Hindawi
Journal of Chemistry
Volume 2023, Article ID 5394315, 18 pages
https://doi.org/10.1155/2023/5394315

Review Article

Effects of Dehulling and Roasting on the Phytochemical Composition and Biological Activities of *Sesamum indicum* L. Seeds

Laila El Hanafi,[1] Ibrahim Mssillou ,[2] Houria Nekhla,[1] Aymane Bessi,[1] Meryem Bakour ,[3] Hassan Laaroussi,[2] Zineb Ben Khadda,[4] Chaimae Slimani,[1] John P. Giesy ,[5,6,7,8] Hassane Greche,[9] Gomaa A. M. Ali ,[10] and Mourad A. M. Aboul-Soud [11]

[1]*Laboratory of Functional Ecology and Genie of Environment, Faculty of Sciences and Technology, Sidi Mohamed Ben Abdellah University, Fez 30000, Morocco*
[2]*Laboratory of Natural Substances, Pharmacology, Environment, Modeling, Health and Quality of Life (SNAMOPEQ), Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez 30000, Morocco*
[3]*The Higher Institute of Nursing Professions and Health Techniques (ISPITS), Fez 30000, Morocco*
[4]*Laboratory of Epidemiology and Research in Health Sciences, Faculty of Medicine and Pharmacy, Sidi Mohammed Ben Abdellah University, Fez 30050, Morocco*
[5]*Toxicology Centre, University of Saskatchewan, Saskatoon, SK S7N 5B3, Canada*
[6]*Department of Veterinary Biomedical Sciences, University of Saskatchewan, Saskatoon, SK S7N 5B4, Canada*
[7]*Department of Integrative Biology, Michigan State University, East Lansing, MI 48824, USA*
[8]*Department of Environmental Sciences, Baylor University, Waco, TX 76706, USA*
[9]*Applied Organic Chemistry Laboratory, Faculty of Science and Technology of Fez, Sidi Mohamed Ben Abdellah University, Fez, Morocco*
[10]*Chemistry Department, Faculty of Science, Al-Azhar University, 71524 Assiut, Egypt*
[11]*Department of Clinical Laboratory Sciences, College of Applied Medical Sciences, King Saud University, P.O. Box 10219, Riyadh 11433, Saudi Arabia*

Correspondence should be addressed to Mourad A. M. Aboul-Soud; maboulsoud@ksu.edu.sa

Received 16 March 2023; Revised 3 June 2023; Accepted 6 June 2023; Published 13 June 2023

Academic Editor: Mahmood Ahmed

Recently, processed foods have become an important part of human eating habits. However, several processing techniques, such as dehulling and roasting, are applied to raw foods. Roasting is a thermal process that depends on temperature and time and improves the extraction yield of oil by generating pores in the oilseed cell walls. Sesame (*Sesamum indicum* L.) is an annual plant belonging to Pedaliaceae and is considered to be one of the oldest oil crops. Nowadays, the cultivation of this plant is economically important in several countries. This review clarifies the botanical characteristics and nutritional importance of sesame seeds, reviews their phytochemical composition, and discusses the effects of dehulling and roasting on their nutritional quality. *S. indicum*, which is known to contain several classes of bioactive compounds, including fatty acids, phenolic compounds, amino acids, and lignans, has been reported to possess a wide range of biological activities such as antioxidant, anti-inflammatory, anticancer, antimicrobial, and cardioprotective activity; however, processing such as dehulling eliminates undesirable chemical constituents while roasting provides the best chemical composition at moderate temperatures.

1. Introduction

Recently, the basics of human nutrition have changed significantly. Traditional foods have been replaced by processed products [1]. Evaluation of the impacts of various industrial processes on the composition of foods is of major interest. Among these processes, roasting plays an important role in the development of some sensory characteristics appreciated by consumers. However, the nutritional qualities of foods can also be affected by roasting [2, 3].

Sesame seed (*Sesamum indicum* L.) is one of the oldest oilseed crops, belonging to the Pedaliaceae family [4] and is used as a food item dating back to 5500 BC. While Africa contains a significant number of primitive species [5], results of recent cytological, genetic, and biochemical studies [6] have demonstrated that sesame was first domesticated in India, then transported to Africa, Asia, and the south of the Mediterranean basin.

