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Peony Seed Products as Emerging Functional Foods: Bioactive Compounds, Extraction Technologies, and Future Directions

Nabila Jabbar[1]

[1]*School of Chemistry and Chemical Engineering, North University of China, Taiyuan 030051, Shanxi, China*

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Corresponding Author:
Nabila Jabbar
Email:
samkhan191181@gmail.com

ABSTRACT

Peony-derived products, especially peony seed oil (PSO), are garnering increasing attention due to their notable nutritional, therapeutic, and commercial potential. Herbaceous peonies (Paeonia lactiflora Pall.), historically cultivated in China for their ornamental and medicinal properties, have recently emerged as a dual-purpose crop. Beyond their traditional use for bioactives such as paeonol and paeoniflorin, the seeds once considered industrial waste are now recognized as a rich source of unsaturated fatty acids, essential amino acids, polyphenols, stilbenoids, and minerals. Among these, PSO stands out for its exceptionally high content of α-linolenic acid and γ-tocopherol, which contribute to its potent antioxidant capacity. Modern extraction technologies, including solvent-based methods, ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE), have significantly improved the yield and bioactivity of PSO constituents. These techniques facilitate the efficient recovery of functional compounds while maintaining their structural integrity. Extensive pharmacological studies have demonstrated that PSO possesses a wide range of biological activities, including antioxidant, anti-inflammatory, antidiabetic, hypolipidemic, and hepatoprotective effects. Recent evidence also highlights its potential role in ameliorating metabolic disorders such as non-alcoholic fatty liver disease (NAFLD), positioning PSO as a promising candidate in functional food and nutraceutical development. Due to its safety and nutritional value, PSO has been approved as a new food resource by Chinese regulatory authorities, further stimulating research into its comprehensive health effects, molecular mechanisms, and industrial scalability. However, challenges remain in optimizing extraction efficiency, ensuring product stability, standardizing cultivation practices, and validating health claims through clinical studies. Future research should prioritize the development of eco-friendly production systems, quality control standards, and diversified applications in food, pharmaceutical, and cosmetic industries. The growing body of evidence supports PSO as high-value plant oil with significant implications for human health, economic development, and sustainable agriculture.

Introduction

Herbaceous peony (Paeonia suffruticosa) is a widely cultivated traditional Chinese ornamental plant with an expanding presence across Asia, Europe, and North America. While historically valued for its aesthetic appeal, numerous peony species have also been recognized for their medicinal properties. Studies has particularly focused on bioactive constituents such as paeonol, paeoniflorin, and other phytochemicals found in various plant parts, including the corolla, leaves, and root bark (Li et al., 2009). Due to its high ornamental and therapeutic value, peony holds considerable cultural and economic significance, particularly in China, Japan, Europe, and the United States. The genus Paeonia L. (family Paeoniaceae) comprises approximately 33 species and 25 subspecies, classified into three sections: Moutan DC., Onaepia Lindl., and Paeonia (Yong et al., 2015). China represents the natural distribution center for this genus, harboring 15 species and 5 subspecies, and has played a central role in its domestication and use. Notably, the dried root bark of P. suffruticosa, known as mudanpi in traditional Chinese medicine, has been included in all editions of the Chinese Pharmacopoeia and is commonly used to promote blood circulation and alleviate blood stasis (Sevim et al., 2013). Despite this long-standing utilization of roots and flowers, peony seeds were historically discarded as industrial waste. However, over the past decade, growing interest has emerged in valorizing this underutilized plant part. Recent studies have highlighted that peony seeds especially their oil are rich in health-promoting compounds such as unsaturated fatty acids (notably α-linolenic acid), essential amino acids, stilbenoids, and various antioxidants, making them a promising resource for functional food and nutraceutical development (He et al., 2013).

Polyphenolic Extraction

There has been growing scientific interest in dietary and medicinal plants due to their high content of bioactive compounds such as polyphenols, flavonoids, proteins, and vitamins distributed across various plant organs (Sekhon-Loodu & Rupasinghe, 2019). Among these, polyphenols a broad class of plant-derived secondary metabolites have gained significant attention for their diverse biological functions. Containing one or more aromatic rings bearing hydroxyl groups, polyphenols exhibit potent antioxidant, anticancer, and antimicrobial activities, which have positioned them as promising agents in both preventive and therapeutic healthcare, including applications in modern allopathic medicine. Polyphenols are now recognized as essential micronutrients in the human diet, with accumulating evidence supporting their role in mitigating the onset and progression of various degenerative diseases, such as cardiovascular disorders, neurodegenerative conditions, cancer, and diabetes. However, despite their considerable therapeutic potential, polyphenols face several limitations, including low stability, poor membrane permeability, light and heat sensitivity, susceptibility to oxidation, and limited bioavailability. To address these challenges, advanced strategies have been developed to enhance their stability and biological efficacy, including conjugation with macromolecules and direct polymerization techniques. Polymerization methods such as step-growth, free-radical, and enzyme-catalyzed reactions have been successfully employed to stabilize polyphenol monomers and produce high-molecular-weight derivatives. These include polymers derived from common polyphenols like rutin, tannic acid, epicatechin, quercetin, epigallocatechin gallate (EGCG), ferulic acid, and catechin, resulting in molecular weights ranging from 890 to 77,000 Da (Mehmood et al., 2022). These polymeric polyphenols exhibit enhanced antioxidant activity and improved therapeutic profiles. Furthermore, phenolic compounds exhibit potent antimicrobial, antifungal, and antiviral effects, contributing to their widespread use in pharmaceutical formulations aimed at combating antibiotic-resistant pathogens (Li et al., 2018). Due to their multifunctionality, natural origin, and favorable safety profiles, polyphenol-rich plants continue to serve as a valuable resource for the development of novel therapeutic agents. Ongoing research into their mechanisms of action, bioavailability enhancement, and clinical efficacy is essential to fully harness their potential in combating a wide spectrum of human diseases.

Different Polyphenol Extraction Methods

A number of extraction techniques, including microwave, ultrasonic, Soxhlet, heatreflux and ultrahigh-pressure extraction, have been reported for polyphenol extraction(Wang etal.,2009).

