

Physicochemical properties, nutritional and health benefits of soybean oil: A review

Muhammad Asim Qaisrani¹, Naveed Khan¹ and Bamimore Rokeeb Akayode^{2*}

¹College of Life Sciences and Agri-forestry, Southwest University of Science and Technology, Mianyang 621010, Sichuan, China

²Department of Food Science, Faculty of Food and Consumer Sciences, Ladoke Akintola University of Technology (LAUTECH), Ogbomosho, Oyo State, Nigeria

*Corresponding author's email: rokeebbamimore908@gmail.com

Abstract

Soybean oil ranks among the most widely consumed and commercially significant edible vegetable oils worldwide because of its nutritional value, functional properties, and diverse food applications. This review comprehensively examines the chemical composition of soybean seed and oil, physicochemical characteristics, fatty acid profile, minor bioactive compounds, extraction methods, genetic modification, and nutritional and health-promoting properties of soybean oil. Soybean seed contains substantial amounts of proteins, lipids, carbohydrates, minerals, vitamins, and biologically active compounds. Soybean oil contains a substantial proportion of unsaturated fatty acids, with linoleic acid, oleic acid, and α -linolenic acid being the predominant components. Its physicochemical characteristics are evaluated using parameters such as iodine value, saponification value, peroxide value, free fatty acid content, density, viscosity and oxidative stability, are important determinants of oil quality, processing behavior, storage stability, and suitability for food applications. In addition to major lipid components, soybean oil and associated soybean fractions contain several minor compounds, including phytosterols, phospholipids, saponins, ferritins, and isoflavones, which

contribute to their functional and biological significance. Different soybean oil extraction methods influence oil yield, composition, quality, and retention of bioactive constituents, while genetic modification provides opportunities to alter fatty acid composition and improve desirable technological and nutritional characteristics. Particular attention is given to the health effects of soy carbohydrates, lipids, isoflavones, and soy-derived phosphatidylserine. Evidence indicates that these constituents may contribute to improved lipid metabolism, cardiovascular health, blood pressure regulation, bone health, cognitive and memory function, and reduced risks associated with certain chronic diseases. Soy isoflavones are also discussed in relation to menopausal symptoms, cardiovascular disease, bone health, and cancer prevention. Overall, soybean oil and other soybean-derived bioactive components represent valuable nutritional resources with considerable potential for promoting human health. A better understanding of their composition, processing, and biological activities can support the development of improved soybean varieties, optimized extraction and processing technologies, and healthier food products. © 2026 The Author(s)

Keywords: Fatty acids, Health benefits, Physicochemical properties, Phytosterols, Soybean oil, Soy isoflavones

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Introduction

Nutraceuticals are food-derived constituents that can provide physiological benefits in addition to supplying nutrients. They include compounds such as antioxidants, phytochemicals, minerals, probiotics and prebiotics. Vegetable oils are important sources of lipids and nutritionally relevant fatty acids, while triacylglycerols represent their principal structural component (Karuna and Prasad, 2015). Soybean (*Glycine max* (L.) Merr.), a member of Fabaceae, is one of the major legume and oilseed crops cultivated globally. Its taxonomic position and key botanical features are summarized in Fig. 1. Historical evidence places soybean cultivation in China

several millennia ago, followed by its introduction into other regions, including the United States (Giancola et al., 2002). Based on utilization, soybeans are commonly considered in terms of oilseed and food uses; they supply vegetable oil, protein-rich ingredients and foods consumed directly or after processing (Saldivar et al., 2011). Soybean seeds contain approximately 40% protein, 20% oil and 33% carbohydrate, although these proportions vary with genotype and growing conditions (Qiu et al., 2015; Zhao et al., 2015; Zheng & Zhixi, 2015). Soy protein is regarded as nutritionally valuable because its amino-acid pattern is relatively complete. Soy foods can therefore contribute an affordable source of dietary protein, particularly where access to animal protein is limited (Agarwal et al., 2013). Soybean meals are also extensively

incorporated into poultry and aquaculture feeds and supplies vitamins, minerals, dietary fiber and phytoestrogenic compounds (Reynolds et al., 2006).

