Biological Activities of Soybean (*Glycine max* L.) Oil and Its Bioactive Constituents: A Focus on Volatile Fractions and Functional Potential

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ABSTRACT: Soybean oil is one of the most widely consumed vegetable oils globally, valued not only for its affordability and functional properties but also for its rich profile of bioactive compounds. This review critically synthesizes current knowledge on the non-volatile bioactive constituents of crude and refined soybean oil, particularly polyunsaturated fatty acids, tocopherols, phytosterols, phospholipids, and saponins, as well as volatile bioactives present in soybean essential oil. Emphasis is placed on their antioxidant, anti-inflammatory, cardioprotective, metabolic, antimicrobial, and dermatological activities, alongside their relevance for functional foods, nutraceuticals, cosmeceuticals, and pharmaceutical applications. The review examines how oil refining, storage, thermal processing, genotype, environmental conditions, and post-harvest handling influence the concentration, stability, and bioactivity of these compounds, highlighting the trade-off between shelf-life extension and loss of health-promoting constituents. Although soybean essential oil contains biologically active volatiles with demonstrated antimicrobial and antioxidant effects, their extremely low abundance limits practical applications. Advances in breeding strategies, optimized agronomic practices, and green extraction technologies are discussed as promising approaches to enhance bioactive retention and oil quality. While substantial *in vitro* and preclinical evidence supports the therapeutic potential of soybean oil components and volatiles, human clinical data remain limited. Future research should focus on well-designed clinical trials, synergistic interactions among bioactives, standardized processing protocols, and long-term health outcomes. Overall, soybean oil emerges as a multifunctional plant-derived ingredient with significant potential for health promotion and sustainable industrial use.

KEYWORDS: Bioactive compounds; oil; soybean; mechanism

1 Introduction

Soybean (*Glycine max* L.) is one of the most widely cultivated oilseed crops worldwide, valued not only for its high oil and protein content but also for its rich composition of bioactive compounds [1,2]. Soybean seeds contain phenolic compounds such as phenolic acids and isoflavones, tocopherols (vitamin E), phytosterols, and saponins, which collectively contribute to its nutritional, functional, and health-promoting properties [1,3].

Soybean is an abundant and cost-effective source of edible oil commonly used for cooking and frying. Global consumption and demand for soybean oil are rising steadily, reflecting its central role in both human nutrition and industrial applications. Recent USDA ERS [4] estimates indicate that global production of

soybean oil since 2020 varies between 59–62 million metric tons annually, positioning soybean oil among the top three global vegetable oils after palm oil and sunflower oil. According to another report [5], worldwide consumption of soybean oil reached approximately 62 million tons in 2024, showing a trend of growth in demand, driven by food, feed, and industrial sectors. Major soybean producers, and therefore major sources of global supply for the soybean oil industry, are the United States, Brazil, and Argentina [2]. On the other hand, as of 2024, China, the United States, and Brazil together account for about 64% of global soybean oil production [6]. The ubiquity and high production volumes help ensure that soybean oil remains affordable and widely available across different regions. Furthermore, the global soybean oil market size is expected to reach 71.9 million tons by 2032 according to the projections, exhibiting a growth rate (CAGR) of 1.8% during 2023–2032, mainly due to higher food and biodiesel demands [7].

Soybean oil is a non-volatile fixed oil composed mainly of triacylglycerols, which are products of fatty acid esterification [8]. Soybean oil fatty acid composition affects the oil's use nutritional value, stability, and taste [9]. High content of saturated fatty acids (palmitic and stearic) in food-grade oil is a concern due to its link with dietary health issues such as high cholesterol and increased risk of coronary heart disease [10]. On the other hand, polyunsaturated fatty acids (PUFAs), i.e., linoleic and linolenic acids, are considered essential, supporting the cardiovascular, reproductive, immune, and nervous systems, crucial for manufacturing and repairing cell membranes [11]. However, these PUFAs are susceptible to oxidation, so they reduce the shelf life of the oil, causing low stability at high cooking temperatures as well as off-flavors [12]. Commercially available dietary soybean oil is refined, i.e., odorless, bland, and oxidatively stable oil [13,14]. Although the main goal of crude oil refining is removing residual solvent, chemical pollutants and unfavorable compounds limiting the stability of the oil and causing unpleasant taste and odor, all of the refining steps strongly affect the concentration of bioactive compounds in the refined soybean oil [15,16]. In comparison to refined oil, crude soybean oil is richer in bioactive compounds such as polyunsaturated fatty acids, phospholipids, glycolipids, tocopherols (vitamin E), phytosterols, and saponins, which provide nutritional value and determine organoleptic properties [3,17–21]. Some of these compounds are considered bioactive and are responsible for soybean's therapeutic potential. Bioactive compounds are those that have antioxidant, antimicrobial, anti-inflammatory, cytoprotective and cardioprotective activities [17].