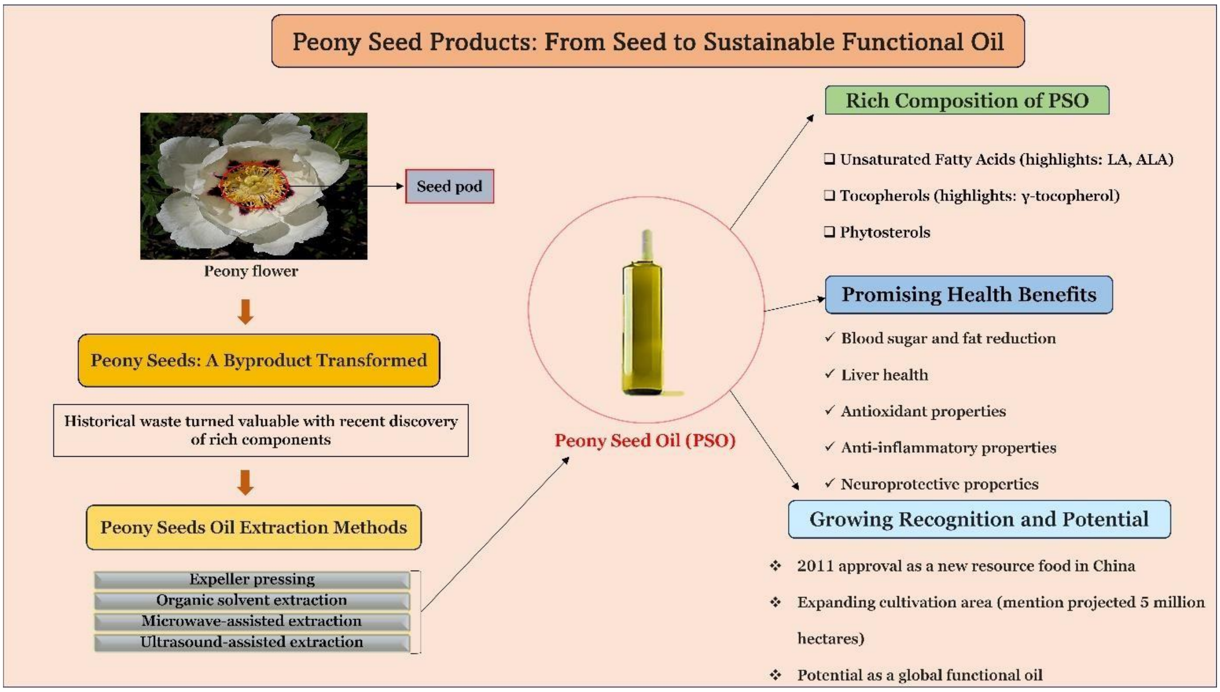

Figure 1: The graphical abstract highlights the transformation of peony seeds into functional oil, highlighting its rich composition, potential health benefits, and growing recognition as a sustainable resource.

Hydrophilic polyphenols including aglycones, glycosides and oligomers are typically extracted using water or polar organic solvents such as methanol, ethanol, acetonitrile, and acetone, often in combination with water to enhance solubility. When target polyphenols exhibit limited solubility in these media, liquid-liquid partitioning with solvents such as ethyl acetate is commonly employed to isolate specific fractions. The extraction process is also influenced by pH, with acidic conditions (low pH) aiding in the stabilization of polyphenols by maintaining them in their neutral molecular forms, thus improving their partitioning into organic solvents (Khoddam et al., 2013). Conventional extraction techniques, such as water bath extraction, have been utilized for decades and rely on indirect, controlled heating to facilitate the release of bioactive compounds from plant matrices. Optimal temperatures generally range between 20°C and 50°C; temperatures above 70°C may accelerate polyphenol degradation, leading to diminished yields. Mild heating enhances extraction efficiency by increasing the permeability of cell walls, improving compound solubility and diffusivity, and lowering solvent viscosity, thereby facilitating solvent penetration and compound migration. However, prolonged exposure to temperatures exceeding 50°C can reduce the recovery of thermolabile polyphenols and proanthocyanidins due to thermal degradation. Due to the limitations of conventional methods, advanced techniques such as microwave-assisted extraction (MAE) have gained prominence since their introduction in the late 1980s. MAE including solvent-free (SFMAE) and pressurized (PMAE) variants offers a rapid, cost-effective, and solvent-efficient approach to polyphenol extraction. This method enables high-throughput processing with improved reproducibility and reduced environmental impact. MAE is particularly well-suited for extracting temperature-sensitive flavonoids and has been shown to yield high levels of antioxidant-rich compounds, such as epigallocatechin gallate (EGCG), in significantly shorter time frames (Cao et al., 2022). Ultrasound-assisted extraction (UAE) is another modern approach that uses high-frequency ultrasonic waves to enhance mass transfer, disrupt plant cell walls, and facilitate solvent penetration through capillary action. Elevated temperatures during UAE can further improve solubility, diffusivity, and extraction kinetics. Common setups include ultrasonic probes and ultrasonic baths, which are widely used for their effectiveness in diverse solvent systems. However, UAE may suffer from lower experimental reproducibility due to variability in acoustic energy distribution and operational conditions (Chiang et al., 2005). Overall, the selection of an appropriate extraction method depends on the specific polyphenol profile, plant matrix characteristics, and desired efficiency, with modern techniques like MAE and UAE offering promising alternatives to traditional solvent extraction for maximizing yield and preserving compound integrity.

Table 1: Health benefits of polyphenol

Beneficial Effect	**Polyphenols Examples**
Antioxidant	Curcumin
	Catechin
	Epi gallote ching allate (EGCG)
	Sily marin
	Apigenin
Anti-inflammatory	Curcumin
	Resveratrol
	Baicalin
	Rutin
	Hesperetin
	Silybin
Anticancer	Resveratrol
	Quercetin
	Curcumin
	EGCG
	Hypericin
	Silymarin
Antimicrobial	Curcumin
	Silymarin
	Teapolyphenol
	Rutin
Pro-oxidant	Resveratrol
	Gallicacid
	Daidzein
	Curcumin

Antidiabetic	Catechin
	EGCG
	Curcumin
	Quercetin
Antihypertensive	Curcumin
	Teapolyphenol
	Procyanidin
	Resveratrol
Antiobesity	Daidzein
	Curcumin
	Quercetin
	Catechin
Antiatherosclerotic	Curcumin
	Ellagicacid
	EGCG
	Resveratrol

