"The Multifaceted Role of Sesame (Sesamum indicum L.): From Nutritional and Phytochemical Insights to Industrial Innovations"

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DOI: https://doi.org/10.51244/IJRSI.2025.120700232

Received: 02 Aug 2025; Accepted: 10 Aug 2025; Published: 26 August 2025

ABSTRACT

Sesame (Sesamum indicum L.), a member of the Pedaliaceae family, is one of the earliest known oilseed crops utilized by humans. It is extensively cultivated and widely appreciated for its mild flavour and high nutritional content, making it a valued component of the human diet. Sesame seeds are rich in proteins and lipids and are associated with numerous health benefits. Various in vitro, in vivo, and clinical studies have demonstrated that sesame seeds contain lignan-like bioactive compounds with diverse pharmacological activities, including antioxidant, cholesterol-lowering, lipid-regulating, hepatoprotective, nephroprotective, cardioprotective, anti-inflammatory, and anti-tumour properties. These effects contribute significantly to human health. Moreover, aqueous extracts of sesame have been shown to be safe in animal studies. As a food with both nutritional and medicinal value, sesame is utilized across multiple sectors including food, animal feed, and cosmetics. The growing interest in functional foods has led to increased exploration of sesame's health-promoting applications. This review highlights recent advancements in research concerning the nutritional value, phytochemical composition, pharmacological properties, and industrial applications of sesame, with the aim of promoting its further development and utilization.

Keywords: sesame, nutritional value, phytochemical composition, bioactivity, food use, sesamin

INTRODUCTION

Sesame (Sesamum indicum L.), belonging to the family Pedaliaceae, is one of the earliest oilseed crops cultivated and consumed by humans. Alongside rapeseed, soybean, and peanuts, it is recognized as one of China's four major oil crops [1]. Archaeological evidence traces the origin of sesame back to ancient sites in present-day Pakistan, indicating its long history of domestication and use [2]. Today, sesame is widely distributed across countries such as India, China, and Malaysia. Historical records show that sesame has been used in China for over 5,000 years [1,3]. Globally, the leading producers of sesame include India, Sudan, Myanmar, China, and Tanzania. In recent years, sesame cultivation in African countries has grown significantly, with Tanzania surpassing India as the world's largest sesame producer. According to the Food and Agriculture Organization (FAO) of the United Nations, global sesame production in 2017 reached 5.899 million metric tons, with Tanzania contributing 806,000 tons and China producing 733,000 tons [4].

Sesame is widely cultivated and appreciated for its distinctive aromatic profile and mellow flavor. In daily life, sesame seeds are commonly used to prepare a variety of food products, including sesame oil, sesame paste (tahini), and as a garnish in culinary applications. The nutritional and medicinal value of sesame was officially recognized in 2002, when it was included in the list of medicinal and edible substances by the former Chinese Ministry of Health.

Despite the growing interest in sesame, comprehensive reviews remain limited. In recent years, only one detailed review has focused on the phytochemistry and ethnopharmacology of sesame [5]. Other existing literature tends to address specific aspects, such as particular chemical constituents [6], selected pharmacological activities [7], or the technical and agronomic aspects of sesame production [8]. In contrast, the present review aims to provide a broader and more integrated perspective by exploring not only the

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VII July 2025

phytochemical and pharmacological properties of sesame but also its nutritional significance, economic value, and potential for industrial application.

Sesame, belonging to the genus Sesamum in the family Pedaliaceae, exhibits considerable diversity in seed coat color, which serves as an important classification criterion. Based on germplasm coloration, sesame is generally categorized into white, black, and yellow varieties, with white and black sesame being the most commonly cultivated and widely distributed types (Figure 1). Black sesame is known for its vigorous growth, as well as its strong resistance to lodging and drought. In contrast, white sesame is prized for its higher oil content and superior quality, and it occupies the largest cultivation area globally. Yellow and other variegated varieties, which are less common, typically exhibit a more branched plant structure. Notably, a general trend has been observed in which oil content tends to decrease as the seed coat color darkens [9].

Morphology

Sesame (Sesamum indicum L.) is an erect annual herbaceous plant that typically grows to a height of 60–150 cm. The stem is either hollow or filled with white pith. Leaves are simple, measuring 3–10 cm in length and 2.5–4 cm in width, and are generally ovate or rectangular in shape with a slightly hairy (pubescent) surface. They are arranged singly or in groups of 2–3 within the leaf axils.

The calyx lobes are lanceolate, 5–8 mm long and 1.6–3.5 mm wide, and covered with fine hairs (pilose). The corolla is tubular, 2.5–3 cm long, and approximately 1–1.5 cm in diameter. It is usually white, often accompanied by a purplish-red or yellow halo. The four stamens are enclosed within the flower, and the ovary is superior, 4-loculed, and externally pilose. Flowering typically occurs in late summer to early autumn.

The fruit is a rectangular capsule, 2–3 cm long and 6–12 mm in diameter, characterized by longitudinal ribs and a hairy (pubescent) outer surface. The seeds are small and either black or white, commonly referred to as black sesame and white sesame, respectively [9,10,11]. The developmental stages and morphological variations of sesame seeds are illustrated in Figure

Fig-1 Sesame seeds of different colors. (**a**) Black sesame; (**b**) white sesame.

Cultivation

Fig-2 Sesamum indicum L

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ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VII July 2025

Sesame (Sesamum indicum L.) is a short-day, thermophilic crop primarily grown in subtropical regions. Its major areas of production include Central Asia and North Africa. Based on branching characteristics, sesame is broadly categorized into two main cultivation types. The **monopodial type** is generally unbranched, with short internodes, and bears two to three capsules per node. It has a hard stem, tends to mature late, and is well-suited for dense planting. In contrast, the **branched type** matures earlier, possesses long internodes, typically produces one capsule per node, and is not suitable for high-density cultivation [12,13].