The nutritional and technological performance of soybean oil is strongly influenced by its five principal fatty acids. Palmitic and stearic acids are saturated, whereas oleic, linoleic and linolenic acids are unsaturated and contribute to different physiological and functional properties (Mostofsky et al., 2001). Consequently, fatty-acid composition is an important consideration when selecting soybean oil for food or industrial purposes (Panthee et al., 2006). Oils rich in unsaturated fatty acids are generally favored nutritionally, whereas greater saturation can improve resistance to oxidation and benefit certain industrial uses (Spencer et al., 2003; Li et al., 2015). Unsaturated fatty acids have also been associated with favorable effects on blood cholesterol and cardiovascular health (Connor, 2000). A limitation of soybean oil is the oxidative sensitivity of polyunsaturated fatty acids, particularly linolenic acid, which can adversely influence storage stability and flavor through lipid oxidation (Wangsuntonpakdee et al., 2023; da Silva et al., 2026). Agarwal et al. (2013) also reported favorable observations among Chinese infants consuming soybean milk in place of cow's milk.

Growing population size and urbanization have increased demand for edible vegetable oils, which are important components of the human diet (Sivasankaran, 2010). Soybean has consequently become a major global source of edible oil, supported by advances in lipid science and oil-processing technology (Agarwal et al., 2013). The meal remaining after oil recovery is widely used as a

protein-rich feed for cattle, poultry and swine. Soybeans also serve as raw materials for numerous food ingredients and functional products, including lecithin (Mateos-Aparicio et al., 2008). Because lecithin has useful emulsifying properties, it is employed in food formulations and other industrial applications (Taylor & Kabourek, 2003). Major soybean-producing regions include the United States, Brazil, Argentina, China and the European Union.

Soybean is processed and consumed in many parts of the world, although patterns of utilization differ by region. Asian diets traditionally include numerous soybean foods, whereas Western processing has historically emphasized oil and meal production. USDA data indicated that in 2011/2012 about 54% of U.S. soybeans were processed domestically for oil, 4% was directed to seed, feed and other uses, and 42% was exported (USDA, 2013). Industrial processing commonly begins by cracking beans to produce flakes, followed by solvent extraction when high oil recovery is required. Full-fat material can also be used in feeds or milled into flour, while the defatted flakes are processed into soybean meal. This meal is an important protein ingredient for animal nutrition and can be further converted into textured vegetable protein, concentrates and isolates. Such ingredients are used in products ranging from infant foods and meat alternatives to bakery products, desserts, beverages and soups. Soybean oil itself has applications in cooking, salad dressings, frying, baking, margarine and biodiesel production (Iowa State University Extension Service, 2013). Soy foods are additionally valued for protein, fiber and phytoestrogenic compounds that may support favorable blood cholesterol levels and other aspects of chronic-disease prevention (Kang et al., 2010).

Kingdom	Plantae
Sub-kingdom	Tracheobionta (Vascular plants)
Super-division	Spermatophyta (Seed plants)
Division	Magnoliophyta (Flowering plants)
Class	Magnoliopsida (Dicotyledons)
Sub-class	Rosidae
Super-order	Rosanae
Order	Fabales
Family	Fabaceae (Leguminosae)
Sub-family	Faboideae
Tribe	Phaseoleae
Sub-tribe	Glycininae
Genus	Glycine
Species	Glycine max (L.) Merr



Fig. 1 Botanical description of Soybean (Singh, 2017)

Chemical composition of soybean seed and oil

Soybean seeds are generally oval, although dimensions and composition differ among cultivars (Nichols et al., 2006). For U.S.-grown soybean, Brumm and Hurburgh (2002) reported approximate contents of 40.69% protein, 29.4% carbohydrate and 21.38% oil, with smaller proportions of ash and other constituents. Crude soybean oil obtained by pressing or solvent extraction contains mainly neutral lipids together with fatty acids, phospholipids and minor unsaponifiable substances. The neutral lipid fraction is dominated by monoacylglycerols, diacylglycerols and, particularly, triacylglycerols. Phytosterols, tocopherols and compounds such as squalene occur in smaller quantities, while trace metals including iron and copper may also be present. Triacylglycerols account for approximately 94.4% of crude soybean oil under the conditions reported in the literature.

Physicochemical properties of soybean oil

Fatty acid composition

Omega-3 and omega-6 fatty acids occur in soybean oil in relatively balanced proportions and function as important bioactive components involved in several physiological processes, including maintenance of membrane fluidity, cellular signaling, regulation of gene expression, and eicosanoid metabolism (Clements & Decker, 2008). Other biologically active constituents of soybean include phytosterols, conjugated linoleic acid (CLA), and carotenoids. Soybeans are therefore considered valuable plant-based sources of omega-3 and omega-6 fatty acids, phytosterols, and carotenoids. This composition is crucial for good yield as well as other important agronomic characteristics and it may be selected through normal breeding procedures. The lines with too high or too low palmitic acid produce low oil contents, while lines with high stearic acid give low yield due to poor germination (Cardinal et al., 2007). In typical soybean oil, high contents of linoleic acid and low contents of linolenic acid are essential for human health as these are essential fatty acids and have great dietary importance. But they cause oxidative instability of oil due to which commercial value of oil is limited. This instability can be overcome by hydrogenation and lipid modification through traditional breeding or genetic engineering. The composition of fatty acids in soybean oil varies with maturity and deposition of seed oil (Dhakal, 2019).