Extraction and Analysis of Peony Seed Oil

A variety of techniques have been employed to extract peony seed oil (PSO), including traditional methods such as expeller pressing and organic solvent extraction, as well as more advanced technologies like microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE). These methodologies differ in their efficiency, environmental impact, and ability to preserve the integrity of bioactive compounds. Notably, PSO has gained increasing recognition as a high-value functional food, recently approved by the Chinese government for dietary use. It is particularly remarkable for its exceptionally high content of polyunsaturated fatty acids (PUFAs), which exceed 90% of the total fatty acid profile. Among these, α-linolenic acid a key omega-3 fatty acid accounts for up to 40% of the total lipid content (Zhu et al., 2014). Peony seeds have garnered significant scientific interest due to their rich composition of health-promoting unsaturated fatty acids, including α-linolenic acid, linoleic acid, oleic acid, and palmitic acid. For instance, seed oil derived from *Paeonia veitchii* contains α-linolenic acid at levels as high as 36.14%, surpassing concentrations found in other well-known edible oils such as camellia, olive, and avocado oils (Zhang et al., 2018; Haiyan et al., 2007). Similarly, *P. decomposita* seed oil exhibits a total unsaturated fatty acid content ranging between 91.94% and 93.70%, with individual fatty acid contributions varying between 40.45% and 47.68% by weight (Yong et al., 2015). In addition to its PUFA richness, herbaceous peony seed oil is abundant in γ-tocopherol, a potent form of vitamin E with strong antioxidant properties (Ning et al., 2015). Beyond its lipid profile, peony seeds are a source of diverse phytochemicals with pharmacological relevance. These include oligostilbenes, monoterpene glycosides, flavonoids, flavanols, and other phenolic compounds. Notably, *P. rockii* and *P. decomposita* subsp. *rotundiloba* seeds have been identified as rich sources of natural antioxidants (Oidovsambuu et al., 2013). Studies have also detected the presence of methyl gallate, albiflorin, and paeoniflorin in the fruit of *P. anomala*, indicating the therapeutic potential of lesser-known peony species (He et al., 2010). Peony roots are typically cultivated for 4–5 years before harvesting, large volumes of seeds are generated as agricultural by-products. Utilization of these seeds for oil production not only enhances the overall economic value of peony cultivation but also contributes to sustainable agriculture by reducing waste. Recent studies have underscored the nontoxicity, high nutritional value, and broad spectrum of health benefits associated with PSO. These include antioxidant, anti-inflammatory, anti-anaphylactic, hypoglycemic, hypolipidemic, hepatoprotective, anti-tumor, and neuroprotective effects, as well as cardiovascular protection, improvement of skin conditions, enhancement of nonspecific immunity, and potential in the management of climacteric syndrome and rheumatoid arthritis (Sun et al., 2013; Zhang et al., 2014). The comprehensive nutritional and medicinal value of PSO highlights its promise as novel edible oil with functional food applications. Further research into its bioavailability, clinical efficacy, and mechanisms of action could pave the way for its integration into therapeutic and preventive healthcare.

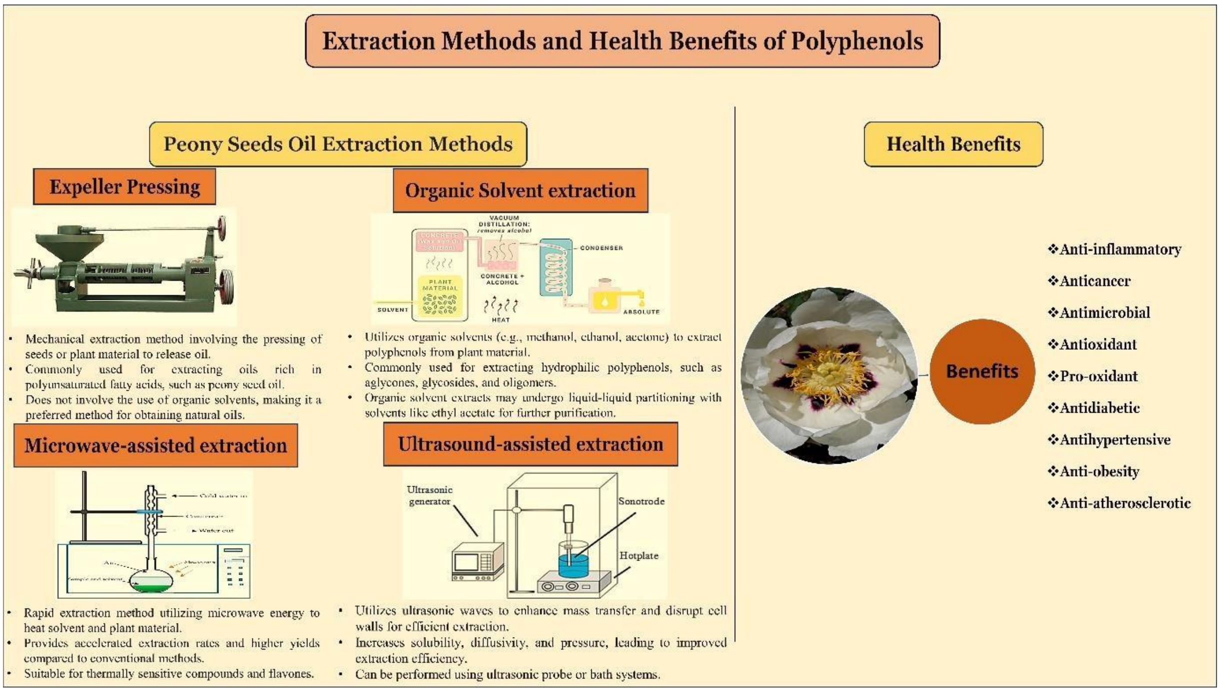

Figure 2: Graphical abstract illustrating extraction methods, health benefits

Tocopherols, a class of fat-soluble antioxidants, are critical indicators of the nutritional quality of seed oils. These compounds play a vital role in human health by scavenging free radicals, thereby mitigating oxidative stress and protecting polyunsaturated fatty acids (PUFAs) from lipid peroxidation. Although α-tocopherol has historically been the primary focus of dietary supplementation, emerging research indicates that γ-tocopherol may possess superior antioxidant efficacy due to its broader reactive nitrogen species-scavenging ability and enhanced biological activity (Li et al., 2013). Peony seed oil (PSO) is particularly notable for its high γ-tocopherol content, which distinguishes it from many conventional edible oils. In comparative studies, PSO has demonstrated greater free radical-scavenging capacity than extra virgin olive oil, underscoring its potential as a potent dietary antioxidant. Moderate consumption of PSO has shown significant protective effects against oxidative damage in vivo. For example, PSO supplementation has attenuated acute liver injury induced by carbon tetrachloride in mice and ameliorated diet-induced hyperlipidemia in rats. Investigations into the biochemical mechanisms underlying these effects have revealed strong correlations between PSO's antioxidant activity and its unique tocopherol and fatty acid composition (Yang et al., 2017). These findings highlight PSO as a promising functional food component with potential applications in the prevention and management of oxidative stress-related diseases.