S. indicum is a plant of nutritional significance. Its seeds are an intrinsic part of diets in several countries around the world. According to the latest statistics available on the database of the Food and Agriculture Organization of the United Nations [7], the cultivated area on an international scale exceeds 2.25 million hectares, with 3.7 million tons produced annually. Asian countries are the largest producers in the world; China, India, and Myanmar are major producing countries with respective rates of 0.7, 0.6, and 0.5 million tons, while Sudan, Uganda, and Nigeria are the largest producers in Africa [7].

The nutritional richness of *S. indicum* seeds makes them one of the most widely consumed oil seeds in the world, which opens up many possibilities for their use in the food industry [8]. Furthermore, in many countries, dehulled sesame seeds are used in the manufacture of several food preparations, such as "Tahini," which is a paste obtained after dehulling, roasting, and grinding sesame seeds [9]. Oil, extracted from sesame seeds, contains saturated fatty acids, unsaturated fatty acids, proteins, and other minor nutrients, such as vitamins and minerals, especially iron, magnesium, copper, and calcium. Moreover, sesame seed oil contains some important organic molecules, such as sesamin, sesamol, sesamolin, and tocopherols [10–12].

Roasting is a technique used in food processing to improve the digestibility and sensory appeal of food materials. This technique depends on heating (90–260°C) to cook, gelatinize, and expand/pop/puff the product evenly and transform it into a more pleasant, appetizing, and attractive form [13, 14]. During roasting, heat promotes the generation of pores in the walls of oilseed cells, which improves the yield of oil. It also helps to increase the total polyphenol content of the oil [15]. Many studies have been conducted to determine how roasting affects the quality and stability of various foods. Based on the results of previous studies, roasting initiates a series of metabolic processes [16] that result in a variety of chemicals that can have both positive and negative consequences for food products [17, 18]. Therefore, a thorough understanding of the roasting process and how it affects foods is necessary for planning particular roasting operations.

Dehulling consists of removing the seed coats [19]. This process can affect the physical properties, chemical composition, and techno-functional properties of the seeds [20]. Dehulling generally decreases undesirable factors mainly present in the seed coat [21].

Before this article, there had not been a comprehensive evaluation of roasting and the resulting changes in oilseeds, especially sesame, which requires a methodical and thorough endeavor to synthesize various studies and establish reliable conclusions. However, this review aims to clarify the chemical composition of *S. indicum* and its biological potential, and discuss the influence of roasting and dehulling processes on the nutritional quality of the transformed seeds.

2. Botanical and Morphological Aspects of *S. indicum*

S. indicum is an annual plant, a unique food, and a very old cultivated crop belonging to the genus *Sesamum*, which comprises approximately 20 species [22]. Several countries depend on the cultivation of this plant, such as India, Sudan, China, and Burma. These countries are mainly the major producers of *S. indicum* with a global production dominance exceeding 60%. This species is also cultivated in other countries such as Egypt, Thailand, Afghanistan, Pakistan, Bangladesh, Sri Lanka, Turkey, and all over Africa and South America [23, 24]. Several synonyms of *S. indicum* have been reported in the literature such as *Sesamum africanum* Tod., *Sesamum occidentalis* Heer and Regel., *Sesamum orientale* L., *Sesamum oleiferum* Sm., *Dysosmon amoenum* Raf., *Volkameria orientalis* (L.) Kuntze [25].

As mentioned in Figure 1, sesame plants are characterized by a height of 0.5–2 m and a well-developed root. *S. indicum* has a multiflower system and a fruit capsule where the seeds are covered and characterized by a branched and longitudinally furrowed stem [25, 26]. Flowers of this species are large and white, with bilateral symmetry (zygomorphic). Generally, the flowers are tubular in shape, have a short pedicel, and are presented in groups of two or three flowers or individual forms axillary to the leaves [27]. Seeds of this plant are small about 1–2 mm in width and 2–4 mm in length, smooth, reticulate, flat-oval, and have a large variety of colors, including shades of brown, brick red, black, yellow, beige, gray, and white, depending on the cultivar [28, 29].

3. Phytochemical Composition and Biological Activities of *S. indicum* Seeds

S. indicum is known for its health-promoting properties, and the results of several studies have demonstrated that polyphenolic compounds and lignans found in sesame oil are responsible for its therapeutic efficacy [30].