Although not a typical essential-oil plant, soybean seed contains essential oils, i.e., volatile aromatic fractions recoverable by distillation [22,23]. Soybean volatiles include many different compounds, some of which have functional properties similar to those non-volatile bioactive compounds found in crude and refined soybean oil, but their yield tends to very low [24]. Therefore, while volatile compounds found in soybean seed may show antimicrobial or antioxidant activity in isolated laboratory preparations, the extremely low content in the seed limits their practical use potential.

Overall, the combination of high nutritional value, rich bioactive composition, and functional properties underscores soybean's importance as a crop with significant therapeutic and industrial potential. Understanding the variation in bioactive compounds among genotypes can guide breeding strategies and support the development of soybean-based products with enhanced health benefits. Moreover, environmental factors, such as temperature, drought stress, and soil composition, have been shown to substantially modulate the levels of bioactive compounds in soybean, making genotype × environment interactions an important consideration for both breeders and industry [25]. Certain agronomic practices and post-harvest processing can significantly influence the levels of bioactive compounds as well, allowing targeted strategies to maximize nutritional and health benefits [26–29]. This variability further

emphasizes the need for integrated agronomic and biochemical approaches in optimizing soybean oil for functional applications.

Rich bioactive profile along with soybean's adaptability to diverse agricultural systems, make soybeans an effective tool for enhancing public health and promoting environmental sustainability [30]. Despite substantial progress in understanding the nutritional and biochemical composition of soybean oil, a comprehensive synthesis connecting its bioactive constituents, antioxidant properties, and functional/therapeutic benefits is still lacking. This gap is particularly notable given the rapid growth in global consumption and the increased demand for plant-based bioactive ingredients in food, cosmetic, and pharmaceutical sectors. In addition, rising interest in sustainable plant-derived compounds and the shift toward "clean-label" formulations have intensified the need to better characterize soybean oil's natural bioactivities and its potential to replace synthetic additives in industrial applications [31]. Therefore, the purpose of this review is to critically examine the bioactive compounds in soybean oil and bioactive volatiles in soybean essential oil, while also summarizing its functional and therapeutic potential. By integrating current biochemical, nutritional, and applied research, this review aims to provide a clearer understanding of how soybean oil can serve as both a key component of the global food supply and a promising source of health-enhancing compounds.

2 The Most Important Bioactive Compounds in Crude Soybean Oil

Increasing scientific interest in soybean oil has highlighted its potential therapeutic properties, especially related to cardiovascular health, inflammation, metabolic function, and skin health. To better understand these benefits, it is important to consider the bioactive molecules present in crude and refined soybean oil (Table 1). Crude soybean oil is rich in bioactive compounds such as polyunsaturated fatty acids, phospholipids, glycolipids, tocopherols (vitamin E), phytosterols, and saponins, which provide nutritional value and determine organoleptic properties [3,17–21]. Although many of these compounds have antioxidant, antimicrobial, anti-inflammatory, cytoprotective, and cardioprotective activities, some are removed from crude oil during refining, which is aimed at extending the oil's shelf life [5,27]. However, Martin-Rubio et al. [32] noted that refined soybean oils with lower concentrations of protective minor components, including tocopherols and sterols, are more susceptible to oxidative degradation during storage, leading to earlier formation of peroxides and secondary oxidation products that compromise oil stability and quality. This emphasizes the need for improving the composition of bioactive components in crude soybean oil, as well as adapting the specific oil refining processes. The most important crude soybean oil bioactive compounds with potential therapeutic properties are listed in the following text.

Table 1: Main Bioactive Compounds in Crude Soybean Oil and Their Functional/Therapeutic Properties.