Genetic studies have shown that soybean fatty-acid biosynthesis can be modified to obtain oils with characteristics suited to food and industrial applications (Wilson et al., 2002). Low-palmitic soybean oils have been developed, although their commercial adoption has remained limited. Low-linolenic oils have likewise faced competition from other vegetable oils with naturally favorable fatty-acid profiles. The economic benefit of producing specialized soybean oils can be reduced by

additional costs for contract production, segregation and dedicated processing. High-oleic soybean oil, in contrast, offers greater oxidative stability and is well suited to repeated heating, although it may influence the sensory properties of fried foods. Consumer acceptance of genetically modified soybean products has also affected commercialization. Soybeans contain minor furan-containing lipid-related compounds that can participate in the formation of volatile odor compounds during photo-oxidation (Müller et al., 2020).

Refined soybean oil is composed predominantly of triglycerides but also contains minor constituents, including phospholipids and lecithin, which can affect the color and oxidative stability of the finished oil. Approximately 80% of the fatty acids in soybean oil are unsaturated, with linoleic acid representing the major unsaturated fatty acid (Da Rosa et al., 2025). The relative oxidative reactivity of oleic, linoleic, and linolenic acids is approximately 1: 10: 20, respectively (Martin-Rubio et al., 2020). Because the presence of linolenic acid contributes to the comparatively poor oxidative stability of soybean oil, breeding programs have focused on developing soybean varieties with reduced linolenic acid content, including through genetic modification (O'Brien, 2004). The fatty acid composition of soybean oil comprises approximately 15.65% saturated fatty acids, 22.78% monounsaturated fatty acids, and 57.74% polyunsaturated fatty acids, with the latter fraction containing about 7% linolenic acid and 54% linoleic acid (Wolke, 2007). Soybean is considered a nutritionally valuable food because of its diverse range of nutrients and bioactive constituents. It provides high-quality plant protein, oligosaccharides, dietary fiber, phytochemicals, particularly isoflavones, and essential minerals.

Minor compounds

Phytosterols

Soybean oil contains a substantial fraction of plant sterols, commonly around 300–400 mg per 100 g of oil. β -Sitosterol, campesterol and stigmasterol are generally the dominant sterols, although their proportions vary with genotype and processing (Zhu et al., 2019). These molecules resemble cholesterol structurally but differ mainly in their side-chain configuration. Sterols retain a double bond within the steroid nucleus, whereas the corresponding saturated compounds are classified as stanols. Their structural similarity to cholesterol is relevant to their nutritional and physiological functions.

Phospholipids

Phospholipids normally constitute about 1–3% of soybean oil (Sugano, 2006). Important members include phosphatidylcholine, phosphatidylethanolamine, phosphatidylinositol and phosphatidic acid. Most of these polar lipids are removed during refining, particularly during degumming, but the recovered material can be used as a natural emulsifier in food systems. Beyond their technological value, phospholipids are structural components of biological

membranes and participate in maintaining membrane organization and function.

Saponins

Soybeans contain approximately 2% saponins, a group of triterpenoid glycosides that has received attention because of its chemical diversity and possible biological activities. Soy saponins are predominantly oleanane-type compounds. Their classification depends on features of the aglycone, substitution around C-22 and the carbohydrate chains attached at C-3 (Kamo et al., 2014). Around 30 soy saponin types have been described, although their abundance varies with genotype and production conditions. Reported activities include antioxidant, hypolipidemic, hepatoprotective, anticancer and anti-HIV effects (Hwang, 2017).

Ferritins

Soybeans contain ferritin, a multimeric protein that serves as an important storage form of iron (Lonnerdal, 2009). Evidence indicates that the iron stored in soybean ferritin can be absorbed and utilized by the body to an extent comparable to iron obtained from animal-derived foods (Lonnerdal, 2009). Consequently, soybean may be considered a valuable dietary source of iron and can be incorporated into diets designed to improve iron intake, particularly for individuals at risk of iron deficiency.