3.1. Phytochemical Composition. The chemical composition of *S. indicum* seeds depends on the horticultural variety, the environment in which it is grown, and cultural practices. However, the oil fraction, mainly distributed in the internal

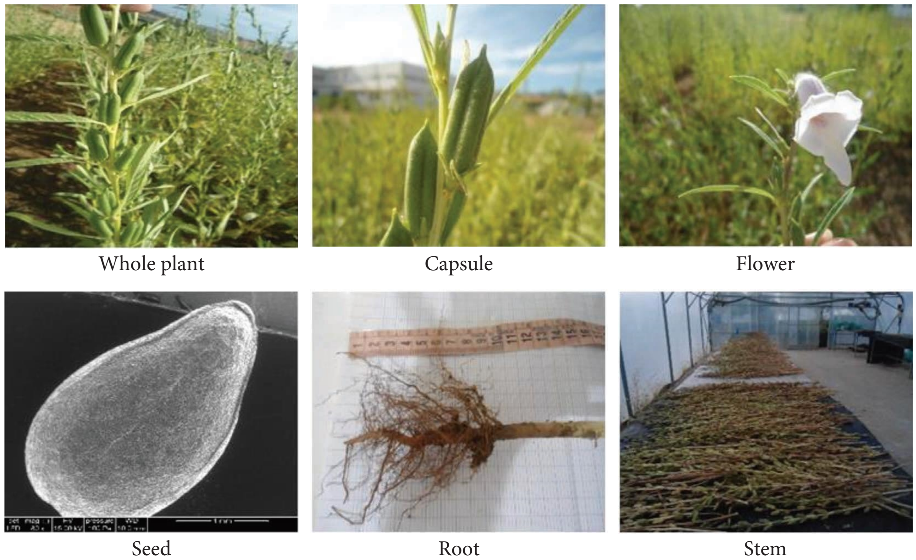

Figure 1: *S. indicum* and its various parts.

layers of the endosperm, represents a significant proportion of the mass of the fruit, ranging from 37 to 63% of the total mass [31].

Fatty acids are organic compounds with a common RCOOH structure, composed of a methyl end, a hydrocarbon chain (R), and a carboxylic terminus [32]. The oils contain a predominance of unsaturated fatty acids (80%), especially oleic acid and linoleic acid [29]. Other saturated fatty acids such as palmitic, stearic, arachidic, and lignoceric acids have been observed in sesame seed oil [29]. The content of fatty acids in sesame seeds has been reported previously for samples from various regions, such as Ethiopia-Volega, Ethiopia-Humera Afghanistan, Burkina Faso, India, Mozambique, Uganda, Ethiopia Niger-Benje, Niger-Wadaguri, and Niger-Kany, the results obtained revealed that myristic acid was 0.02% in all studied samples, palmitic acid (7.93–9.55%), palmitoleic acid (0.11–0.14%), margaric acid (0.04–0.07%), stearic acid (5.10–6.20%), elaidic acid (0.05–0.07%), oleic acid (35.88–44.54%), linoleic acid (37.41–47.44%), linolenic acid (0.30–0.42%), arachidic acid (0.57–0.68%), gondoic acid (0.18–0.21%), behenic acid (0.14–0.18%), clupanodonic acid (0.03–0.17%), and lignoceric acid (0.01–0.10%) [33]. Similarly, other varieties of sesame in several countries such as India, Morocco, and Ethiopia revealed the richness of this plant in saturated and unsaturated fatty acids with the predominance of oleic acid (17.06–41.9%) and linoleic acid (19.38–44.31%) [34–36].

Sesame oil is known for its resistance to auto-oxidation. In fact, its stability is facilitated by the presence of tocopherols (vitamin E) [37], which protect the phospholipids of the cell membrane by eliminating free radicals [38].

Amino acids are the basic units of proteins. They bind together by covalent bonds named "peptide bonds." They are involved in many biological processes such as the participation in the reception and transmission of cellular signals and the regulation of genetic expression [39]. Sesame seeds contain between 17 and 32% protein. Globulin is a primary constituent comprising 67.3% of the total protein content [40]. Glutamic acid (3.28–23.61 g/100 g), arginine (2.36–20.25 g/100 g), aspartic acid (1.62–9.54 g/100 g), and leucine (1.30–9.04 g/100 g) are the most abundant amino acids present in sesame. These findings were confirmed in many studies conducted in several countries around the world (Table 1) [33, 44, 45].

Sesame seeds contain 14 to 25% carbohydrates, which are mostly reducing sugars and also the dietary fibers found in the outer layers (envelopes) where hemicellulose (type A and type B) is present at a rate between 0.58% and 2.59% [29].