In China, sesame cultivation extends as far north as 45° N latitude, with major production concentrated along the Yellow River Basin and the middle and lower reaches of the Yangtze River. As per recent statistics, the national sesame cultivation area covers approximately 790,000 hectares, yielding around 580,000 metric tons annually [14].

Due to its upright growth habit and minimal shading, sesame is frequently intercropped with shorter crops such as sweet potatoes, peanuts, and soybeans [15]. Its drought resistance complements the moisture tolerance of leguminous crops, making sesame–bean intercropping a viable method to manage both drought and waterlogging risks [16].

The oil content of sesame seeds varies significantly, ranging from 37% to 63%, depending on cultivar and environmental conditions [17]. Ecological factors such as precipitation, sunlight exposure, and temperature influence not only oil yield but also seed composition and morphology. These factors affect the seed's size, color, and quality parameters [18,19].

Karyotype

Sesame (Sesamum indicum L.) is a monoecious, diploid, and predominantly self-pollinated oilseed crop [20]. In 1961, Joshi classified 36 species within the genus Sesamum based on the Kewensis Index, identifying S. indicum as the only cultivated species. Cytogenetic studies revealed that cultivated S. indicum possesses three pairs of satellite chromosomes, and its karyotype typically falls under types 2A and 3A.

The first detailed cytological study was conducted by Morinaga et al., who reported the somatic chromosome number of cultivated sesame as 2n = 26, with chromosomes exhibiting relatively uniform size and morphology [21]. In China, cytogenetic research on sesame began in the 1980s, utilizing the traditional squash method for chromosome observation. These studies confirmed that four major cultivated varieties of sesame in China also possess a diploid chromosome number of 2n = 26. In contrast, a wild sesame species introduced from Zambia (Sesamum laciniatum Klein) was found to have a chromosome number of 2n = 32, indicating cytological diversity within the genus [22].

Nutritional Components

Sesame seeds are rich in fat, protein, minerals, vitamins, and dietary fiber. Sesame oil, which is obtained through traditional oil production methods, is rich in unsaturated fatty acids, fat-soluble vitamins, amino acids, etc. Studies have found that sesame seeds contain 21.9% protein and 61.7% fat, and are rich in minerals such as Fe and Ca [23]. Sesame seeds are rich in nutrients and have the reputation of being an “all-purpose nutrient bank” and the “crown of eight grains” [24]. The content of the main nutrients in sesame seeds is shown in Table 1. The nutrient fractions in sesame seeds are shown in Table 2.

Table 1.

Main nutritional constituents of sesame.

Component	Value	Min	Max
Protein (g/100 g)	17.6	17	18
Protein, crude, N × 6.25 (g/100 g)	20.8	3.2	21.3

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ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VII July 2025

Carbohydrate (g/100 g)	9.85		
Fat (g/100 g)	49.7		
Selenium (µg/100 g)	26.5	2.2	51.9
Starch (g/100 g)	4		
Sugars (g/100 g)	3	0.29	0.31
Fibers (g/100 g)	14.9	11.8	18
Ash (g/100 g)	4.48	4.45	4.5
Fatty acid saturated (g/100 g)	7.09	6.7	7.6
Fatty acid mono (g100 g)	18.8		18.9
Fatty acid poly (g/100 g)	21.8		21.9
Fatty acid 14:0 (g/100 g)	85	0.048	0.13
Fatty acid 16:0 (g/100 g)	4.22		4.59
Fatty acid 18:0 (g/100 g)	2.78	2.09	2.96
Fatty acid 18:1 *n*-9 cis (g/100 g)	18.7	18.6	
Fatty acid 18:3 9c, 12c, 15c (*n*-3) (g/100 g)	26	0.14	0.38
Calcium (mg/100 g)	962	714	1150
Copper (mg/100 g)	1.58	1.5	4.08
Iron (mg/100 g)	14.6		
Magnesium (mg/100 g)	324	318	351
Manganese (mg/100 g)	1.24	1.17	2.46
Potassium (mg/100 g)	468		
Phosphorus (mg/100 g)	605	453	694
Sodium (mg/100 g)	2.31	0.88	11
Zinc (mg/100 g)	5.74	5.3	7.75
β-Carotene (µg/100 g)	5		
Vitamin E (mg/100 g)	25		
Vitamin B1 or thiamin (mg/100 g)	79		

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Vitamin B2 or riboflavin (mg/100 g)	25		
Vitamin B3 or niacin (mg/100 g)	4.52		
Vitamin B5 or pantothenic acid (mg/100 g)	5		
Vitamin B6 (mg/100 g)	79		
Vitamin B9 or folate (µg/100 g)	97		

Source: https://ciqual.anses.fr/

Protein

Sesame protein is classified as a complete protein, with an essential amino acid profile closely matching the requirements of the human body [29]. It comprises several types of storage proteins, including globulins, albumins, prolamins (alcohol-soluble proteins), and glutelins, with **globulin** being the most abundant and **prolamin** the least [30,31].

Sesame meal, a by-product obtained after oil extraction, contains approximately 50% protein, making it a valuable protein source for both human consumption and animal feed. In vitro digestibility studies using pepsin-pancreatin enzyme systems have demonstrated that sesame protein isolate exhibits a high digestibility rate of 89.57% [32].

The high protein digestibility, along with its balanced amino acid composition, highlights the potential of sesame protein isolate as a functional ingredient for enriching food systems. This is especially relevant for developing countries, where protein-energy malnutrition remains a significant public health concern, particularly among children.

Recent studies have demonstrated that peptides derived from sesame not only serve as nutritional components essential for growth and development but also play critical roles in physiological regulation and overall health. In traditional Asian medicine and dietary practices, black sesame seeds are considered more beneficial to health compared to white sesame seeds, primarily due to their darker seed coat, which is associated with higher levels of certain bioactive compounds [33].