Genetically modified Soybean oil

The composition and functional performance of soybean oil can be modified through breeding, mutagenesis and genetic engineering. These approaches have generated soybean lines with altered fatty-acid profiles for specific food and industrial applications. Low-linolenic cultivars containing roughly 2–6% linolenic acid have been developed to improve oxidative stability and reduce the need for hydrogenation. Other breeding programs have targeted oleic, stearic and palmitic acid concentrations, producing oils with different stability and processing characteristics. Low-linolenic soybean lines have mainly been produced through conventional breeding and mutagenesis (Fehr, 2007). Some lines contain below 1% linolenic acid while retaining acceptable seed yield and major seed constituents. RNA-interference approaches have also been used to suppress FAD3 genes, which encode omega-3 fatty-acid desaturases involved in conversion of linoleic acid to linolenic acid (Flores et al., 2008). Conversely, increasing FAD3 expression can enhance linolenic-acid accumulation (Clemente & Cahoon, 2009).

Breeding has also generated soybean cultivars with approximately 30–70% oleic acid in the seed oil (Peregrine et al., 2008). However, very high oleic-acid levels have sometimes been accompanied by lower yield or environmental instability, and warmer conditions may

favor greater oleic-acid accumulation (Primomo et al., 2002; Scherder & Fehr, 2008; Bachlava & Cardinal, 2009). Genetic engineering has therefore been investigated as another route for suppressing FAD2 activity and increasing oleic acid (Spear et al., 2013). One genetically engineered approach introduced an additional FAD2-1 gene copy to suppress endogenous FAD2 expression (Fehr, 2007). This strategy reduced linoleic-acid synthesis and produced seed oil containing approximately 84.6% oleic acid without major changes in agronomic performance. Commercial development was subsequently discontinued because of the selectable marker used in the transformation process. Other engineered soybean lines have also achieved oleic-acid concentrations above 80%, illustrating the potential of targeted fatty-acid modification.

Stearic-acid enrichment has been obtained by reducing the activity of Δ^9 -stearoyl-acyl carrier protein desaturase (SACPD), especially the SACPD-C isoform expressed in seeds (Boersma et al., 2012). The SACPD enzymes catalyze conversion of stearic acid to oleic acid by introducing a double bond at the C9 position. Mutations in SACPD-C have produced soybean lines with substantially increased stearic acid, providing potential alternatives to partially hydrogenated fats. Chemical mutagenesis has also been used to alter palmitic-acid biosynthesis. Mutations affecting 3-ketoacyl-ACP synthase II can increase conversion patterns within the pathway and produce seed oils with much higher palmitic-acid concentrations (Oltmans-Deardorff et al., 2013). Some mutant lines have reached about 42.7% palmitic acid, but agronomic limitations such as lower yield, reduced oil content, poorer germination and smaller seeds have restricted their commercial use. Conversely, reduced palmitic acid has been achieved by modifying genes involved in palmitate formation, providing lines with much lower palmitic-acid concentrations.

Soybean oil extraction methods

Commercial soybean oil is obtained mainly by mechanical pressing or solvent extraction. Continuous screw presses are commonly used for mechanical recovery, whereas large processing plants generally rely on continuous countercurrent solvent extraction. In either case, the beans are subjected to cleaning, conditioning and size-reduction operations before oil separation. These pretreatments improve oil recovery, facilitate handling and help maintain the quality of both the extracted oil and the protein-rich meal. Incoming soybeans are cleaned to remove plant residues, soil, stones, damaged kernels and foreign seeds. Screens and aspiration equipment are commonly used for this purpose. Dehulling is beneficial because the hulls contain little oil and protein and contribute considerable fiber. Soybean hulls represent roughly 7–8% of bean mass. The cleaned beans are typically cracked into several pieces with corrugated rollers, after which the hulls can be separated from the cotyledons by aspiration. Conditioning through controlled heating, drying and moisture equilibration helps loosen the hulls and improves subsequent separation. Effective dehulling can also increase the protein concentration of the resulting meal while reducing its fiber content (Brumm et al., 1990).

Solvent extraction remains the principal commercial route for obtaining high oil yields from soybeans, particularly at large processing scales. A number of solvents have been investigated historically, but mixtures based on petroleum-derived hexane are commonly used because of their extraction efficiency and suitable boiling range. Commercial extraction solvents may contain a high proportion of n-hexane, which typically boils near 65–71 °C. Despite its effectiveness, n-hexane presents occupational and environmental concerns and has recognized neurotoxic potential at sufficiently high exposure (Guinn, 2002). After cleaning and dehulling, the cotyledons are heated to soften the material and then passed through smooth rollers to produce thin flakes. Proper conditioning is important because the process must disrupt cellular structures enough to expose oil bodies while avoiding excessive fines that hinder solvent movement. Breaking cell walls and the membranes surrounding oil bodies increases contact between the solvent and the oil and thereby facilitate extraction (Bakhshabadi et al., 2025; Samant & Kaliappan, 2025).