Phenolic compounds are secondary metabolites known for their bioactive potential and protective role against abiotic aggressions. They include several classes and subclasses depending on their chemical structure. Polyphenols and lignans are the main compounds in sesame seeds (Table 1). Flavonoids are polyphenols that are often located in epidermal cells [51]. Contrary to tannins, which are often bound to other compounds such as polysaccharides and proteins [52], phenolic compounds such as gallic acid, chlorogenic acid, caffeic acid, *p*-coumaric acid, and quercetin are widely found in sesame seeds [41, 43]. In addition, 16 types of lignans were identified in sesame seeds, with a predominance of soluble aglycones in the oil fraction, of which sesamin and sesamolin are the main compounds (Figure 2) [53]. According to bibliographic research, the chemical composition changes according to geological factors (Table 1). In the Indian variety, sesamin ranged from 2.10 to 18.6 mg/g while sesamolin ranged from 1.52 to 10.6 mg/g [34, 47]. The sesame from Egypt showed a content of 13.3 mg/g in sesamin and 2 mg/g in sesamolin [46]. Sesame from Korea and Japan contain an amount of sesamin ranging from 0.185 to 8.205 mg/g and from 0.83 to 2.52 mg/g, respectively, while for sesamolin the concentrations ranged from 0.203 to 6.809 mg/g and from 0.07 to 0.82 mg/g, respectively [48,49]. In Iran, the content of sesame seeds in

Table 1: Phytochemical composition of *S. indicum* in geographical areas around the world.

Phytochemical compositions	Countries	Components	Quantities	References
Phenolic compounds	Iran	Gallic acid	0.90–1.02 mg/100 g	[41]
		Protocatechuic acid	8.17–9.14 mg/100 g	
		p-Coumaric acid	3.08–4.74 mg/100 g	
		4-Hydroxybenzoic acid	5.32–7.11 mg/100 g	
		Chlorogenic acid	4.43–5.59 mg/100 g	
		Ferulic acid	12.41–15.02 mg/100 g	
		Caffeic acid	1.03–1.56 mg/100 g	
		Catechin	0.11–0.17 mg/100 g	
		Rosmarinic acid	3.32–4.37 mg/100 g	
		Quercetin	7.12–9.47 mg/100 g	
	México	Gallic acid	73.6 ± 1.3 mg/kg	[42]
		Protocatechuic acid	901.4 ± 16.6 mg/kg	
		Ferulic acid derivative	265.5 ± 1.4 mg/kg	
		p-Coumaric acid	433.9 ± 5.1 mg/kg	
		Ferulic acid	1944.4 ± 44.0 mg/kg	
	China	2-(4-Hydroxyphenyl) ethanol	2.00 μg/kg	[43]
		Cinnamic acid	0.36 μg/kg	
		3,4-Dihydroxybenzoic acid	0.90 μg/kg	
		p-Coumaric acid	0.06 μg/kg	
		2-Hydroxycinnamic acid	0.06 μg/kg	
		Vanillic acid	0.21 μg/kg	
		Gallic acid	6.55 μg/kg	
		Caffeic acid	0.48 μg/kg	
		Ferulic acid	0.06 μg/kg	
		Syringic acid	0.48 μg/kg	
		Sinapic alcohol	0.40 μg/kg	
		Sinapic acid	0.50 μg/kg	
		trans-resveratrol	0.06 μg/kg	
		Apigenin	0.20 μg/kg	
		Luteolin	0.50 μg/kg	
		Catechin	0.25 μg/kg	
		Epicatechin	0.48 μg/kg	
		Quercetin	0.12 μg/kg	
		Daidzein	0.09 μg/kg	
		Genistein	0.09 μg/kg	
		Daidzin	0.03 μg/kg	
		Genistin	0.06) μg/kg	
		Sesamin	43.00 μg/kg	

Table 1: Continued.