Bioactive Compound	Type	Functional/Therapeutic Properties	Reference
Linoleic acid (LA; Omega 6)	Polyunsaturated fatty acid (PUFA)	Cardiovascular support, reduces low-density lipoprotein (LDL) cholesterol	[11]
α-Linolenic acid (ALA; Omega 3)		Anti-inflammatory, cardiovascular support	
Lecithin	Mixture of phospholipids, triglycerides, glycolipids, carbohydrates	Cardiometabolic disease prevention	[21,33]

Table 1: *Cont.*

Bioactive Compound	Type	Functional/Therapeutic Properties	Reference
α-tocopherol, γ-tocopherol, δ-tocopherol	Lipid-soluble vitamin (vitamin E homologs)	Antioxidant (protects lipids from oxidation)	[26]
β-sitosterol, campesterol	Phytosterols	Cholesterol-lowering, anti-inflammatory	[21]

2.1 Polyunsaturated Fatty Acids

The main polyunsaturated fatty acids (PUFAs) in soybean oil, linoleic acid (Omega-6) and α-linolenic acid (Omega-3). Both, crude and refined soybean oils are major sources of these PUFAs. Linoleic and linolenic acids are considered essential, supporting the cardiovascular, reproductive, immune, and nervous systems, and are crucial for manufacturing and repairing cell membranes. Along with other essential fatty acids, the primary function of linoleic and linolenic acid is the production of prostaglandins, which regulate body functions such as heart rate, blood pressure, blood clotting, fertility, conception, and immune function by regulating inflammation and encouraging the body to fight infection [11,34]. However, these PUFAs are susceptible to oxidation, so they reduce the shelf life of the oil, causing low stability at high cooking temperatures as well as off-flavours [25]. Linoleic and α-linolenic acids have been shown to reduce low-density lipoprotein (LDL) cholesterol levels [35]. A meta-analysis evaluating supplementation with a low linoleic acid−to−α-linolenic acid ratio reported significant reductions in total cholesterol, LDL-cholesterol, and triglycerides [36]. Similarly, a comprehensive review on linoleic acid and cardiometabolic health demonstrated consistent associations between higher linoleic acid intake and a lower risk of cardiovascular disease [37]. Their anti-inflammatory activity is mediated, in part, through modulation of inflammatory pathways and reduced production of pro-inflammatory cytokines [38−40]. These properties support the incorporation of soybean-derived oils into nutraceutical, cosmetic, and functional food formulations aimed at reducing inflammation or promoting skin health. Furthermore, emerging evidence highlights the cytoprotective and anti-aging potential of soybean oil, particularly in dermatological applications. Owing largely to its high linoleic acid content, soybean oil improves skin barrier function, supports collagen synthesis, and provides emollient effects, reinforcing its value in cosmetic and pharmaceutical formulations [41]. This aligns with growing industry interest in plant-based, multifunctional skincare ingredients that deliver both protective and restorative benefits. Soybean oil, like other plant oils, has been reported to enhance skin hydration and barrier integrity, potentially reducing transepidermal water loss, although clinical evidence remains limited and outcomes vary across study conditions [42]. Mechanistically, linoleic acid may be metabolized into ω-hydroxy-ceramides and incorporated into epidermal barrier lipids, thereby strengthening barrier function [41]. In addition, soybean-germ oil has been shown to protect the skin from UVB-induced erythema and damage [43]. An optimal intake ratio of linoleic to linolenic acid is 5−10:1 [38]. Linoleic/linolenic acid imbalance in the human diet is linked with serious health conditions, such as heart attacks, cancer, insulin resistance, asthma, lupus, schizophrenia, depression, postpartum depression, accelerated aging, stroke, obesity, diabetes, arthritis, ADHD, and Alzheimer's Disease, among others [44].