A genome-wide association study (GWAS) conducted by Cui et al. revealed that the protein content in sesame seeds tends to increase with the darkening of the seed coat, indicating that black sesame seeds generally contain more protein than their white counterparts [34]. Among the protein fractions reported in sesame seeds are albumin, globulin (α and β forms), prolamin, and glutelin, with these fractions commonly used in protein classification studies [17]. These protein types have been isolated and identified in various sesame cultivars and are summarized in Table 2.

In addition to its protein fractions, sesame is also a rich source of amino acids. Nineteen amino acids—including essential ones—have been identified from various parts of the sesame plant (roots, seeds, flowers, stems, and leaves). These include alanine, arginine, aspartic acid, cysteine, glutamic acid, glycine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, serine, threonine, tyrosine, valine, tryptophan, proline, and γ-aminobutyric acid (GABA) [25]. The essential amino acids isolated from sesame seeds are also detailed in Table 2.

Lipids

Lipids are a major nutritional component of sesame (*Sesamum indicum* L.), primarily concentrated in the seeds. Among major oilseed crops, sesame has the highest oil content—ranging from 45% to 57%—earning it the title “Queen of Oil” in ancient texts [35]. Sesame oil is especially valued for its lipid profile, which consists predominantly of unsaturated fatty acids (approximately 80%), with only a small proportion of saturated fatty acids [36].

Among the unsaturated fatty acids, linoleic acid (C18:2) and α-linolenic acid (C18:3) are essential fatty acids that cannot be synthesized by the human body and must be obtained through dietary intake. Linoleic acid plays a crucial role in cholesterol metabolism and supports vascular health by enhancing the elasticity of endothelial cells. In contrast, linolenic acid contributes to immune function by promoting B-cell differentiation and proliferation, thereby improving acquired immunity [37].

Sesame oil is particularly rich in oleic acid (C18:1) and linoleic acid (C18:2), with their combined concentration ranging from 26.60% to 54.85%. Other minor unsaturated fatty acids are present in concentrations ranging from 0.13% to 0.89%. The content of saturated fatty acids varies from 0% to 10.58%, making sesame oil an excellent source of essential fats [33].

Interestingly, a study by C. Li et al. revealed a strong negative correlation between oil content and protein content in sesame seeds. Using 112 polymorphic SSR markers, their research showed that both traits are significantly influenced by genotype and environmental conditions, such as year and location [38].

Additionally, several unique lipid compounds have been identified in sesame flowers, including latifonin, a newly reported lipid [26]. Sesame seeds have also been found to contain twelve major fatty acids, both saturated and unsaturated. These include oleic acid, linoleic acid, palmitic acid, stearic acid, arachidic acid, linolenic acid, palmitoleic acid, lignoceric acid, caproic acid, behenic acid, myristic acid, and margaric acid [9,27]. These are listed in Table 2.

Despite the numerous health benefits of sesame oil, caution should be exercised regarding excessive consumption. High levels of unsaturated fatty acids, particularly omega-3 fatty acids, while beneficial in moderate amounts, can lead to weight gain and gastrointestinal discomfort if consumed in excess. Overconsumption may also cause endocrine imbalances and increase the risk of hypotension and bleeding due to platelet inhibition [39–42]. Moreover, sesame seeds contain certain antinutritional factors, such as oxalic acid and phytic acid, which can interfere with the digestion and absorption of minerals and proteins and may increase the risk of kidney stone formation [43].

Carbohydrates

The sesame seed hull, a major by-product of oil extraction, consists predominantly of carbohydrate polymers, comprising approximately 70–80% of its dry weight. These include hemicelluloses, cellulose, and pectic polysaccharides, which contribute to its dietary fiber content and potential applications in food and feed industries [44]. In terms of simple and oligosaccharides, seven carbohydrates have been identified in sesame seeds: D-glucose, D-galactose, D-fructose, raffinose, stachyose, planteose, and sesamose [17]. These are detailed in Table 2, highlighting sesame's potential as a low-glycemic and fiber-rich food source.

Mineral Elements

Sesame seeds are a rich source of essential macro- and micro-minerals that play important roles in human nutrition. The mineral composition of sesame seeds includes:

- **Potassium (K):** 525.9 mg/100 g
- **Phosphorus (P):** 516 mg/100 g
- **Magnesium (Mg):** 349.9 mg/100 g
- **Sodium (Na):** 15.28 mg/100 g
- **Iron (Fe):** 11.39 mg/100 g

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VII July 2025

- **Zinc (Zn):** 8.87 mg/100 g
- **Manganese (Mn):** 3.46 mg/100 g [45]

These values underline sesame's role as a mineral-dense food, particularly important in vegetarian and plant-based diets where such nutrients can be limited.

Antinutrients

Antinutrients are naturally occurring compounds in plant-based foods that interfere with the absorption and utilization of nutrients, potentially affecting health and growth, particularly in animals and vulnerable populations [43]. The primary antinutritional factors in sesame seeds are oxalic acid, phytic acid, and small amounts of tannins [46].

Oxalic Acid:

Oxalic acid can bind with calcium to form calcium oxalate, an insoluble complex that limits calcium bioavailability. Farran et al. reported concentrations of 13% oxalic acid and 1.12% phytic acid in sesame hulls [46]. As a result, more than half of the calcium present in sesame may exist as calcium oxalate, which is poorly absorbed by the digestive system, particularly in monogastric animals [47].

Cooking methods (boiling, roasting), fermentation, and food pairing with calcium-rich ingredients can significantly reduce soluble oxalate levels and mitigate its negative effects. A balanced dietary calcium intake of 800–1000 mg/day is generally sufficient to counteract oxalate's impact on mineral absorption [43].

Phytic Acid (Phytate):

Phytic acid, or myo-inositol hexakisphosphate, is another key antinutrient. Structurally composed of an inositol ring bonded to six phosphate groups, phytate can strongly chelate divalent and trivalent mineral ions such as Ca^{2+}, Zn^{2+}, Fe^{3+}, and Cu^{2+} [48]. These phytate-mineral complexes are largely insoluble at neutral pH and indigestible by human enzymes, thereby hindering mineral bioavailability.