Table 2: Contents of main fatty acids, unsaponifiable matters, total tocopherols, and phenolics in PSO

Main fatty acids (%)	
Palmiticacid	7.5±2.8
Stearic acid	1.8±0.2
Oleicacid	24.1±3.7
LA	27.2±1.7
ALA	39.5±5.1
(B)Unsaponifiable matters(mg/100g)	
γ-Tocopherol	63.4±2.6
Stigmasterol	30.8±1.2
γ-Sitosterol	955±33
(C)Total tocopherols(mg/100g)	76.0±3.1
(D)Total phenolics(mg/100g)	3.34±0.15

Impact on Lowering Sugar and Fat

Peony seed oil (PSO) has garnered increasing attention for its potential therapeutic effects in metabolic disorders, particularly diabetes mellitus and non-alcoholic fatty liver disease (NAFLD). In a study investigating its antidiabetic properties, streptozotocin (STZ)-induced diabetic mice were treated with PSO, resulting in a significant reduction in blood glucose levels (Su et al., 2015). Compared to untreated diabetic controls, PSO-treated mice exhibited notable improvements in several metabolic parameters, including increased body weight, liver glycogen storage, serum insulin concentrations, and high-density lipoprotein cholesterol (HDL-C). Concurrently, there were marked reductions in glycosylated hemoglobin (HbA1c), total serum cholesterol, and triglyceride levels, highlighting PSO's potential to modulate glucose and lipid metabolism. PSO's health benefits are largely attributed to its high content of α-linolenic acid comprising up to 40% of total fatty acids as well as its capacity to be metabolically converted into bioactive compounds such as prostacyclin, eicosapentaenoic acid (EPA), and docosa-hexaenoic acid (DHA), which are known to facilitate vasodilation, improve blood circulation, and inhibit platelet aggregation (Li et al., 2014). Furthermore, PSO is rich in antioxidant components that effectively scavenge free radicals and peroxides, thereby inhibiting lipid peroxidation and reducing malondialdehyde (MDA) accumulation in hepatic and neural tissues (Wang et al., 2007). In a study, the efficacy of PSO in alleviating NAFLD was evaluated using a mouse model induced by a high-fat diet (HFD). PSO treatment significantly mitigated HFD-induced increases in body weight, serum triacylglycerol (TG), total cholesterol (TC), glucose, and free fatty acids (FFAs) (Su et al., 2021). Mechanistic investigations revealed that PSO down regulated key markers of endoplasmic reticulum stress (ERS) including GRP78, XBP-1, and phosphorylated IRE1α as well as pro-inflammatory cytokines such as TNF-α, IL-6, and IL-1β. These findings suggest that PSO exerts hepato-protective effects in NAFLD by modulating ERS pathways and suppressing inflammation. Collectively, these studies underscore the promising role of PSO as a functional food with multifaceted metabolic benefits. Further research, particularly in clinical settings, is warranted to validate its therapeutic potential and elucidate the molecular mechanisms underlying its bioactivity.

Exploring the Health Potential of Peony Seed Oil and Related Extracts

Peony seed oil (PSO) has garnered increasing attention for its potential therapeutic effects in metabolic disorders, particularly diabetes mellitus and non-alcoholic fatty liver disease (NAFLD). In a study investigating its antidiabetic properties, streptozotocin (STZ)-induced diabetic mice were treated with PSO, resulting in a significant reduction in blood glucose levels (Su et al., 2015). Compared to untreated diabetic controls, PSO-treated mice exhibited notable improvements in several metabolic parameters, including increased body weight, liver glycogen storage, serum insulin concentrations, and high-density lipoprotein cholesterol (HDL-C). Concurrently, there were marked reductions in glycosylated hemoglobin (HbA1c), total serum cholesterol, and triglyceride levels, highlighting PSO's potential to modulate glucose and lipid metabolism.

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In addition to peony seed oil (PSO), black raspberry seed oil (BRSO), which is similarly rich in α-linolenic acid, has been investigated for its potential to modulate lipid metabolism. In a study involving both high-fat diet (HFD)-induced and genetically obese mice, BRSO administration significantly reduced serum and hepatic levels of triglycerides, non-esterified fatty acids (NEFAs), and total cholesterol compared to control groups (Lee et al., 2018). These lipid-lowering effects were primarily attributed to BRSO's dual action: (1) inhibition of lipogenesis through the downregulation of genes involved in fatty acid synthesis, thereby limiting lipid accumulation; and (2) promotion of fatty acid oxidation via upregulation of key genes and proteins responsible for β-oxidation. Furthermore, the treatment enhanced expression of peroxisome proliferator-activated receptor alpha (PPARα), a crucial regulator of lipid metabolism, contributing to its overall metabolic benefits. These findings support the therapeutic potential of BRSO as functional oil, akin to PSO, for obesity and lipid-related metabolic disorders.

A complementary study conducted in 2022 further elucidated the beneficial effects of PSO on lipid metabolism and gut microbiota in a hypercholesterolemic hamster model (Kwek et al., 2022). PSO supplementation led to dose-dependent reductions in plasma total cholesterol, triglycerides, and arterial plaque formation, while also significantly decreasing hepatic lipid accumulation. Notably, PSO positively modulated gut microbial composition, influencing specific bacterial taxa associated with cholesterol metabolism. This dual action suggests a synergistic effect of PSO on cardiovascular health and gut microbiome regulation, although further mechanistic studies are necessary to elucidate the precise interactions involved. Despite its potential, PSO research faces several challenges, particularly in optimizing extraction techniques and improving oil stability. Various studies have explored enzyme-assisted extraction and solvent optimization to enhance yield and preserve bioactive constituents. Moreover, recent advancements have examined the use of bilayer emulsions to improve the oxidative stability and bioaccessibility of PSO, thereby increasing its functional value and market potential (He et al., 2023). These delivery strategies represent promising avenues for developing PSO-based nutraceuticals and health supplements.