2.2 Tocopherols

One of the major bioactive compounds present in both crude and refined soybean oil are tocopherols (vitamin E), which contribute to antioxidant capacity by quenching free radicals and have functional properties such as cholesterol modulation. According to a review article by Fine et al., [15], encompassing

numerous oil composition studies, tocopherol composition in crude soybean oil is 1094–2484 µg g^{-1}, and in refined soybean oil it is 200–3327 µg g^{-1}. Soybean oil is particularly rich in γ-tocopherol and δ-tocopherol [15]. γ-tocopherol demonstrated superior reactive oxygen species scavenging ability and contributed significantly to antioxidant stability [45]. Beside γ-tocopherol and δ-tocopherol, soybean oil contains α-tocopherol, the major form of vitamin E, which has the highest activity in carrying out the essential antioxidant functions [46]. Tocopherols have the ability to neutralize reactive oxygen species (ROS), prevent oxidative DNA damage, and reduce lipid peroxidation, which are all factors implicated in initiation and progression of cancer [47]. As oxidative stress is involved in carcinogenesis, the potential cancer prevention activity of α-tocopherol has been studied extensively. Lower vitamin E nutritional status has been associated with increased cancer risk, and supplementation of α-tocopherol to populations with vitamin E insufficiency has shown beneficial effects in lowering the cancer risk [47]. According to some recent studies in animal models and cell lines, γ- and δ-tocopherols have much lower systemic bioavailability compared to α-tocopherol but have shown stronger cancer-preventive activities [48–50]. In *in vivo* models, such as mice bearing prostate or lung tumors, dietary δ- or γ-tocopherol significantly reduced tumor growth compared to controls [46,50], while Jiang et al. [51] demonstrated that pure γ-tocopherol can inhibit proliferation of human prostate cancer cell lines, but not of normal prostate epithelial cells.

As mentioned earlier, tocopherols can protect lipids against oxidative damage. Oxidation of LDL particles is a key early event in the pathogenesis of atherosclerosis [52]. By preventing LDL oxidation, these antioxidants reduce the formation of oxidized LDL, which is more atherogenic and more likely to trigger endothelial dysfunction and plaque formation [53]. Tocopherols may even modulate physiological processes such as skin barrier homeostasis, inflammation, and wound healing, as well as anti-wrinkle and anti-aging effects [42,53–55]. Given that the reported effects of tocopherols are primarily based on *in vitro* and animal studies and that bioactive concentrations involved often exceed those achievable through dietary soybean oil intake, caution is warranted when extrapolating these findings to human health outcomes.

2.3 Phytosterols

Sterols are triterpenes located in the membrane lipids of plants. These minor constituents have antioxidant and various other biological activities, including cholesterol-lowering properties and the ability to reduce the risk of cardiovascular diseases [56–59]. They are present in crude oil, but occur in high concentrations in refined vegetable oils as well. According to Piironen et al. [59], the contents of phytosterols in raw soybean oil vary between 2,290 and 4490 µg g^{-1} and between 2210 and 3280 µg g^{-1} in refined soybean oil. According to a review by Fine et al. [15], total sterol content in crude soybean oil ranges between 1500 and 4328 µg g^{-1}, and between 2021 and 3470 µg g^{-1} in refined soybean oil. The major phytosterol is β-sitosterol (52% of total phytosterols), followed by campesterol (25%), and stigmasterol (23%) [17].

In general, phytosterols are known to inhibit cholesterol absorption by competition—intake of 1.5–3 g of phytosterols per day can bring total blood cholesterol and LDL cholesterol lower by 10–15% [60]. Phytosterols intake increases in the rate of endogenous cholesterol synthesis and LDL receptor number and activity in the liver. This enhances the uptake of cholesterol from LDL particles for bile acid synthesis, thereby increasing the elimination of LDL from the circulation. Consequently, levels of LDL cholesterol, and therefore total cholesterol, decrease in humans, without affecting HDL cholesterol or triglyceride levels, which helps decrease atherogenic risk [57,58,61]. However, phytosterols usually have a lower absorption rate in the digestive tract than cholesterol. For example, only 5% of β-sitosterol of the food supply can be absorbed, so phytosterols in foods [17,62]. According to the World Health Organization criteria, the role of phytosterols, especially β-sitosterol, in reducing serum cholesterol noted in animals and human studies

is fairly convincing, but further research is necessary to confirm the association with the prevention of cardiovascular diseases [63].

Phytosterol are known to have antioxidant activity, so their consumption may increase the activity of antioxidant enzymes and reduce oxidative stress in humans [64]. There is also evidence supporting the inhibitory actions of phytosterols on lung, stomach, ovarian, and breast cancer, through multiple mechanisms of action, including inhibition of carcinogen production, cancer-cell growth, angiogenesis, invasion, metastasis, and apoptosis [65−67]. However, the information available is considered insufficient to corroborate these findings [68].