Phytochemical compositions	Countries	Components	Quantities	References
Fatty acids	Ethiopia	Hexadecanoic acid	12.13–14.57%	[36]
		Methyl hexadec-9-enoate	12.86–15.44%	
		Heptadecanoic acid	13.62–16.35%	
		Methyl stearate	15.88–19.08%	
		Oleic acid	17.06–20.49%	
		Linoleic acid	19.38–23.27%	
	Morocco	Myristic acid	0.1 ± 0.01%	[35]
		Palmitic acid	11.3 ± 0.1%	
		Stearic acid	4.9 ± 0.1%	
		Oleic acid	41.9 ± 0.1%	
		Linoleic acid	42.1 ± 0.1%	
		Linolenic acid	0.2 ± 0.01%	
	India	Palmitate	8.94–11.02%	[34]
		Stearate	4.05–5.89%	
		Arachidate	0.34–0.91%	
		Oleate	34.71–45.61%	
		Linoleate	38.49-49.60%	
		Linolinate	0.22–0.46%	
		Gadoleate	0.06–0.40%	
	Ethiopia	Palmitoleic acid	0.08–0.117%	[34]
		Palmitic acid	9.345–11.18%	
		Margaric acid	0.027–0.036%	
		Linoleic acid	42.5–44.31%	
		Oleic acid	37.19–38.95%	
		Cis-vaccenic acid	0.778–0.957%	
		Stearic acid	5.78–6.523%	
		Arachidic acid	0.588–0.634%	
		Behenic acid	0.083–0.094%	
	Afghanistan	Myristic acid	0.02% in all countries	[33]
	Burkina Faso	Palmitic acid	7.93–9.55%	
	India	Palmitoleic acid	0.11–0.14%	
	Mozambique	Margaric acid	0.04–0.07%	
	Uganda	Stearic acid	5.10–6.20%	
	Ethiopia	Elaidic acid	0.05–0.07%	
	Humera	Oleic acid	35.88–44.54%	
	Ethiopia	Linoleic acid	37.41–47.44%	
	Volega	Linolenic acid	0.30–0.42%	
	Niger-Benje	Arachidic acid	0.57–0.68%	
	Niger-Kany	Gondoic acid	0.18–0.21%	
	Niger	Behenic acid	0.14–0.18%	
	Wadaguri	Clupanodonic acid	0.03–0.17%	
		Lignoceric acid	0.01–0.10%	

Table 1: Continued.

Phytochemical compositions	Countries	Components	Quantities	References
Amino acids	India	Histidine	3.46 ± 0.01 g/100 g	[44]
		Leucine	9.04 ± 0.02 g/100 g	
		Lysine	3.59 ± 0.01 g/100 g	
		Threonine	5.04 ± 0.07 g/100 g	
		Tryptophan	1.23 ± 0.03 g/100 g	
		Valine	6.91 ± 0.02 g/100 g	
		Alanine	6.38 ± 0.03 g/100 g	
		Arginine	20.25 ± 0.17 g/100 g	
		Aspartic acid	9.54 ± 0.02 g/100 g	
		Glutamic acid	23.61 ± 0.12 g/100 g	
		Glycine	7.09 ± 0.01 g/100 g	
		Proline	4.86 ± 0.02 g/100 g	
		Serine	6.46 ± 0.01 g/100 g	
	Afghanistan	Taurine	0.03–0.05%	[33]
	Burkina Faso	Hydroxyproline	0.08–0.13%	
	India	Aspartic acid	1.62–2.06%	
	Mozambique	Threonine	0.71–0.89%	
	Uganda	Serine	0.85–1.15%	
	Ethiopia	Glutamic acid	3.28–4.57%	
	Humera	Proline	0.65–0.85%	
	Ethiopia	Glycine	0.96–1.22%	
	Volega	Alanine	0.89–1.14%	
	Niger-Benje	Cysteine	0.36–0.51%	
	Niger-Kany	Valine	0.89–1.12%	
	Niger	Methionine	0.59–0.71%	
	Wadaguri	Isoleucine	0.72–0.91%	
		Leucine	1.30–1.66%	
		Tyrosine	0.61–0.79%	
		Phenylalanine	0.86–1.09%	
		Hydroxylysine	0.01–0.03%	
		Ornithine	0.01% in all studied countries	
		Lysine	0.58–0.69%	
		Histidine	0.49–0.61%	
		Arginine	2.36–3.10%	
		Tryptophan	0.13–0.26%	
Amino acids	Nigeria	Alanine	1.48–1.63 g/100 g	[45]
		Arginine	4.61–4.01 g/100 g	
		Aspartic acid	2.77–2.53 g/100 g	
		Cysteine	0.17–0.14 g/100 g	
		Glutamic acid	7.44–6.80 g/100 g	
		Glycine	1.81–1.58 g/100 g	
		Histidine	0.93–0.80 g/100 g	
		Isoleucine	1.38–1.21 g/100 g	
		Leucine	2.39–2.11 g/100 g	
		Lysine	0.95–0.87 g/100 g	
		Methionine	1.00–0.86 g/100 g	
		Phenylalanine	1.66–1.44 g/100 g	
		Proline	1.28–1.12 g/100 g	
		Serine	1.61–1.42 g/100 g	
		Threonine	1.26–1.11 g/100 g	
		Tyrosine	1.36–1.18 g/100 g	
		Valine	1.70–1.50 g/100 g	

Table 1: Continued.