Species-level differences among tree peonies have also been assessed to identify optimal cultivars for PSO production. Among them, *Paeonia 'Austin'* emerged as a superior candidate due to its high α-linolenic acid content, favorable omega-6 to omega-3 ratio, and abundant phenolic compounds (Mao et al., 2017). *Paeonia ostii* seed oil, obtained via mechanical pressing, demonstrated excellent oxidative stability and sensory characteristics, suggesting its suitability for use in edible oils, nutraceuticals, and healthcare applications. Further phytochemical characterization using high-performance liquid chromatography with diode-array detection (HPLC-DAD)-based metabolic fingerprinting has provided key insights into interspecies variation within the genus *Paeonia*. He et al. (2014) profiled eight tree peony species, identifying distinctive metabolite patterns dominated by monoterpene glycosides and flavonoids. Principal component analysis (PCA) and hierarchical cluster analysis (HCA) revealed four distinct chemotaxonomic groups, offering both confirmation and refinement of traditional botanical classifications. These findings provide a foundational framework for future pharmaceutical development targeting bioactive compounds from specific *Paeonia* species.

Zhiqiang Wang et al. (2019) conducted an extensive metabolomic analysis of tree peonies (*Paeonia* Sect. *Moutan*), aiming to differentiate species and elucidate their phytochemical profiles. Root bark samples from nine tree peony species were analyzed using advanced metabolomics platforms, leading to the identification of 384 compounds, including diverse classes such as monoterpene glycosides, flavonoids, and terpenoids. These compounds were differentially distributed among species, enabling classification into two main subsections: *Vaginatae* and *Delavayanae*. The distinct metabolite patterns not only reinforced taxonomic relationships but also provided valuable insights into the chemical diversity and biosynthetic potential of these often-endangered species. This study significantly advances our understanding of the phytochemical complexity in *Paeonia* species and underscores their value in pharmaceutical and nutraceutical applications. Sun et al. (2021) examined eight intersubgeneric hybrids of *Paeonia* (IHPs), which are created by hybridizing herbaceous and tree peonies. Utilizing high-performance liquid chromatography coupled with quadrupole time-of-flight mass spectrometry (HPLC-Q-TOF-MS/MS), the researchers successfully identified 18 bioactive constituents, including tannins, monoterpene glycosides, phenolic acids, and paeonols. Notably, the IHPs exhibited significantly higher concentrations of tannins and monoterpene glycosides compared to their parental herbaceous and tree peony lines. Cluster analysis further revealed that three hybrid cultivars Prairie Charm,' 'Garden Treasure,' and 'Yellow Emperor' contained the highest diversity and abundance of pharmacologically relevant compounds. These findings highlight the potential of intersubgeneric hybrids as rich sources of bioactive metabolites and suggest their promising application in the development of novel medicinal and functional products.

Exploring the Therapeutic Potential of Paeonia Species: Insights into Metabolites, Activities, and Applications

Yong et al. (2020) investigated the origin and chemical diversity of *Paeonia* species traditionally used in Chinese medicine, particularly in the formulation of *Paeonia Radix Rubra* (PRR). Employing HPLC-Q-TOF-MS, the researchers identified 21 metabolites, including tannins, phenolic compounds, paeonol, and flavonoids, across multiple populations. Cluster analysis of 20 populations resulted in four distinct chemotypic groups, reflecting significant interspecific variations in metabolite composition and abundance. Notably, *Paeonia lactiflora* and *Paeonia mairei* exhibited high concentrations of paeoniflorin and monoterpene glycosides, underscoring their potential as superior medicinal germplasm resources for PRR development. Tong et al. (2021) examined the phytochemical profiles and antioxidant properties of stems and leaves from three *Paeonia* species across six developmental stages. A total of 24 metabolites including paeonol, tannins, flavonoids, and monoterpene glycosides were identified. The results consistently showed that leaf tissues contained significantly higher metabolite concentrations than stems at all stages. Particularly, *Paeonia ostii* leaves reached peak paeoniflorin levels during early growth (Stage 1), indicating the optimal harvest window for pharmaceutical applications. Additionally, the leaves of *Paeonia* 'Hexie' demonstrated stronger antioxidant activity than stems, suggesting their viability as sustainable medicinal alternatives that do not require root harvesting. A comprehensive review by Li et al. (2021) documented ethnopharmacological uses of 21 *Paeonia* species, with roots and root bark being the most commonly utilized parts. The phytochemical inventory comprises over 451 identified compounds, including monoterpenoid glucosides and flavonoids. Pharmacological investigations reveal a wide range of therapeutic effects, with compounds such as paeoniflorin and paeonol emerging as particularly promising due to their bioactive potency. This evidence underscores the genus *Paeonia* as a valuable reservoir of medicinal agents. Further supporting this potential, Bai et al. (2024) conducted an integrated metabolomics analysis of *Paeonia ostii* 'FengDan' leaves and identified 321 metabolites, including key constituents like albiflorin and paeoniflorin. The variation in metabolite composition was closely associated with antioxidant activity. Importantly, leaf extracts exhibited notable antibacterial efficacy, particularly against *Streptococcus hemolyticus β*, and stages S1–S2 were identified as optimal for harvesting based on metabolite abundance. These findings support the utility of *P. ostii* leaves in functional food and pharmaceutical development. In a novel formulation approach, Čutović et al. (2023) encapsulated *Paeonia tenuifolia* L. flower extract into liposomes and biopolymer-based films using a one-step method. Liposomes prepared with Phospholipon demonstrated the highest encapsulation efficiency (72.04%) and favorable release kinetics. Biological assays confirmed the bioactivity of these delivery systems, suggesting promising applications in medicinal and cosmetic formulations.