2.4 Lecithin

Soy lecithin is a mixture of phospholipids, triglycerides, glycolipids, and carbohydrates extracted as a by-product during the degumming stage of crude soybean oil to improve the stability and clarity of the finished oil [19,21,33]. The extracted phospholipid mixtures can be processed into liquid or powdered commercial forms of lecithin with wide applications in the food, pharmaceutical, and cosmetic industries. Lecithin is a standardized food additive E322, a natural emulsifier or surfactant, that promotes stable mixing of phases that are not naturally miscible, which is essential in many food products [69].

The nutritional and physiological importance of lecithin stems from the fact that phosphatidylcholine, the dominant component of soy lecithin, is an important source of choline in the diet, a nutrient considered essential. Choline is required for the synthesis of acetylcholine, a key neurotransmitter involved in cognitive function and neuromuscular transmission. For this reason, lecithin is being investigated in the context of preserving cognitive function, neurological development, especially during the fetal and early postnatal period. Although lecithin supplementation is not a therapy for neurodegenerative diseases, adequate choline intake is considered important for normal brain function [33,70].

Choline also participates in the synthesis of cell membrane phospholipids and in lipid metabolism in the liver, and insufficient choline intake is associated with metabolic disorders resulting in fatty liver (hepatic steatosis). Lecithin is considered a more biologically effective source of choline compared to free choline because phosphatidylcholine has better absorption and stability in the digestive system. Experimental and clinical studies have shown that phosphatidylcholine supplementation can improve biochemical indicators of liver function in people with impaired lipid metabolism [33,71,72]. Some studies suggest that phospholipids from lecithin can reduce intestinal cholesterol absorption, favorably affect the LDL/HDL cholesterol ratio, and contribute to a better blood lipid profile [16]. Due to the above benefits, soy lecithin is used in numerous commercial dietary supplements. However, scientific evidence for the effects of soy lecithin on human health is limited and often not strongly supported by controlled clinical studies, so caution is necessary in interpretation.

2.5 Oil Refining

Crude oil is not consumable by humans because of the residual solvent and other chemical pollutants, free fatty acids, oxidation products, color pigments, phospholipids, and metals. It also contains substances responsible for unpleasant taste and odor and compounds limiting the stability of the oil, thus shortening its shelf-life [15]. Crude oil refining involves a series of chemical or physical purifying steps resulting in odorless, bland, and oxidatively stable oil that is acceptable to consumers [13,14]. The two main industrial technologies used for vegetable oils' refining are chemical and physical refining. Chemical refining uses alkali agents to remove free fatty acids, while physical refining eliminates undesirable compounds (deacidification) by distillation under a high vacuum with steam injection [14]. Both technologies have advantages and

drawbacks. For example, physical refining has lower investment costs, less energy is consumed and fewer by-products generated compared to chemical refining, it is less environmentally harmful but it is not suitable for all types of oils [73]. In general, there are four main processing steps in chemical refining (degumming, neutralization, bleaching, and deodorization) and three steps in physical refining (degumming, bleaching, and deodorization), all necessary for removing unfavorable compounds. Phospholipids and mucilaginous gums—byproducts making bioactive compound lecithin are removed in the degumming step [74]. Free fatty acids, metals, chlorophylls and impurities are removed during chemical neutralization with sodium or potassium hydroxide. Bleaching reduces chlorophyll, carotenoids, peroxides, and residual fatty acid salts. Deodorization removes volatile compounds, carotenoids, free fatty acids and tocopherols to improve the flavor quality and stability of the oil [28]. Although refining extends oil shelf life, it results in the loss of bioactive compounds, such as tocopherols, phospholipids, squalene, polyphenols, and phytosterols [75,76].