Extruding expelling provides another method for soybean oil recovery (Cheng & Rosentrater, 2019). In this process, friction inside a dry extruder generates the heat required to condition the beans, after which the material is pressed mechanically. This approach avoids steam-based heating but can involve higher unit costs when small oil lots must be handled and transported. Comparative work has shown that solvent extraction generally leaves the least residual oil in the meal, approximately 1.2%, whereas screw pressing and extruding expelling may leave about 6.3% and 7.2%, respectively (Wang & Johnson, 2003). Reverse-micelle extraction has been explored mainly for recovery and purification of proteins and other valuable components. Surfactants in a nonpolar solvent can assemble into reverse micelles containing small aqueous cores. During forward extraction, proteins partition into these aqueous cores while oil remains in the organic phase. The process can then be reversed so that proteins are transferred into an aqueous medium for recovery, allowing separation of protein and oil fractions (Zhao et al., 2010; Naoea et al., 2011; Bu et al., 2014).

Enzyme-assisted aqueous extraction (EAEP) has been proposed to reduce dependence on organic solvents by using water as the extraction medium (Cheng et al., 2018). Enzymatic and mechanical pretreatments can improve disruption of soybean tissues and facilitate release of oil, but these operations may require considerable energy. EAEP therefore offers potential safety and environmental advantages over conventional solvent extraction, although separation of oil from stable emulsions remains a major technical limitation. Demulsification can require additional physical or chemical treatment and may increase energy demand (Harada and Yokomizi, 2000; McClements, 2005). Further optimization of enzyme selection, processing conditions, and demulsification strategies could improve oil recovery while reducing energy consumption and enhancing the overall sustainability of EAEP.

Nutritional properties and health benefits of soybean oil

Proteins are fundamental nutrients required for the growth, development, and maintenance of body tissues. Plant proteins may sometimes provide lower nutritional quality than animal proteins. Some proteins may be considered incomplete because they contain insufficient quantities of one or more essential amino acids. In contrast, animal-derived proteins are typically classified as complete proteins, as they supply all essential amino acids necessary for the synthesis, growth, and maintenance of proteins in the human body (Hoffman & Falvo, 2004). Soybean is an important exception among plant protein sources because its protein content is approximately 40% and its amino acid quality is comparable in many respects to that of animal proteins. Methionine (10 mg/g protein) and cystine (25.00 mg/g protein), both sulfur-containing amino acids, are considered the principal limiting amino acids in soybean protein, whereas soybean provides a relatively high concentration of lysine (68.37 mg/g protein) (Wang et al., 2022). Unlike many animal protein sources, which may be accompanied by substantial amounts of saturated fat, soybean provides high-quality protein with a comparatively favorable lipid profile. They can also increase the overall protein content of foods and improve their essential amino acid composition (Jasentuliyana et al., 1998). Soy protein has attracted attention as a dietary component that may support cardiovascular health, particularly in individuals with unfavorable lipid profiles. Maki et al. (2010) reported reductions in total cholesterol, LDL cholesterol and triglycerides after soy-protein consumption in people with hypercholesterolemia. Lerman et al. (2010) observed improvements in several lipid measures when soy protein was consumed with plant sterols in adults with metabolic syndrome. Such findings suggest that soy-based foods may have a useful place in dietary strategies intended to improve cardiovascular risk factors.

Evidence from experimental and population studies has further connected soy intake with cardiovascular outcomes. Torre-Villalvazo et al. (2009) reported lower cardiac-tissue ceramide concentrations following soy-protein consumption, suggesting a possible influence on lipid-related cardiac processes. Regular consumption of soy foods has also been associated with favorable blood-lipid patterns in some populations. Proposed benefits include lower total and LDL cholesterol together with maintenance or improvement of HDL cholesterol (George et al., 2020). During digestion and food processing, soy proteins can generate peptides with biological activity. Some of these peptides have been investigated for their ability to inhibit angiotensin-converting enzyme, providing a possible mechanism for blood-pressure effects. Soy protein preparations have also been examined for potential actions on mammary-cell differentiation, carcinogen metabolism and cellular signaling pathways involved in tumor development (Badger et al., 2005). Protein-rich foods often increase satiety and diet-induced thermogenesis more strongly than foods dominated by carbohydrates or fat. Soy protein may therefore influence appetite and post-meal energy expenditure. Its use as an alternative to some animal proteins has been investigated in relation to body-weight management and

obesity prevention, although the magnitude of these effects depends on the overall diet and energy balance.