Additionally, a study by Zou et al. (2023) highlighted the acaricidal potential of paeonol, a phenolic compound derived from *Paeonia moutan*, against *Aleuroglyphus ovatus*, a major pest of stored grains. Paeonol exhibited potent contact toxicity and induced neurotoxic symptoms in mites, accompanied by alterations in enzyme activity associated with acaricidal mechanisms. These findings point to paeonol's potential as a natural pest control agent with significant agricultural relevance. A study by Tak et al. (2006) explored the acaricidal properties of paeonol and benzoic acid isolated from the root bark of *Paeonia suffruticosa*, targeting *Tyrophagus putrescentiae*, a common storage mite. Both compounds exhibited contact toxicity in fabric-based bioassays, demonstrating comparable efficacy to the conventional acaricide benzyl benzoate. Furthermore, in vapor-phase bioassays, paeonol and benzoic acid showed enhanced toxicity in sealed environments, highlighting their potential as fumigant acaricides. These findings support the application of *Paeonia*-derived monoterpenoids as natural alternatives for mite control. In the investigation of plant part-specific metabolite distribution, Zheng et al. (2023) reported that the root core of *Paeonia* species contains higher levels of paeoniflorin and pentagalloyl glucose (PGG) than the traditionally used medicinal root bark. Petals, which are edible, were found to be rich in quercitrin, while stamens exhibited notable concentrations of methyl gallate and PGG. Leaves contained abundant paeoniflorin, often exceeding that found in root bark, suggesting their potential as alternative sources of pharmacologically active compounds. Additionally, branches were rich in catechin derivatives, and seed coats typically discarded as by-products—showed promise for stilbene extraction. Notably, extracts from all plant parts demonstrated antioxidant properties, with *Paeonia ostii* seed cakes exhibiting CB1 and CB2 receptor agonistic activity, indicating potential for neuroactive applications.Bai et al. (2021) employed UPLC-Triple-TOF-MS and HPLC-ESI-QQQ-MS to identify and quantify 130 metabolites in tree peony fruit tissues, including dominant constituents such as paeoniflorin and trans-resveratrol. Extracts from fruit pods and seed coats exhibited stronger antioxidant, antibacterial, and anti-neuroinflammatory activities compared to seed kernel extracts, positioning these components as promising candidates for functional food and nutraceutical development.

Further advancing the medicinal potential of *Paeonia*, Xia et al. (2021) identified trans-gnetin H, a stilbene compound from peony seeds, as a potent modulator of autophagy. Trans-gnetin H activates AMPK signaling, inhibits mTORC1 activity, and facilitates the nuclear translocation of TFEB by suppressing its phosphorylation. These actions collectively promote autophagy and significantly reduce cancer cell viability, highlighting its value in cancer therapy through metabolic reprogramming.The anti-inflammatory properties of cis- and trans-gnetin H were confirmed by Park et al. (2016), who demonstrated that both compounds suppress cytokine production in LPS-stimulated THP-1 cells. The inhibition of nuclear translocation of p65, along with decreased phosphorylation of key NF-κB pathway proteins IKK-β, IκBα, and p65 suggests a targeted mechanism underlying their immunomodulatory effects. Trans-gnetin H, in particular, showed superior efficacy, reinforcing its potential as a candidate for managing chronic inflammatory conditions. In the context of musculoskeletal health, He et al. (2019) reported that oligostilbenes from *P. suffruticosa* seeds including trans-viniferin and various stilbene trimmers exert protective effects on chondrocytes derived from osteoarthritic rabbit models. These compounds not only enhanced cell viability but also reduced apoptosis, with trans-gnetin H and other trimers outperforming resveratrol and the clinically used drug diacerein at lower concentrations. This highlights the therapeutic promise of oligostilbenes for osteoarthritis management and supports future research into their synergistic effects. Expanding on the anticancer potential, Gao et al. (2017) demonstrated that trans- and cis-gnetin H, along with other oligostilbenes from *P. suffruticosa* seeds, possess potent anti-proliferative and anti-metastatic properties across multiple human cancer cell lines, including lung, breast, and bone cancers. The study emphasized that trans-isomers and higher-order stilbene polymers, such as resveratrol trimers, showed greater efficacy than dimers or monomeric forms. The findings reveal that structural features such as double bond configuration and polymerization degree play a critical role in modulating biological activity, offering valuable insights for the rational design of next-generation stilbene-based chemopreventive agents.

Resveratrol oligomers from Paeonia suffruticosa seeds, trans-andisgnetin H, have been shown to have better action in stopping the growth of human cancer cell lines (A549, BT20,MCF-7, and U2OS), while leaving normal epithelial cells unaffected. By releasing mitochondrial cytochrome c, activating caspase 3/7, and blocking NF-κB activation, these substances cause apoptosis. Moreover, cis-gnetin H shows promise as a natural option for cancer treatment by effectively inhibiting the development of xenograft lung tumors in mice (Gao et al., 2015).

Novel oligo stilbenes called trans- and cis-suffruticosol D were discovered from Paeonia suffruticosa seeds.They show considerable cytotoxicity against human cancer cell lines(A549, BT20,MCF-7,andU2OS)while having little toxicity against normal cells (HMEC,HPL1A). In human lung cancer cells, these oligostilbenes limit cell motility, decrease mitochondrial membrane potential, cause oxidative stress and death, and disrupt the NF-κB pathway. Interestingly, trans-suffruticosol D is more powerful than cis-suffruticosol D, suggesting that they may be useful as cancer-fighting chemotherapeutic drugs (Almosnid et al., 2015). It was discovered that Paeonia suffruticosa seeds contained eight recognized stilbenes in addition to three novel oligostilbenes: trans-suffruticosolD, cis-suffruticosolD, andcis-gnetinH. It was from this plant species that these substances, which include trans-resveratrol and trans-epsilon-viniferin, were initially extracted. This study expands our understanding of the stilbene composition in Paeonia suffruticosa seeds, contributing to a better comprehension of its bioactive constituents (He et al., 2010).Furthermore, seven stilbenes, including a new compound cis-epsilon-vinifera and six known stilbenes, were isolated from Paeonia lactiflora seeds. These compounds, particularly trans- epsilon-vinifera and gnetin H, exhibited significant antioxidative activity, inhibiting 2- deoxyribose degradation and lipid peroxidation in rat liver microsomes. This suggests that these compounds, along with resveratrol, could serve as potential natural antioxidants derived from Paeonia lactiflora seeds (Kim et al., 2002).