All of the refining steps strongly affect the concentration of micronutrients in the refined soybean oil [16]. Tocopherols and phytosterols are bioactives found in crude and refined oil, but their content changes during refining. For example, Gutfinger and Letan [77] concluded that all steps of the refining process caused significant losses of total tocopherols (neutralization, bleaching, and deodorization steps, 11, 13, and 16%, respectively), while bleaching and deodorization were the most destructive steps for phytosterol content. Refining process resulted in a 18% loss of sterols in soybean oil. According to Verleyen et al. [78] neutralization, deodorization (chemical refining), and distillation (physical refining) caused the largest loss of sterols in soybean oil. Total losses in the chemical and physical refining were 33.9 and 12.6%, respectively. Verhe et al. [79], noted a 10−32% sterols loss and 7.7−76.5% tocopherols loss as a result of the physical refining, and a 13−31% sterols loss and 26.8−79.4% tocopherols loss due to the chemical refining. Fine et al. [15] concluded that certain heat treatments increased tocopherol levels, while at the same time they decreased the extraction processing time and energy consumption. Ghazani [80] tested alternative alkaline agents in the neutralization step, all of which significantly decreased the loss of tocopherols and slightly decreased the loss of sterols in comparison to conventionally used NaOH. Beside the loss of bioactive compounds, crude vegetable oil refining can also cause the formation of undesirable compounds such as glycidyl ester, 3-MCPD-esters [81], harmful trans-fatty acids [76,82], and polymeric triacylglycerols [83], which can directly influence the safety level of refined oils. Thus, refining process for crude oils should be aimed at removing undesirable and decreasing the damage to desirable components, as well as avoiding the formation of novel harmful compounds [76,81,84,85].

2.6 Crude and Refined Oil Bioactive Composition Variability

Numerous evidences show that genetic factors (genotype, breeding), environmental factors, storage conditions and processing methods can influence the concentration and activity of bioactive compounds in crude and refined soybean [1,26,56]. Understanding the factors affecting oilseed quality is crucial. It can guide plant breeding and prompt changes in seed production and processing technology to obtain best quality oil, rich in bioactive compounds. Recent genome-wide association studies (GWAS) have identified multiple quantitative trait loci (QTLs) related not only to oil and protein content but also to tocopherol, isoflavone, and phytosterol concentrations, highlighting the feasibility of breeding for enhanced bioactive profiles [86].

The significance of genotype and environmental factors for fatty acid content in soybean oil was determined by many authors as well [87−91]. For example, Bellaloui et al. [91] noted that, cooler temperatures favor the synthesis of linolenic acid in comparison to oleic acid. According to Xue et al. [92], increasing air temperature during pod fill significantly increased oleic acid and significantly decreased

linoleic and linolenic acid contents which was confirmed by Matoša Kočar et al. [89]. Furthermore, Vlahakis and Hazebroek [93] concluded that higher day and night temperatures from flower initiation to seed maturity increased total phytosterol content in soybean seed, while total tocopherols decreased with temperature. The same was confirmed by Dolde et al. [94].

Soybean seed water content strongly influences aging reactions in seeds during storage, with optimal seed water content being in a negative correlation with oil content [95]. For a good prolonged conservation of soybean, the water content in the seed must be lower than 12–13% [96]. Chu and Lin [97] studied the effect of soybean seed moisture during storage on the tocopherol content of crude oil. They concluded that the loss of tocopherols increased with the increase of water content in seeds. The same authors observed that cracked beans during storage impaired the stability of the tocopherol concentration, because they had increased oxidation, especially at high moisture level. Furthermore, high soybean seed storage temperatures lead to lipid degradation and potential losses of antioxidants [96,98]. Poor seed storage conditions lead to the development of molds. Molds grow by consuming the lipids in the seeds, disrupting the cell, increasing the temperature and favoring oxidation. This causes changes in micronutrient composition and content [15].

Modification of soybean via seed germination changes its phytochemical profile. One study found that germinated-soybean oil (after 6 days) had increased α-tocopherol, phytosterols and carotenoids, improving its antioxidant activity and oxidative stability compared to non-germinated oil, highlighting that agronomic and processing practices can substantially influence functional output [29]. The characterization of soybean germ oil and the antioxidative activity of its phytosterols reported that soybean-germ oil's major fatty acids were linoleic acid (~52–55%) and α-linolenic acid (~16–18%) and that the oil was rich in phytosterols (β-sitosterol, campesterol, etc.) [56]. Importantly, the germ oil phytosterols displayed significant antioxidant activity in lipid-oil systems, including radical scavenging and inhibition of lipid peroxidation, suggesting practical value for enhancing oil stability and food preservation.