Additionally, phytate can bind with dietary proteins to form calcium–magnesium phytate–protein complexes, which are resistant to enzymatic breakdown, further reducing protein and mineral utilization [49].

Processing techniques such as soaking, fermentation, sprouting, germination, and cooking can substantially reduce phytate content, improving the nutritional quality of sesame products. In animal feed applications, the addition of the enzyme phytase has been shown to enhance the bioavailability of calcium, phosphorus, and zinc in sesame meal–based diets [43].

Phytochemistry

In addition to its nutritional richness, sesame (Sesamum indicum L.) is known for a diverse array of bioactive phytochemicals with notable functional and therapeutic properties. Key compounds include lignans such as sesamin, sesamolin, sesamol, sesaminol, and sesamolin phenol, among others [50]. These components contribute to sesame's antioxidant, antihypertensive, hepatoprotective, and lipid-regulating effects.

The phytochemical content of sesame varies significantly depending on multiple factors, including the extraction method and environmental growing conditions. For instance, hot-pressed sesame oil typically contains higher levels of sesamol, sesamin, and total lignans compared to cold-pressed or refined sesame oil [51]. Additionally, the strain/genotype, soil composition, climate, and agronomic practices (e.g., irrigation, fertilization, harvest timing) all influence the lignan content and overall phytochemical profile [52].

A wide range of phytochemicals has been identified across sesame seeds, oil, and other plant organs. These include:

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- **Lignans**
- **Polyphenols**
- **Phytosterols**
- **Phenols**
- **Aldehydes**
- **Anthraquinones**
- **Naphthoquinones**
- **Triterpenoids**
- **Other organic compounds**

Lignans

Lignans are the predominant and most bioactive phytochemicals in sesame. These compounds exhibit strong antioxidant properties and are chiefly responsible for the oxidative stability of sesame oil [53]. Epidemiological and experimental studies have linked sesame lignans to beneficial effects on lipid metabolism, hepatoprotection, and anti-inflammatory actions [6].

The primary sesame lignans include:

- **Sesamin** – accounts for approximately 50% of total lignans
- **Sesamolin**
- **Sesamol**
- **Sesaminol**
- **Sesamolin phenol**

On average, sesamin and sesamolin concentrations are approximately 2.48 mg/g (range: 1.11–9.41 mg/g) and 1.72 mg/g (range: 0.20–3.35 mg/g), respectively [6]. During the pressing process, these compounds can undergo thermal or oxidative degradation, forming sesamol, sesaminol, and sesamolin phenol, which also possess antioxidant activity [54].

Influence of Seed Color

There is a strong correlation between seed coat color and lignan content, with black sesame seeds exhibiting significantly higher concentrations of sesamin, sesamol, and total lignans compared to white varieties. The range of total lignan content (in mg/g) across seed colors is as follows [55]:

- **Black:** 3.56–12.76
- **Brown:** 2.66–6.68
- **Yellow:** 2.52–5.94
- **White:** 2.83–5.66

This variation underscores the importance of genotype and pigmentation in determining the functional composition of sesame seeds.

Identified Lignan Compounds

To date, **26 lignans** have been isolated and characterized from sesame seeds and aerial parts, including:

- **Sesamin**
- **Sesamolin**
- **Sesamol**
- **Sesaminol**
- **Sesamolin phenol**
- **(+)-Episesaminone**
- **(+)-Episesaminol 6-catechol**
- **(+)-Pinoresinol**
- **(−)-Pinoresinol 4-O-glucoside**
- **(+)-Pinoresinol di-O-β-D-glucopyranoside**
- **(+)-Sesaminol 2-O-β-D-glucoside**
- **(+)-Sesaminol diglucoside**
- **(+)-Sesaminol 2-O-β-D-glucosyl(1→2)-O-[β-D-glucosyl(1→6)]-β-D-glucoside**
- **(+)-Sesamolinol 4′-O-β-D-glucoside**
- **(+)-Sesamolinol 4′-O-β-D-glucosyl(1→6)-O-β-D-glucoside**
- **Matairesinol**
- **Samin**
- **Sesangolin**
- **Disaminyl ether**, among others [9,28]

Sesamin

Sesamin is the most abundant lignan present in sesame seeds and exhibits a broad spectrum of physiological and pharmacological activities. It possesses strong antioxidant properties and contributes to cholesterol reduction, lipid metabolism regulation, blood pressure stabilization, and anti-cancer effects [3].

In the human body, sesamin undergoes biotransformation primarily via cytochrome P-450 enzymes, resulting in metabolites that are predominantly glucuronidated or sulfate-conjugated forms. These metabolites are excreted through bile, urine, and feces, and the clearance of sesamin occurs mainly via metabolic degradation [56].

Sesamin content varies significantly depending on sesame variety, soil type, and local climatic conditions, typically ranging from 60.14 to 69.10 mg/100 g [57]. Additionally, during decolorization of unroasted, cold-pressed sesame oil using acidic white clay, sesamin can undergo isomerization to form its stereoisomer, episesamin, which is found at a concentration of approximately 0.28% [58].

Sesamolin

Sesamolin is the second most abundant lignan in sesame. Unlike sesamol, sesamolin lacks phenolic hydroxyl groups, which results in relatively weak antioxidant activity under normal physiological conditions. However, under thermal processing, sesamolin undergoes conversion to sesamol, thereby enhancing its functional antioxidant potential.

This thermal degradation characteristic makes sesamolin particularly valuable in food processing applications, as its presence can improve the oxidative stability of oils and fats during heating [5].

Sesamol

Although present in lower concentrations, sesamol is a key contributor to sesame oil's aroma, stability, and antimicrobial and antioxidant qualities. It is considered the primary flavor compound of sesame oil and plays a significant role in maintaining product shelf life.