Soy carbohydrates for improving health

Soybeans contain several carbohydrates that are not completely digested in the human small intestine. Raffinose-family oligosaccharides, including α -galactosides and galactooligosaccharides, can reach the lower gut because human α -galactosidase activity is insufficient for their complete hydrolysis. Soy also contains sucrose and smaller quantities of fructose, rhamnose and arabinose, while glucose is more prominent in immature seeds. These nondigestible carbohydrates are of interest as functional food components because their fermentation and interaction with the intestinal microbiota may contribute to physiological benefits (Souza et al., 2022). Soybean dietary fiber may additionally help support cholesterol regulation and insulin sensitivity.

Soy lipids for improving health

Soybeans contain about one-fifth to one-quarter oil, with triacylglycerols forming the major fraction (Liu, 1999). Minor constituents include phospholipids, free fatty acids, tocopherols, phytosterols, carbohydrates and other unsaponifiable compounds (Delic et al., 2026). The fatty-acid profile is dominated by polyunsaturated linoleic acid, accompanied by linolenic and oleic acids and smaller amounts of palmitic and stearic acids. Reported representative values are approximately 54% linoleic, 4–5% linolenic, 22–25% oleic, 11% palmitic and 4% stearic acid (Martins et al., 2003). Soy products can therefore contribute to plant-derived omega-3 fatty acids where dietary intake is limited (Martin et al., 2008). Processing conditions also matter because severe heating can promote fatty-acid isomerization and formation of trans isomers.

Dietary trans-fatty acids have been associated with an unfavorable lipid profile, particularly increased LDL cholesterol and reduced HDL cholesterol, and have been linked to greater coronary risk when consumed regularly (Fernandez-San, 2009). By comparison, omega-3 fatty acids can influence inflammatory pathways and may affect the stability of atherosclerotic plaques. These actions have contributed to continuing interest in soybean oil as a source of unsaturated fatty acids with potential cardiovascular relevance (Tull et al., 2009). Soybean oils enriched in stearic acid may provide a relatively stable, trans-free fat for applications requiring greater solidity. Compared with several other saturated fatty acids, stearic acid generally has a smaller effect on LDL cholesterol and little influence on HDL concentrations (Hunter et al., 2010). Stearidonic-acid-enriched soybean oil has also been studied because it can increase erythrocyte eicosapentaenoic acid and thereby improve the omega-3 index (Lemke et al., 2010). Other work suggests that omega-3 fatty acids may influence adipose metabolism, insulin sensitivity, adipokines, blood pressure and inflammatory-cell activity (Kelley, 2001;

Kris-Etherton et al., 2003; Moreno-Aliaga et al., 2010; Mori, 2010).

Soy isoflavones for improving health

Soybean isoflavones are plant phenolics commonly grouped among phytoestrogens because they can interact with estrogen-related signaling pathways. They belong to the flavonoid class and are particularly abundant in soybean compared with many other foods (Carrão-Panizzi et al., 2002; Cederroth & Nef, 2009). Their chemical structure differs from that of plant sterols, which possess a steroid-like nucleus related to cholesterol (Abumweis & Jone, 2008). The principal soybean isoflavones occur in conjugated forms. Daidzin, genistin and glycitin are major glucosides, while daidzein and genistein represent important aglycones. Microbial enzymes in the intestine can remove the sugar moieties and release the corresponding aglycones. Acetylated and malonylated derivatives of the major glucosides are also present, so the final isoflavone profile depends on soybean genotype, processing and food preparation (Torrezan et al., 2008). Although isoflavones are not essential nutrients, their biological activities have made them important components of soy foods (Sacks et al., 2006; Carrara et al., 2009). Concentrations vary among cultivars and processed products, and processing can reduce the amount retained in foods. For example, tofu manufacture has been associated with substantial but variable isoflavone losses depending on the soybean material and processing conditions (Ciabotti et al., 2006; Mateos-Aparicio et al., 2008). Consequently, regular consumption of soy foods has been investigated in relation to several chronic health outcomes (Rajasree et al., 2009; Dong & Qin, 2011).