Furthermore, soybean's phytochemical complexity makes it highly responsive to food-processing interventions. Lipid oxidation and enzymatic degradation of soybean oil result in many unfavorable volatile compounds [99,100]. Exposure of soybean oil to heat results in creation of volatile aldehydes, alcohols, ketones, furans, aromatic compounds and acids/esters. For instance, gas chromatography–mass spectrometry analysis of heated soybean oil identified 72 volatile compounds overall, including 27 aldehydes (e.g., hexanal, heptanal, pentanal, etc.), 14 alcohols, 10 ketones, 6 furans, 9 aromatics, and 6 acids/esters [101]. In another recent study of volatile components of soybean oil exposed to heating or different types of radiation, 82 volatile compounds were identified, including: 18 alkanes, 19 alkenes, 30 aldehydes, 5 ketones, 4 alcohols, 2 furans and 4 benzene-derived aromatic compounds [99]. Such extensive formation of secondary volatiles during heating underscores how thermal stress reshapes the chemical profile of soybean oil, often diminishing health-promoting compounds while generating oxidation products associated with flavor deterioration or reduced stability [102]. The unsaturated fatty acid degradation process occurring in the presence of oxygen results in a complex mixture of unwanted products as well, affecting taste and causing the development of rancid flavors [103]. Long heat or oxygen exposure during food-processing and storage, causes oxidation of phytosterols and production of oxyphytosterols which could be mutagenic and a source of free radicals. They can affect cell viability, stimulate inflammation, cause oxidative changes in the retina, and affect hormonal activity [17].

Overall, the evidence indicates that integrating optimized breeding strategies with carefully controlled postharvest handling and processing technologies is essential to preserve health-promoting compounds, enhance oxidative stability, and maximize the nutritional and functional value of soybean oil. Recent advances in green extraction methods, such as supercritical CO_2 extraction have enabled more selective

recovery of bioactive lipids, antioxidants, and minor components from plant materials, improving purity and preserving heat-sensitive compounds compared to traditional solvent extraction or cold pressing [104].

3 Bioactive Volatile Compounds in Soybean Essential Oil

Essential oil by definition refers to the volatile aromatic fraction of the plant material, consisting of low-molecular-weight compounds recoverable by distillation [22,23]. Soybean grain is rich in bioactive compounds among which there are volatiles, whose yield tends to be low, as soybean is not a typical essential-oil plant. Soybean volatiles include acids, alcohols, aldehydes, esters, furans, benzenes, ketones, lactones, nitrogen-containing compound, sulfur-containing compound, hydrocarbons, terpenes, phenols, and pyrazines [24]. Their distribution and concentration differ depending on cultivar, environmental stress, seed maturity, post-harvest handling and storage conditions [24,105,106].

Ghahari et al. [107] identified 40 components representing 96.68% of the total essential oil isolated from soybean grain. The major constituents of the oil were carvacrol (13.44%), (E,E)-2,4-decadienal (9.15%), p-allylanisole (5.65%), p-cymene (4.87%), and limonene (4.75%). The isolated soybean seed essential oil did show proton-donating ability, meaning it could potentially serve as free radical inhibitor or scavenger, suggesting its potential as a natural antioxidant source. The results of the bioassays showed that the oil exhibited moderate to strong antibacterial and antifungal activities against some of the tested pathogens. The maximum antibacterial activity was noted against *Rathayibacter toxicus* and *Pseudomonas syringae* subsp. *syringae*, followed by *Staphylococcus aureus*, *Bacillus subtilis* and *Escherichia coli*, *Pseudomonas aeruginosa*, *Pseudomonas viridiflava*. No growth inhibition was determined for *Xanthomonas campestris pv. Campestris*. The maximum antifungal activity was observed against *Pyricularia oryzae*, followed by *Sclerotinia sclerotiorum*, *Fusarium oxysporum* and *Botrytis cinerea*. No inhibitory effect was found for *Alternara alternata* and *Rhizoctonia solani*. This is relevant as recent reviews documented a growing trend toward using plant-derived antimicrobials, including essential oils and phytochemicals, as clean-label alternatives to synthetic preservatives in food systems [40].