Sesamol is photostable, making it suitable for storage under light-exposed conditions. Moreover, it exhibits compatibility with food-grade minerals such as Zn^{2+} and Mg^{2+}, but should not be used in combination with strong oxidizing agents [59].

Sesaminol

Sesaminol is a lipophilic lignan found in trace amounts in sesame seeds. Despite its low natural abundance, it has been identified as a potent antioxidant with good thermal stability. It is particularly important in thermally processed sesame products.

Sesaminol is formed through the acid-catalyzed conversion of sesamolin, a process that can be optimized in industrial applications to improve the bioactive profile of sesame-derived products [60].

Sesame Product Development

With rising global health awareness and improved living standards, the consumption and demand for sesame products have increased significantly. On the international market, major importers of sesame seeds include Japan, South Korea, Turkey, Egypt, the United States, and Israel.

In China, sesame plays a vital role in the culinary industry, especially in oil and paste production. The utilization breakdown of sesame seeds in China is as follows [61]:

- **45%** for **sesame oil** processing
- **22%** for **sesame paste** production
- **22%** for **peeled sesame** processing
- **5%** in **baked goods**
- **6%** for **miscellaneous applications**

This growing demand has encouraged innovation in the development of value-added sesame-based products, including functional foods, nutraceuticals, and cosmeceuticals. Selected studies and innovations in sesame applications are summarized in Table 3.

Food Applications of Sesame

Sesame is widely recognized for its culinary versatility and nutritional value, contributing to its prominent role in both traditional and modern food products. In China, sesame is extensively utilized in various forms, including sesame oil, paste, confections, and bakery products. This diverse utilization reflects its broad consumer appeal and cultural significance.

Sesame Oil

Sesame oil, a key product of sesame seed processing, is traditionally extracted through water substitution, pressing, or leaching, and more recently, through advanced methods such as supercritical CO_2 extraction, microwave-assisted, hydro-enzymatic, and alkaline extraction. The oil is characterized by its rich content of essential fatty acids, particularly linoleic acid (46.9%) and oleic acid (37.4%), as well as γ-tocopherol (90.5% of total vitamin E), lignans, and phytosterols [83, 84].

Compared to olive oil, sesame oil offers a comparable level of unsaturated fatty acids (74.59%) [74], with a distinctive aromatic profile aligning well with traditional Chinese dietary preferences. Furthermore, sesame oil demonstrates multiple bioactive properties, including anti-inflammatory, emollient, and wound-healing effects, making it valuable not only as a food product but also in functional and medicinal applications [85].

Sesame Meal

Sesame meal, a byproduct of oil extraction, serves as a nutrient-rich ingredient with high protein and dietary fiber content. It contains bioactive lignans, such as sesamin triglucoside and sesamin diglucoside, which contribute to its antioxidant capacity [86]. Its prebiotic fiber supports gastrointestinal health by promoting beneficial gut microbiota, enhancing immune function, and modulating appetite-related hormonal activity, which may contribute to weight regulation [87, 88].

Composite and Functional Sesame-Based Products

Recent developments in sesame processing emphasize its integration with other food matrices to create nutritionally enhanced composite products. Combinations of sesame with legumes, grains, nuts, fruits, and vegetables—such as yams, red dates, soybeans, and peanuts—have led to the creation of innovative beverages and functional food products [89].

The incorporation of sesame protein isolates into wheat-based bakery products has shown significant improvements in nutritional quality. For instance, muffins fortified with 15% sesame protein isolate demonstrated enhanced protein content and received favorable sensory evaluations [62]. These isolates, typically derived via aqueous extraction, also function as thickeners, binders, and emulsifiers in various food applications [32].

Furthermore, blending sesame oil with other oils—such as chia, palm stearin, or kiwi oil—has been shown to optimize the omega-3 to omega-6 ratio, enhance oxidative stability, and produce healthier fat-based products. Notably, blends can be formulated into trans-fat-free margarines and ghee alternatives suitable for baking and general culinary use [63–65].

Owing to the presence of lignans and phenolics, sesame oil exhibits a wide range of health-promoting effects, including cholesterol reduction, antioxidant activity, protection of vitamin E, support for liver function, and anti-aging properties. These attributes reinforce sesame's potential as a functional ingredient in health-focused foods [66, 67, 90].

Antioxidant Properties of Sesame

In culinary and food processing applications, the addition of antioxidants to cooking oils is crucial to retard oxidative degradation and extend shelf life. Refined sesame oil naturally possesses strong antioxidant activity, a

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VII July 2025

making it a desirable ingredient in the food industry. This antioxidant capacity is attributed to the thermal roasting process involved in oil production, which induces Maillard reactions between reducing sugars and amino acids. These reactions not only enhance the oil's aroma and flavor but also improve its antioxidant profile.

During roasting, the lignan sesamolin thermally decomposes and converts into sesamol, a potent antioxidant. Unroasted sesame oil contains relatively low levels of sesamol, but the roasting process causes a significant increase in its concentration, thereby improving the oxidative stability of the oil and its resistance to rancidity.

Furthermore, antioxidant components in sesame, such as sesamin and sesaminol, may undergo transformation under heat to enhance functional properties. These antioxidants are also utilized in stabilizing other oils. For example, extracts derived from the sesame seed coat can be added to sunflower oil to significantly improve its resistance to oxidation and prolong its shelf life [68].

Application in Traditional Chinese Medicine (TCM)

Sesame seeds have been revered in Traditional Chinese Medicine (TCM) for their therapeutic benefits since ancient times. As recorded in the *Shennong Ben Cao Jing*, sesame is recognized for its capacity to replenish energy, strengthen the five vital organs, stimulate muscle growth, and nourish bone marrow.