Furthermore, Suffruticosol A, a significant component of Paeonia lactiflora seeds, showed neuroprotective properties by enhancing cell survival and reducing the neurotoxic effects of scopolamine in SH-SY5 cells. Central infusion of suffruticosol A reversed cholinergic deficiencies, improved BDNF signaling in the hippocampus, and restored memory and cognitivefunctionsinamousemodelwithscopolamine-inducedimpairments.Furthermore, at a popular bleaching treatment (Klontza et al., 2021). Using LC- ESI-QqQ-MS, the research It was shown that there are differences in main chemical producers between seeds and pods, including methyl gallate, benzoicacid, luteolin, and trans- resveratrol. At some phases, levels of on Paeonia rockii fruit detected and measured 29 bioactive components during development. pheoniflorin and trans-resveratrol were noticeably higher, suggesting that tree peony fruit has the potential to be a highly concentrated source of bioactive substances. According to Baietal.(2020),the fruit exhibited noteworthy antibacterial and antioxidant characteristics, indicating its potential use and functional qualities. It was shown that there are differences in main chemical producers between seeds and pods, including methyl gallate, benzoic acid, luteolin, and trans-resveratrol. At some phases, levels of pheoniflorin and trans-resveratrol were noticeably higher, suggesting that tree peony fruit has the potential to be a highly concentrated source of bioactive substances. According to Bai et al. (2020), the fruit exhibited noteworthy antibacterial and antioxidant characteristics, indicating its potential use and functional qualities.

Additionally, tree peony (*Paeonia* spp.) blossoms were found to contain seventeen flavonoids identified for the first time, marking a significant advancement in the phytochemical profiling of the species. Petal extracts exhibited strong antioxidant activity, as demonstrated through various in vitro assays. Li et al. (2009) reported robust correlations between antioxidant capacity and total polyphenol content, including specific contributions from quercetin, kaempferol, and luteolin glycoside derivatives. Moreover, a subsequent study by He et al. (2013) revealed the consistent presence of six key compounds across all analyzed seed samples, although compounds 2 and 3 were found in trace or undetectable amounts in some accessions. Based on the chemical profiles, the seed samples were taxonomically categorized in alignment with established *Paeonia* classifications, offering insights into the chemotaxonomic relationships among species.

Current Application of Poeny Seed Oil

The official recognition as a novel food resource by the Chinese Ministry of Health in 2011, peony seed oil (PSO) has garnered increasing scientific and industrial interest due to its exceptional nutritional profile, functional bioactivities, and potential for commercial application. Extensive research has been directed toward elucidating its phytochemical composition, optimizing extraction methodologies, evaluating health-promoting effects, ensuring toxicological safety, and developing value-added derivatives. PSO is distinguished by its high content of polyunsaturated fatty acids (PUFAs), predominantly linoleic acid (LA) and α-linolenic acid (ALA), which are essential for human health and known to confer cardiovascular and anti-inflammatory benefits. Additionally, PSO is enriched with diverse lipophilic bioactives including phytosterols, squalene, tocopherols, and phenolic compounds, all of which contribute synergistically to its reported antioxidant, hepatoprotective, immunomodulatory, antidiabetic, anti-inflammatory, and anticancer activities (Deng et al., 2022). The rapid expansion in the cultivation of oil peony (*Paeonia* spp.), the primary botanical source of PSO, further underscores its agricultural and economic relevance. Presently, over one million hectares are under cultivation in China, with projections indicating a fivefold increase exceeding five million hectares within the next 5 to 10 years. The crop's high adaptability to diverse ecological conditions, perennial growth habit, and resilience to abiotic stressors make it a viable candidate for large-scale sustainable cultivation. As a woody oil crop capable of producing both high-value oil and biomass, oil peony not only represents a promising avenue for functional food development, but also holds the potential to enhance rural livelihoods, optimize land use, and support national food security strategies through agricultural diversification (Deng et al., 2022).

Complementing the valorization of PSO, considerable attention is being directed toward the comprehensive utilization of its byproducts, namely peony seed cake (PSC) and peony seed shell (PSS), which collectively account for over 70% of the total seed biomass post oil extraction. PSC is particularly rich in proteins, flavonoids, monoterpene glycosides, and phytosterols, while PSS harbors abundant polyphenols, oligostilbenes, and natural melanins. These bioresidues exhibit a spectrum of biological activities such as antioxidant, anti-inflammatory, antimicrobial, and neuroprotective properties, suggesting significant potential for applications in the pharmaceutical, nutraceutical, and functional food industries. Systematic chemical characterization and bioactivity profiling of PSC and PSS are essential to support zero-waste biorefinery models, contributing to the sustainable advancement of the PSO industry (Deng et al., 2022). Furthermore, enhancing the oxidative stability of PSO critical for maintaining its nutritional quality and extending shelf life has become a focal area of functional food research. Bai et al. (2018) investigated the efficacy of natural antioxidants, including tea polyphenols, bamboo leaf flavonoids, and rosemary extract, under accelerated storage conditions. Their findings revealed that tea polyphenols at a concentration of 0.04% significantly delayed lipid peroxidation, while a synergistic blend of tea polyphenols, dihydromyricetin, and ascorbyl palmitate offered the highest antioxidative protection. These results strongly advocate the preferential use of natural antioxidant systems over synthetic stabilizers, aligning with clean-label trends and health-conscious consumer preferences. Such advancements not only improve the functional performance of PSO but also support its positioning as a premium, health-promoting edible oil suitable for incorporation into diverse dietary formulations and therapeutic applications.

The high concentration of alpha-linolenic acid (ALA) and advantageous minor components such phytosterols, tocopherols, squalene, and phenolics in tree peony seed oil (TPSO) has drawn attention. The nutritional makeup, health advantages, digestion, absorption, bioavailability, and encapsulation of TPSO are all methodically outlined in this review. Regulations, commercial uses, adulteration identification, and extraction processes are covered. Although TPSO has anti-obesity, hypoglycemic, hypolipidemic, and antioxidant properties, its limited bioavailability and stability make it difficult to use. Its full potential in the food and cosmetic industries must be realized through efficient delivery methods such as micro encapsulation and emulsion, underscoring the necessity of more research in nutrition and product development (He et al., 2023).A study investigating Herbaceous peony(HP)seed oil from China found it to be rich in various bioactive compounds, including monounsaturated and polyunsaturated fatty acids (particularly α-linolenic acid in the Fushao variety), tocopherol, phytosterol, and polyphenols (highest in Fushao). This oil also exhibited strong cellular antioxidant activity, with the Fushao variety demonstrating the most potent effect. These findings suggest that herbaceous peony seed oil, especially the Fushao variety, could be a valuable source of essential fatty acids, antioxidants, and other beneficial phytochemicals, potentially offering health benefits like other vegetable oils. However, the study highlights the importance of selecting the appropriate variety when extracting oil for industrial purposes (Wu et al., 2020).