Soy isoflavones for improving menopause

Interest in soy isoflavones during menopause arises partly from their ability to interact with estrogen receptors. Populations with traditionally high soy intake, including Japan, have often reported fewer menopausal complaints and different rates of cardiovascular and skeletal disorders than populations with lower soy consumption (Cho et al., 2010; Vitolins et al., 2010). Clinical investigations have examined whether soy or isoflavone intake affects hot flashes, sleep and other menopausal symptoms, although responses have varied among studies. Some trials have reported fewer hot flashes and improved sleep measures after supplementation (Ryan-Borchers et al., 2006; Cancelo-Hidalgo & Castelo-Branco, 2010; Chedraui et al., 2010; Hachul et al., 2010; Kang et al., 2010; Vitolins et al., 2010).

Soy isoflavones for preventing heart disease

Dietary patterns rich in plant foods have been studied as approaches for improving blood lipids and reducing chronic-disease risk. Soy foods are of particular interest because they provide protein together with isoflavones. Epidemiological research has linked greater flavonoid intake with lower occurrence of several cardiometabolic conditions (Ghosh &

Schhepens, 2009). In an intervention study, Sagara et al. (2004) provided 20 g soy protein and 80 mg isoflavones daily and observed reductions in blood pressure and selected lipid measures. A meta-analysis by Taku et al. (2010) reported a small but statistically significant reduction in systolic pressure with soy-isoflavone supplementation in normotensive and prehypertensive adults. LDL cholesterol is a major modifiable cardiovascular risk factor, so possible effects of soy-containing diets on lipid metabolism and atherosclerosis have received considerable attention (Nagarajan, 2010). Atherosclerosis develops through interacting metabolic and inflammatory pathways involving obesity, insulin resistance, diabetes, dyslipidemia and chronic inflammation. Experimental work suggests that isoflavones may influence lipid metabolism more effectively when consumed with soy protein. Studies in animal models have also proposed that soy proteins may facilitate tissue exposure to isoflavones, including in the liver and skeletal muscle (Greaves et al., 1999; Mikkola et al., 2003; Nikander et al., 2004). Oxidative stress and endothelial dysfunction can contribute to vascular injury in people with elevated blood glucose. Genistein and daidzein have shown protective effects in experimental oxidative-stress models (Xu et al., 2009). Soy isoflavones may also interact with nuclear receptors such as liver X receptor, farnesoid X receptor and PPARs, which regulate genes involved in lipid turnover and glucose metabolism. Such interactions have been proposed as one explanation for observations linking soy isoflavones with lipid regulation and insulin responsiveness (Carrara et al., 2009).

Soy isoflavones for improving bones

Bone loss becomes more pronounced after menopause as reduced estrogen production accelerates bone turnover. Because estrogen contributes to the balance between bone formation and resorption, estrogen deficiency can increase susceptibility to osteoporosis. This has encouraged investigation of soy foods and isoflavones as nutritional approaches to skeletal health. Their estrogen-responsive activity and differences in soy consumption between Asian and Western populations have been proposed as possible explanations for some observed differences in bone outcomes (Nilsson & Gustafsson, 2002; Bawa, 2010; Bitto et al., 2010). Experimental and clinical studies have suggested several possible skeletal effects of soy isoflavones. Genistein has been associated with greater osteoblast activity and reduced osteoclast-mediated resorption, while daidzein has also been investigated for postmenopausal bone benefits. Bawa (2010) summarized evidence of improved bone mineral density, particularly at the lumbar spine, in some supplementation studies. Yamori et al. (2002) reported reduced urinary markers of bone resorption in postmenopausal women receiving approximately 37.3 mg/day isoflavones for 10 weeks. Soy-

derived materials have additionally been studied in biomaterials research; Perut et al. (2010) reported an osteoblastic response to a porous bone-cement material containing soybean- and gelatin-derived components.

Soy isoflavones for reducing cancer

Research on soy and cancer has included epidemiological studies and laboratory experiments. Genistein has received particular attention because it can affect signaling pathways involved in cell proliferation, migration, metastasis and apoptosis (Liss et al., 2010; Pavese et al., 2010). Observational evidence has also suggested that higher soy-isoflavone consumption may be associated with lower breast-cancer incidence or recurrence in some Asian populations (Kang et al., 2010; Dong & Qin, 2011). These findings have encouraged further investigation of soy foods and genistein as potential components of cancer-prevention strategies, although they do not establish a therapeutic effect (Cho et al., 2010). Several mechanisms have been proposed for genistein's biological activity. Experimental studies indicate that it can affect tyrosine-kinase signaling and interact with estrogen receptor- β . Latratch et al. (2010) reported enhanced trastuzumab activity in HER2-positive breast-cancer cells exposed to genistein *in vitro*. Other experimental work has examined copper-associated prooxidant signaling as a possible route to cancer-cell death, while antioxidant and anti-inflammatory effects have also been investigated in relation to tissue protection during cancer treatment (Tacyildiz et al., 2010; Ullah et al., 2010).