Black sesame, in particular, is traditionally believed to "tonify" the liver and kidneys, lubricate the intestines, and act as a gentle laxative. It has been used to address various ailments such as constipation, hemorrhoids, dysmenorrhea, amenorrhea, cough, and alopecia. Topical applications of sesame-based preparations have been used for pain relief, skin ulcers, and to promote lactation and urination. Additionally, sesame oil is widely used as a carrier or base for herbal preparations due to its excellent ability to penetrate the skin barrier and deliver active compounds transdermally [24].

Pharmaceutical Applications

Sesame seeds and sesame oil exhibit multiple pharmacological effects, particularly benefiting the liver, spleen, kidneys, and gastrointestinal system. Due to its high oil content and nutrient density, sesame oil acts both as an internal organ tonic and a natural laxative.

Topically, sesame oil supports wound healing and has been traditionally used to treat minor burns and sunburns due to its soothing, anti-inflammatory, and skin-regenerating properties. In pharmaceutical formulations, it serves as a solvent, carrier oil for lipophilic drugs, emollient, and even a natural sunscreen due to its UV-absorbing properties [50].

Recent clinical evidence also supports the analgesic effects of sesame oil when used in massage therapy. For instance, patients experiencing chemotherapy-induced phlebitis reported reduced pain severity after sesame oil massage [70]. Similarly, it has shown efficacy in managing acute limb pain caused by trauma [69].

Use in Animal Feed

Sesame meal, a by-product of oil extraction, contains over 45% crude protein and a rich spectrum of essential amino acids, positioning it as a valuable plant-based protein source in animal nutrition [92]. Despite its nutritional merits, raw sesame meal contains anti-nutritional factors such as oxalic acid and phytic acid, which can interfere with mineral absorption and animal growth. To address this, microbial fermentation is employed to reduce these compounds, improving digestibility and bioavailability [72].

Fermented sesame meal has been shown to partially or fully replace soybean meal in livestock diets. In broiler chickens, such substitution enhances nutrient uptake and improves growth performance [71]. In dairy production, feeding lactating ewes with sesame meal resulted in improved milk yield and reduced production costs without compromising quality. These findings support the use of sesame meal as a sustainable and cost-effective feed component in animal husbandry [73].

Application as Fertilizer

Sesame meal, the residual by-product after oil extraction, contains approximately 5.9% nitrogen, 3.3% phosphoric acid, and 1.5% potassium oxide, making it a nutrient-rich organic fertilizer. Its use has shown positive effects on crop quality and yield. When applied to crops like watermelon, strawberries, and grapes, fermented sesame meal significantly enhances fruit quality, including improvements in sugar content, vitamin C levels, and fiber composition.

In tobacco cultivation, sesame-based fertilizers have been found to enhance leaf quality and increase production value. Additionally, its application improves soil microbial activity, as it promotes the proliferation of bacteria, actinomycetes, and fungi, while also increasing organic matter content in the soil, thereby enriching soil fertility and structure [74].

Potential Use as Fuel

Historically, sesame stalks were utilized as traditional fuel sources. In modern applications, alternative fuels are being developed by combining waste cooking oil derived from sesame with sesame flour, which not only minimizes environmental waste but also contributes to food safety and energy sustainability [94].

Due to increasing global energy demands and depletion of fossil fuel resources, there is a growing interest in renewable alternatives. Sesame oil has shown potential as a biodiesel feedstock. Through transesterification with methanol in the presence of NaOH, biodiesel yields up to 92% have been achieved at 60 °C [76]. Studies indicate that sesame biodiesel and its blends perform comparably to mineral diesel in terms of fuel consumption, thermal efficiency, and engine output. Nonetheless, the feasibility of sesame biodiesel depends on its technical viability, economic competitiveness, environmental acceptability, and availability [96].

Cosmetic Applications

The U.S. Food and Drug Administration (FDA) approved sesame oil for cosmetic use as early as 1987. In Japan, sesame oil is used in pharmaceutical ointments, injectable diluents, and a wide range of cosmetic products including lipsticks, eye shadow creams, and moisturizers [24].

Advances in sesame research have led to the extraction of fragrances from sesame flowers and stems, which are used in perfume manufacturing. Moreover, myristic acid, a component of sesame seeds, is commonly incorporated as an ingredient in cosmetic formulations due to its emollient and cleansing properties [79].

Use as Insecticide

Sesamin, a prominent sesame lignan, exhibits both insecticidal and fungicidal properties. It has been used as a synergist in pyrethroid insecticides to enhance efficacy [78]. Sesame oil has also been applied as a preventive treatment for lice infestations in children and is used in wood protection formulations to deter termite damage in forestry and agricultural fields [77].

Environmental Protection

Sesame oil cake can be converted into activated carbon using thermal, sulfuric acid, or zinc chloride methods. This bio-derived activated carbon has demonstrated the ability to remove hexavalent chromium from chromium plating wastewater, offering an effective, eco-friendly approach to industrial wastewater treatment and environmental remediation [80].

Applications in Biotechnology

In the field of biotechnology, genetic engineering using sesame-derived genes has shown promising results. In one experiment, diacylglycerol acyltransferase (SiDGAT1) from sesame was introduced into the Dongnong 47 soybean variety using Agrobacterium-mediated transformation.

The transgenic soybean lines showed a more than 1% increase in seed oil content, confirming the role of SiDGAT1 in enhancing lipid accumulation. However, this modification also led to a reduction in protein and soluble sugar content, indicating a metabolic trade-off. These findings demonstrate that sesame genes can be strategically engineered to enhance the oil yield and nutritional value of other crops [81].

Other Industrial Applications

Sesame has a diverse range of **non-food applications**:

- **Hot-pressed sesame oil** is utilized in the production of **copy paper**.
- The **fumes from burnt sesame oil** are used to manufacture **high-quality ink**.
- In the industrial sector, sesame oil derivatives are employed to make **lubricating soaps** [97].