Carvacrol, limonene and p-cymene, major constituents of soybean essential oil, are well-established bioactive volatiles also found in classical essential oils with relevant biological properties [36,107−109]. According to the extensive review by Sharifi-Rad et al. [108], carvacrol possesses antimicrobial, antioxidant, and anticancer activities putatively useful for clinical applications. It is particularly effective against food-borne pathogens such as *Escherichia coli*, *Salmonella*, and *Bacillus cereus*, inhibiting their growth and the production of toxins, as well as against fungi, for example *Candida*. Carvacrol has high antioxidant activity and has been successfully used as dietary phytoadditive to improve animal antioxidant status. The anticancer properties of carvacrol have been reported in preclinical models of breast, liver, and lung carcinomas, but human trials are lacking, which impedes any conclusions of clinical relevance. Based on the reviews of numerous research papers, preclinical and clinical trials [110,111], limonene exhibits significant antioxidant, anti-inflammatory, wound-healing, antidiabetic, anticancer, and immunomodulatory activities. Although conventionally used in soaps and perfumes, and in the production of pesticides and insect repellents, limonene can act as a solvent for cholesterol and it was proven efficient in dissolving gallstones. It can neutralize gastric acid and provide relief from burning sensations and gastroesophageal reflux [112]. *In vitro* studies of p-cymene report its multi-targeted anticancer effects in hepatocellular carcinoma cells, emphasizing the need for further evaluation in *in vivo* models and potential combination therapies for improved therapeutic outcomes [113]. Asle-Rousta and Perovy [114] investigated the effect of thymol and its precursor p-cymene on immobilized male rats, concluding that both may be effective in preventing neurodegenerative diseases as they reduce oxidative stress and neuroinflammation. In another study [26],

the joint action of thymol and p-cymene showed additive or synergistic effect and significant toxic activity against the red flour beetle (*Tribolium castaneum*), the cigarette beetle (*Lasioderma serricorne*), and the booklouse (*Liposcelis bostrychophila*), indicating that they possess great potential of use as plant-derived biopesticides that will be safe for humans and the environment.

Despite encouraging evidence from *in vitro*, animal, and preclinical investigations of the volatiles which can also be found in soybean seed, the current data are insufficient to support clinical relevance, underscoring the need for additional *in vivo* research, including rigorously conducted human studies and clinical trials. Furthermore, the extremely low abundance of volatile constituents in soybean seed essential oil suggests that their biological relevance and potential practical use may be limited.

4 Conclusions and Future Perspectives

Non-volatile bioactive compounds found in crude and refined soybean oil and volatile bioactives found in soybean essential oil exhibit a wide array of biological activities, including anti-inflammatory, antimicrobial, cardioprotective, anticancer, metabolic, hepatoprotective, and dermatological effects. These activities are primarily attributed to its polyunsaturated fatty acids (linoleic acid and α-linolenic acid), tocopherols and phytosterols. Although substantial preclinical evidence supports the biological activity of soybean oil and derived compounds, human clinical trials remain limited. Additional well-designed studies are required to establish their efficacy, determine optimal dosing strategies, and evaluate safety across diverse populations. Advances in green extraction technologies, particularly supercritical CO_2 extraction, present promising avenues to enhance the recovery and stability of bioactive compounds from soybean oil, while minimizing thermal and chemical degradation. Future research should also investigate potential synergistic interactions among individual components of soybean oil, as well as their combined effects with other bioactive dietary factors. Long-term intervention studies will be important for assessing sustained metabolic, cardiovascular, and inflammatory outcomes. The incorporation of soybean oil into functional foods, nutraceuticals, and cosmeceutical formulations offers considerable potential; however, progress in these areas will require standardized extraction and formulation protocols, rigorous quality control, and mechanistic studies that link specific components to defined biological effects. Moreover, optimizing the dietary balance between ω-6 and ω-3 fatty acids, within the broader context of overall dietary patterns, will be essential to maximize the health benefits of soybean oil while mitigating possible adverse metabolic or inflammatory responses. Collectively, current evidence positions soybean oil as a versatile and multifunctional ingredient with significant potential for health promotion. Continued research integrating molecular, clinical, and technological approaches will be crucial for translating its bioactive properties into effective applications in human nutrition, medicine, and dermatological care.

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