Soy isoflavones for improving blood pressure

Hypertension is a major modifiable contributor to cardiovascular disease, making dietary approaches to blood-pressure control of considerable interest. Studies of soy protein and isoflavones have reported favorable changes in blood pressure, including diastolic pressure. Proposed mechanisms include effects on vascular compliance, sodium handling, amino-acid composition and nitric-oxide availability. Because nitric oxide promotes vascular relaxation, enhanced nitric-oxide signaling could contribute to lower vascular resistance. Experimental and clinical observations have provided support for continued investigation of these effects (Galleano et al., 2010).

Soy-derived phosphatidylserine and memory function

Phosphatidylserine is a membrane phospholipid found at high levels in neural tissues and has been investigated for possible effects on cognition. Interest in dietary phosphatidylserine increased when bovine-brain sources became less desirable because of limited recovery and concerns related to bovine spongiform encephalopathy. Soy lecithin provides a plant-derived source, and enzymatic conversion using L-serine can be used to produce soy phosphatidylserine. This provides an alternative ingredient for nutritional and functional applications (Ritcher et al., 2010). Kato-Kataoka et al. (2010) studied soy-derived phosphatidylserine in Japanese adults aged

50–69 years who reported subjective memory difficulties. After six months of supplementation, several neuropsychological and memory measures improved, and the authors regarded the ingredient as safe for dietary use. Together with findings from Vakhapova et al. (2010), these results support further research into soy-derived phosphatidylserine for cognitive health in older adults.

Conclusion

Soybean oil is a nutritionally valuable and versatile vegetable oil with considerable importance in human nutrition, food processing, and health promotion. Its distinctive chemical composition, characterized by a high proportion of unsaturated fatty acids, particularly linoleic, oleic, and α -linolenic acids, contributes substantially to its nutritional significance. The physicochemical properties of soybean oil, including its fatty acid profile, iodine value, saponification value, peroxide value, free fatty acid content, and oxidative stability, determine its quality, storage behavior, and suitability for different food applications. In addition to its major lipid components, soybean and soybean oil contain several biologically important minor compounds, including phytosterols, phospholipids, saponins, ferritins, and isoflavones, which may contribute to their functional and health-promoting effects. Extraction technologies and processing conditions substantially influence oil yield, composition, quality, and retention of bioactive compounds, while genetic modification provides opportunities to develop soybean varieties with improved fatty acid profiles and enhanced technological characteristics. Evidence reviewed in this article indicates that soybean-derived carbohydrates, lipids, isoflavones, and phosphatidylserine may have beneficial effects on several aspects of human health. Soy isoflavones, in particular, have attracted considerable attention because of their potential roles in alleviating menopausal symptoms and supporting cardiovascular, bone, and metabolic health, as well as their possible protective effects against certain cancers. Soy-derived phosphatidylserine may also have potential benefits for cognitive performance and memory function. Nevertheless, the magnitude of these health effects can vary according to the composition of soybean products, dose, processing conditions, individual characteristics, and overall dietary patterns. Therefore, soybean oil and other soybean-derived components should be considered as part of a balanced and diversified diet rather than as isolated therapeutic agents. Continued research on soybean genetics, extraction technologies, processing methods, bioactive compounds, and long-term human health outcomes is essential for maximizing the nutritional and functional potential of soybean oil while ensuring its quality, safety, and sustainable utilization.

Declarations

i. Ethics approval and consent to participate

Ethical approval and informed consent were not required for this study as it did not involve human participants, human data, or animals.

ii. Consent for publication

Consent for publication is not applicable.

iii. Data availability

All data generated or analyzed during this study are included in this article.

iv. Competing interests

Authors have declared that no competing interests exist.

v. Authors' contributions

M.A.Q. conceived and designed the review; N.K. conducted the literature search and organized the relevant literature; B.R.A. contributed to the interpretation and synthesis of the reviewed literature; M.A.Q. wrote the first draft of the manuscript; N.K. and B.R.A. critically reviewed and revised the manuscript. All authors read and approved the final manuscript.

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viii. SDGs addressed

Zero Hunger (SDG 2), Good Health and Well-Being (SDG 3), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13)

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