Furthermore, defatted sesame powder can serve as a natural stabilizer in oil-in-water emulsions, particularly in soybean oil systems. It helps reduce droplet size, enhances emulsion stability, and facilitates the formation of gel-like textures with improved resistance to agglomeration. Incorporating 3.0% defatted sesame powder has been shown to significantly improve the structural integrity and oil retention of emulsified products [82].

Pharmacological Effects of Sesame and Its Bioactive Compounds

Antioxidant Activity

Oxidative stress, caused by the excessive production of reactive oxygen species (ROS), disrupts the redox balance in the body. Sesamin, a major lignan in sesame, has demonstrated potent antioxidant properties. Ruankham et al. [102] showed that sesamin reduced ROS levels in H_2O_2-exposed human neuroblastoma cells and enhanced antioxidant enzyme activities such as catalase (CAT) and superoxide dismutase (SOD). It also restored the levels of SIRT1 and SIRT3, which are vital in oxidative stress regulation via the SIRT1–SIRT3–FoxO3a signaling pathway. Additionally, sesamin reversed H_2O_2-induced apoptosis by downregulating BAX and upregulating BCL-2.

Similarly, Fan et al. [103] reported that sesamin normalized SIRT3 and SOD levels in aortic-constricted mice and alleviated cardiac remodeling by reducing oxidative stress, suggesting its cardioprotective potential.

Lipid and Cholesterol Regulation

Sesamin has been found to exert lipid-lowering effects by modulating lipid metabolism and cholesterol transport pathways. Liang et al. [104] demonstrated that sesamin downregulated key genes involved in cholesterol absorption, including NPC1L1, ACAT2, and MTP. It also suppressed HMG-CoA reductase (HMGCR) expression while enhancing CYP7A1 expression, which is involved in bile acid synthesis. These changes contribute to reduced cholesterol synthesis and increased fecal cholesterol excretion.

Furthermore, sesamin positively influences reverse cholesterol transport (RCT) by upregulating sterol transporters such as ABCA1 and ABCG1 through the activation of PPARγ, LXRα, and MAPK signaling pathways [119]. As a result, it can decrease LDL, VLDL, and triglycerides, while increasing HDL, offering protective benefits against atherosclerosis.

Hepatorenal Protection

Sesamin exhibits significant liver and kidney protective effects. In liver fibrosis models, it reduced elevated levels of ALT, AST, and total bilirubin, while enhancing antioxidant enzyme activity (SOD, GSH-Px) and suppressing inflammatory markers like IL-6 and COX-2 [100]. Guo et al. [101] also found that sesamin mitigated adriamycin-induced hepatotoxicity and nephrotoxicity by reducing oxidative stress markers (MDA, 4-HNE) and boosting antioxidant defense.

Rousta et al. [105] observed that sesamin alleviated LPS-induced acute kidney injury by decreasing serum urea nitrogen and creatinine, normalizing NF-κB, TLR4, TNF-α, and IL-6 expression, and reducing oxidative stress and DNA damage. Additionally, Cao et al. [106] reported that sesamin protected carp kidneys from fluoride-induced damage by inhibiting ROS production and downregulating the JNK signaling pathway.

Anti-Inflammatory Activity

Sesamin possesses potent anti-inflammatory properties. Khansai et al. [109] demonstrated that sesamin suppressed TNF-α-induced expression of IL-1 and IL-6 in human synovial fibroblasts, indicating potential benefits in conditions such as rheumatoid arthritis [108]. Moreover, sesamin metabolites—especially catechol glucuronides—have shown enhanced anti-inflammatory activity in macrophage-like cells by inhibiting interferon-β and iNOS expression [110]. One such metabolite, SC1, exhibited stronger anti-inflammatory action than sesamin itself.

Hypoglycemic Effects

Sesame oil and sesamin have shown promising hypoglycemic effects. In diabetic rats, dietary intake of 12% white sesame oil significantly reduced fasting blood glucose from 248.4 ± 2.8 mg/dL to 202.1 ± 1.0 mg/dL over 60 days, along with improved insulin sensitivity and decreased liver stress biomarkers [111].

Furthermore, Devarajan et al. [112] conducted an 8-week clinical trial where sesame oil, either alone or combined with glibenclamide, significantly lowered fasting/postprandial glucose, HbA1c, and lipid markers while increasing HDL levels in type 2 diabetic patients. These findings support the role of sesame oil in managing hyperglycemia and improving lipid profiles.

Cardiovascular Protection

Hypertension is a major risk factor for cardiovascular disease, with over 1.5 billion individuals projected to be affected by 2025. Diets rich in polyunsaturated fatty acids and vitamin E are known to mitigate hypertension and cardiovascular risk. Sesame seeds, being abundant in polyunsaturated fatty acids, lignans, phytosterols, and vitamin E, contribute positively to cardiovascular health [113,120].

A clinical trial by Helli et al. [114] revealed that sesamin supplementation in patients with rheumatoid arthritis significantly decreased serum malondialdehyde (MDA) levels while increasing total antioxidant capacity (TAC). Additionally, reductions in body weight, BMI, and systolic blood pressure were observed, suggesting cardiovascular benefits of sesamin.

Khosravi-Boroujeni et al. [121] also reported a reduction in blood pressure with sesame seed consumption, though the extent of the effect requires further investigation. Li et al. [122] demonstrated that sesamin supplementation in spontaneously hypertensive rats significantly reduced heart and left ventricular weights, cardiomyocyte size, and cardiac hypertrophy ratios. It also improved cardiac tissue integrity, reduced mitochondrial damage, suppressed blood pressure elevation, and inhibited oxidative and fibrotic markers such as MDA, nitrotyrosine, and TGF-β1.

Furthermore, Thuy et al. [115] found that oral administration of sesamin for four weeks improved cardiovascular parameters, including heart rate, blood pressure, and QT interval in a streptozotocin-induced diabetic model. Collectively, these findings highlight the cardioprotective potential of sesamin.