A double-blind, randomized trial investigated the potential benefits of combining hemp seed and evening primrose oil with a "Hot-nature" diet for relapsing-remitting multiple sclerosis (RRMS)patients. After 6 months, patients receiving the co-supplemented oils (with or without the diet) showed improvement in clinical scores, reduced relapse rates, and improved immune markers compared to a control group. The group receiving both the oils and the diet showed the most significant improvement, suggesting a constructive collaboration between the interventions. However, the study does not explain the mechanisms of action and lacks details on the specific "Hot-nature" diet. Overall, the findings suggest promise for co-supplemented oils, particularly with a specific dietary approach, as a complementary therapy for RRMS, but further research is necessary (Rezapour-Firouzi et al., 2013).A study compared the effects of different solvents on peony seed oil extraction. Hx: Iso (hexane/isopropanol mix) yielded the most oil (35.63%), but other solvents offered specific advantages: Chf: Me (chloroform/methanol mix) excelled in extracting linolenic acid and certain glycerides. On the other hand, sterols and squalene were most extracted using petroleum ether. Remarkably, isopropanol yielded extracts with the greatest polyphenol concentration and maximum antioxidant potential even though it generated less oil. These results indicate that the best solvent to utilize will depend on the intended application of the peony seed oil, enabling producers to give certain fatty acids, trace amounts, or total antioxidant capability priority(Cao et al., 2022).Optimization of extraction parameters plays a critical role in enhancing the efficiency and quality of peony seed oil (PSO) production. Using response surface methodology (RSM), Lin et al. (2021) systematically evaluated the impact of key variables extraction time, temperature, ultrasonic power, and liquid-to-solid ratio—on oil yield. The optimal conditions were determined to be 45 minutes extraction time, 45 °C temperature, 90 W ultrasonic power, and a 7:1 liquid-to-solid ratio, achieving a maximal oil yield of 33.90%. Notably, the fatty acid profile of the extracted PSO revealed a high concentration of polyunsaturated fatty acids (PUFAs), with α-linolenic acid (ALA, 39.75%), linoleic acid (LA, 26.32%), and oleic acid (23.66%) collectively accounting for over 89% of the total fatty acid content. This composition not only underscores the nutritional superiority of PSO but also confirms the efficiency of the RSM-optimized method in producing high-quality, health-promoting edible oil.

Wei et al. (2021) explored an enzyme-assisted solvent extraction (EASE) strategy using a synergistic combination of cellulase and hemicellulase under finely tuned conditions (pH 5.1, 68 minutes, 50 °C), which resulted in a 37.4% enhancement in oil yield relative to traditional extraction techniques. The extracted PSO was particularly enriched in ALA (43.33%), further emphasizing its cardioprotective and anti-inflammatory potential. Importantly, this study extended beyond extraction efficiency to evaluate the neuroprotective effects of PSO using a Drosophila melanogaster model of Alzheimer's disease (AD). Oral administration of PSO significantly improved learning and memory performance in transgenic AD flies, as demonstrated by behavioral assays. Histological examination of brain tissue revealed a reduction in neurodegenerative changes, suggesting that PSO may mitigate neurotoxicity and oxidative stress associated with AD pathogenesis. Together, these findings validate the utility of both RSM and EASE-based extraction approaches in maximizing PSO yield and quality while preserving its bioactive components. Moreover, the therapeutic implications of PSO particularly its neuroprotective efficacy highlight its potential as a multifunctional natural product for use in functional foods, nutraceuticals, and potentially as an adjunct in neurodegenerative disease prevention strategies. These results provide a compelling foundation for future clinical and mechanistic studies aimed at further elucidating the health benefits and molecular targets of PSO.

Challenges and Future Research Directions

The growing scientific and commercial interest in peony seed-derived products, particularly peony seed oil (PSO), has brought to light a range of research challenges and future development priorities. Although the large-scale cultivation of oil peony has expanded significantly, there remain unresolved issues related to standardized agronomic practices, post-harvest handling, and sustainable production systems. Advancing green, efficient extraction technologies such as enzyme-assisted, supercritical fluid, and ultrasonic-assisted methods should be a key focus of future investigations to maximize oil yield while preserving the bioactivity of key compounds. Furthermore, maintaining physicochemical stability and product integrity during processing and long-term storage presents a critical challenge, particularly given the high unsaturated fatty acid content of PSO, which is susceptible to oxidative degradation. Addressing this necessitates targeted research into natural antioxidant systems, packaging innovations, and optimized storage conditions. Given the increasing use of PSO in functional foods, nutraceuticals, and cosmetic formulations, it is imperative to establish comprehensive safety evaluations and regulatory frameworks to ensure product quality, standardization, and consumer safety. Future studies should also focus on the bioavailability, pharmacokinetics, and metabolic pathways of PSO-derived bioactive compounds in vivo; to better understand their mechanisms of action and therapeutic potential. Importantly, while numerous in vitro and animal studies suggest a wide spectrum of health-promoting effects, including antioxidant, anti-inflammatory, hepatoprotective, and neuroprotective activities, well-designed clinical trials are essential to substantiate these claims and facilitate evidence-based applications. In parallel, exploring novel delivery systems and product formulations, alongside consumer perception and market behavior analyses, can support the broader integration of PSO into health-promoting product lines. Collectively, addressing this multifaceted research needs will not only unlock the full economic and therapeutic potential of peony seed products but will also contribute to the advancement of sustainable, science-driven development in the medicinal plant and functional food industries.

Conclusion

The exploration of peony seed-derived products particularly peony seed oil (PSO) has revealed substantial nutritional, therapeutic, and economic potential. This comprehensive review underscores the rich biochemical composition of PSO, its multifaceted health benefits, and its expanding applications across food, pharmaceutical, and cosmetic industries. The cultivation and industrial utilization of oil-producing peony varieties hold significant promise for advancing global agricultural diversification and for serving as a sustainable source of high-quality, functional vegetable oils. Nevertheless, several challenges remain, necessitating continued research to optimize agronomic practices, refine extraction and processing technologies, ensure safety and quality standards, and identify innovative uses. As a premium edible oil, PSO is well-positioned to contribute meaningfully to public health promotion and the development of environmentally sustainable food systems.

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