market was sized at USD 712.97 billion, and is projected to register a compound annual growth rate (CAGR) of 8.4% from 2024 to 2030. Market growth is primarily driven by rising lifestyle, non-communicable diseases, preventive healthcare, and the added awareness about the benefits of a healthy diet among consumers (Kausar et al., 2024). Moreover, nutraceuticals are thriving on account of the rising purchasing power of consumers in high-growth economies, and is expected to fuel the demand. The increasing number of athletes at national- and international-level sports is to fuel demand for nutraceutical products. Considering the rising consumer inclination toward natural and functional foods and beverages, manufacturers are involved in developing novel nutraceutical products to meet different demographic needs (Nori et al., 2023). With research and development being a rapidly evolving field, scientists are continuously working to discover new bioactive compounds, thereby pushing product innovations in this area. The growing demand for dietary supplements and nutraceuticals is also a consequence of the evolving consumer paradigm toward self-care in lifestyle disorder treatment, such as malnutrition and cardiovascular disorders.

By 2032, dietary supplements product segment from nutraceutical market is anticipated to hold market of USD 279.6 billion. Vitamins, minerals, herbal extracts, and probiotics are consumed as dietary supplements, which can better complement and improve nutrition (Cencic & Chingwaru, 2010). In addition, the growing awareness toward preventive healthcare and increasing prevalence of self-care are other factors that have driven the growth of dietary supplements' market over the years. Also, the increasing population base afflicted with scarcity of minerals is to propel expansion of this segment (Srivastava & Bhatnagar, 2012). Consumer perceptions and purchasing behaviors are influenced by labeling requirements about ingredients, health claims, and dosage recommendations (Nori et al., 2023).

8. HEALTH BENEFITS OF NUTRACEUTICALS

Nutraceutical foods have gained significant global attention over recent years. The increase is supported primarily by a shift in consumer mindset, with growing interest and

concerns over nutrition and wellness (Bagchi & Nair, 2016). The present-day consumers are aware and enlightened about the importance of certain nutrients and bioactive compounds that can preserve immune health, decrease inflammation, and modulate the parameters associated with chronic diseases, such as heart disease, diabetes, and obesity. Consequently, the demand for such functional ingredients, such as omega-3 fatty acids, fiber, antioxidants, and probiotics, has increased considerably due to their promising benefits. Owing to the global increase of life expectancy, more aged people are contemplating for methods to live a healthy and quality life (Nielsen, 2016). Nutraceutical foods are targeted to the people nearing or at retirement age with benefits for joints' health, cognitive support, and immune resilience. Curcumin, glucosamine, and resveratrol in foods and supplementations are well-known common choices of the elderly to maintain joints and bone health, and omega-3 products are used for their prospective cognitive functioning (Gul et al., 2016). Since the elderly population is more prone to chronic diseases, this increases the demand for nutraceuticals. Thus, nutraceuticals are perceived as a viable tool for alleviating the healthcare burden, including supporting heart health, blood sugar regulation, and anti-inflammatory responses (Dillard & German, 2000).

The demand for functional foods and dietary supplements has increased significantly in the aftermath of the COVID-19 pandemic. Over the past year, immunity-boosting supplements have become increasingly popular, resulting in a substantial shift in consumer behavior and purchasing patterns (Wróbel et al., 2021). Additionally, the implementation of preventive healthcare measures, including dietary supplements, has become an integral component of daily routine of individuals. Consequently, the COVID-19 pandemic has created an opportunity for nutraceuticals to create and establish their robust presence globally (Alkhatib, 2020).

9. CONCLUSION

Among cereals, barley has numerous health benefits, such as enhancing the health and betterment of the digestive and immunity systems. Consumption of beta glucan-rich barley diminishes several cardiovascular risk factors in hypercholesterolemic patients.

Gamma oryzanol, present in rice bran, is effective in mitigating blood serum cholesterol and decreases triglycerides in hyperlipidemic patients. The most active lignan compound SDG, which is extracted and concentrated from flaxseeds, has a great promise in providing therapeutic effects in certain hormone-dependent cancers, cardiovascular diseases, diabetes as well as other immune-mediated disorders. It is also noted as one of the richest sources of phenolic compounds.

High temperature treatment used in some processing methods, will destroy several nutritional components. The identified and chosen nutraceuticals (beta glucans, gamma oryzanol, and lignans) from their raw materials (barley flour, RBO, and flaxseeds) are heat-stable. Thus, owing to high temperature and short-time processing of extrusion technology, it is possible to retain important nutritional elements. The swollen appearance and crisp nature of extruded products appeal consumers. A lot of focus must be directed to high-nutrient extruded products.

AUTHOR CONTRIBUTIONS

Geetanjali Gupta: Collection and/or assembly of data, data analysis and interpretation, and writing of the article.

Sarvesh Rustagi: Research concept and design, critical revision of the article, and final approval of the article.

CONFLICTS OF INTEREST

There is no conflict of interest among authors

FUNDING

Not applicable

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