Antitumor Effects

Sesamin exhibits notable anticancer activities, including anti-proliferative, pro-apoptotic, anti-inflammatory, anti-metastatic, anti-angiogenic, and autophagy-promoting effects. While the complete molecular mechanisms remain under investigation, key signaling pathways such as STAT3, JNK, ERK1/2, p38 MAPK, PI3K/AKT, caspase-3, and p53 have been implicated in mediating its anticancer action [3].

Cavuturu et al. [123] demonstrated that sesamin inhibits the β-catenin/Tcf4 complex formation, thereby blocking the Wnt signaling pathway associated with colon cancer development. These findings position sesamin as a promising candidate for cancer prevention and treatment.

Other Health Benefits

Bone Health

Sesamin has been shown to inhibit osteoclastogenesis. Wanachewin et al. [116] investigated its effects on osteoblast differentiation and function. Treatment with sesamin significantly reduced TRAP-stained osteoclasts and suppressed osteoclast-associated gene expressions like Cathepsin K (CathK), TRAP, and DC-STAMP. Though NFATc1 expression remained unaffected, sesamin effectively inhibited precursor cell recruitment, F-actin ring formation, and bone resorption activity—indicating its potential to prevent bone degradation.

Hearing Protection

Sesamin and sesame oil have demonstrated protective effects against hearing loss. In zebrafish models, treatment with sesame oil promoted auditory cell proliferation and increased kinocilia density, with enhanced regeneration observed in sensory neurons [117]. Upregulation of hearing-related genes, particularly *Tecta*, was also noted. Furthermore, in a murine model of noise-induced hearing loss (NIHL), sesame oil administration reduced auditory threshold shifts, highlighting its potential to prevent or reverse hearing impairment.

Safety and Toxicity Evaluation

As the use of nutritional supplements grows—especially in aging populations—understanding the safety of food-derived compounds like sesamin is crucial. Since food-drug interactions can alter therapeutic efficacy, evaluating sesamin's interaction with common medications is essential.

Sakaki et al. [124] conducted in vivo studies in rats and found no significant differences in diclofenac pharmacokinetics (C_max, T_max, AUC) between control and sesamin-treated groups. This suggests sesamin does not significantly interfere with drug metabolism at standard doses.

Additionally, acute toxicity studies confirm sesame oil's safety. Oral administration of sesame oil at doses up to 3.0 g/kg in mice showed no signs of toxicity or mortality after 48 hours [125]. Similarly, ethanolic extracts of sesame seeds administered to rats at doses between 50–2000 mg/kg produced no adverse effects or behavioral changes even after 7 days [126]. Typical toxicity signs such as convulsions, diarrhea, or motor impairment were absent. These findings support the safety of sesame and its bioactive compounds for human consumption within recommended doses.

Gaps, Challenges, and Future Perspectives

Despite extensive research on the nutritional, phytochemical, and pharmacological properties of sesame, several important gaps and challenges remain. Firstly, the majority of pharmacological evidence is derived from in vitro or animal studies, with relatively few well-designed, large-scale randomized clinical trials in humans. This limits the strength of conclusions about efficacy and safety in real-world populations. Secondly, sesamin and other lignans often exhibit low bioavailability due to poor water solubility and rapid metabolism. Although strategies such as nanoencapsulation, lipid-based carriers, and co-administration with absorption enhancers have been proposed, their effectiveness in humans remains insufficiently validated. Thirdly, while sesame seeds and oil are generally considered safe at dietary levels, there is limited long-term safety data for high-dose or concentrated lignan supplements. Potential side effects, allergenicity, and interactions with medications (especially anticoagulants and antihypertensives) require further evaluation. Additionally, inconsistencies in analytical methods, variations in sesame varieties, and differences in processing techniques contribute to variability in reported lignan and nutrient contents, complicating cross-study comparisons.

Addressing these gaps will require standardized methodologies, interdisciplinary collaboration, and translation of promising laboratory findings into robust human trials.

CONCLUSIONS

Sesame (*Sesamum indicum* L.), one of the oldest cultivated oilseed crops, is a highly versatile plant with exceptional nutritional and economic value. Beyond oil extraction, sesame seeds are processed into a variety of products such as sesame paste, sesame milk, and other functional foods. With ongoing scientific research, more bioactive compounds are being identified and utilized, driving innovation and growth in the sesame processing industry. This has sparked increasing interest in sesame as a nutritionally rich and economically valuable crop. To date, more than 180 phytochemical constituents have been isolated and identified from sesame seeds, seed oils, and other plant organs. These include lignans, polyphenols, phytosterols, phenols, anthraquinones, cerebrosides, fatty acids, vitamins, proteins, essential amino acids, and sugars. Studies consistently show that sesame seeds and oils contain a higher concentration of these phytochemicals and exhibit superior nutritional value compared to other parts of the plant. Compounds such as sesamin and sesamol have demonstrated a broad spectrum of pharmacological activities, including anti-inflammatory, antioxidant, anti-cancer, anti-melanogenic, cholesterol-lowering, anti-aging, and organ-protective effects, especially for the heart, liver, and kidneys. Despite these promising attributes, research on sesame genetics, genetic variation improvement, and root system development remains limited. Further genetic and agronomic studies are essential to enhance sesame yield, quality, and resilience. Moreover, the pharmacokinetics, drug conformation, and bioavailability of sesame-derived bioactive compounds are still underexplored. Many experimental studies lack essential pharmacological controls, including appropriate dosing regimens, time-course evaluations, and reference standards. These gaps hinder reproducibility and long-term application. Therefore, more robust, well-designed studies are needed to elucidate the pharmacological mechanisms and clinical potential of sesame compounds.

Sesame's resilience to drought and its suitability for intercropping make it a promising crop, especially in arid and semi-arid regions. In areas such as sub-Saharan Africa, expanding sesame cultivation can contribute to food security, create employment, and boost local economies. With the advancement of agricultural and processing technologies, the global production scale of sesame is expected to grow significantly, unlocking even greater economic and health benefits.

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