Phytochemical compositions	Countries	Components	Quantities	References
Lignans	Egypt	Sesamin Sesamolin	13.3 mg/g 2 mg/g	[46]
	India	Sesamol Sesamin Sesamolin	0.16–3.24 mg/g 2.10–5.98 mg/g 1.52–3.76 mg/g	[34]
	India	Sesamin Sesamolin	3.1–18.6 mg/g 2.3–10.6 mg/g	[47]
	Korea	Sesamin Sesamolin	0.185–8.205 mg/g 0.203–6.809 mg/g	[48]
	Japan	Sesamin Sesamolin	0.83–2.52 mg/g 0.07–0.82 mg/g	[49]
	Japan	Sesaminols	0.00168–0.00399 mg/g	[50]
	Iran	Sesamin Sesamolin Sesamol	0.0013–0.0016 mg/g 0.0007–0.0008 mg/g 0.0126–0.0167 mg/g	[41]
	México	Sesamol Sesamin Sesamolin	0.5438 ± 0.0086 mg/g 0.696 ± 0.008 mg/g 2 ± 0.0946 mg/g	[42]

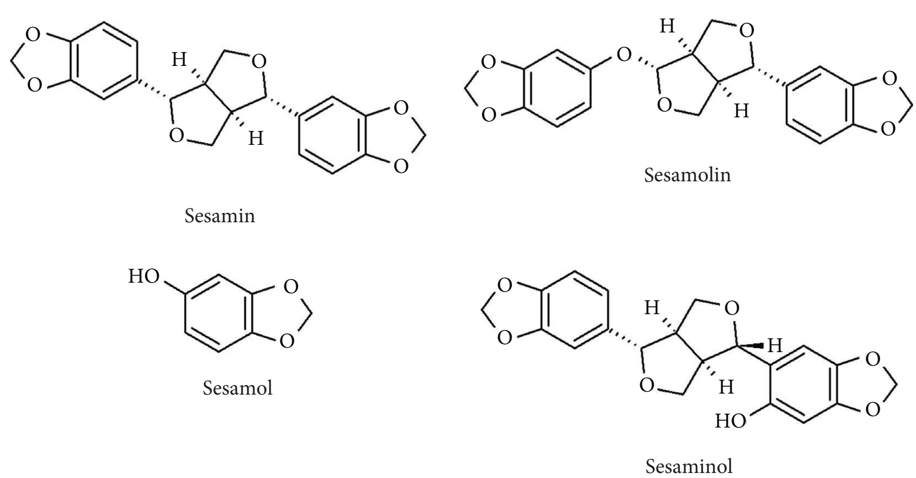

Figure 2: Chemical structures of major lignans in *S. indicum*.

sesamin varied from 0.0013 to 0.0016 mg/g, sesamolin varied from 0.0007 to 0.0008 mg/g, and sesamol varied from 0.0126 to 0.0167 mg/g [41], while in Mexico, the content in sesamol was 0.5438 mg/g, in sesamin was 0.696 mg/g and in sesamolin was 2 mg/g [42]. As for the glycosidic lignans, they include mono, di, and triglucosides of sesaminol and pinoresinol [54].

3.2. Biological Activities and Therapeutic Potential. Throughout the world, the use of plants in traditional medicine is still valuable. According to the World Health Organization (WHO), a significant population (80%) uses herbal preparations based on medicinal and aromatic plants, as a source of primary health care [55]. Various studies have shown the therapeutic potential of sesame. Because of its biologically active ingredients and therapeutic properties, sesame seed is regarded as a miracle cure-all paraphraser (Figure 3). For example, the hypocholesterolemic effect was revealed in patients given a diet rich in sesame seeds, which reduced cholesterol in the blood of hypercholesterolemic patients [56]. Sesamin decreases cholesterol absorption and reduces the activity of the enzyme 3-hydroxy-3-methylglutaryl coenzyme A reductase, which limits cholesterol biosynthesis [31].

3.2.1. Anti-Inflammatory Properties. Sesame belongs to a long list of functional foods with considerable biological properties [57]. Alternative interventions using medicinal plants, organic products, and/or their by-products play a crucial role in the prevention and treatment of various health disorders in both developing and developed countries [58]. The anti-inflammatory effect of sesame seed and sesame oil has been investigated widely *in vivo* in various model animals. The anti-inflammatory effect of sesamin and sesame oil was investigated using the carrageenan-induced rat paw edema model [59]. Doses of sesamin of 50, 100, or 200 mg/kg

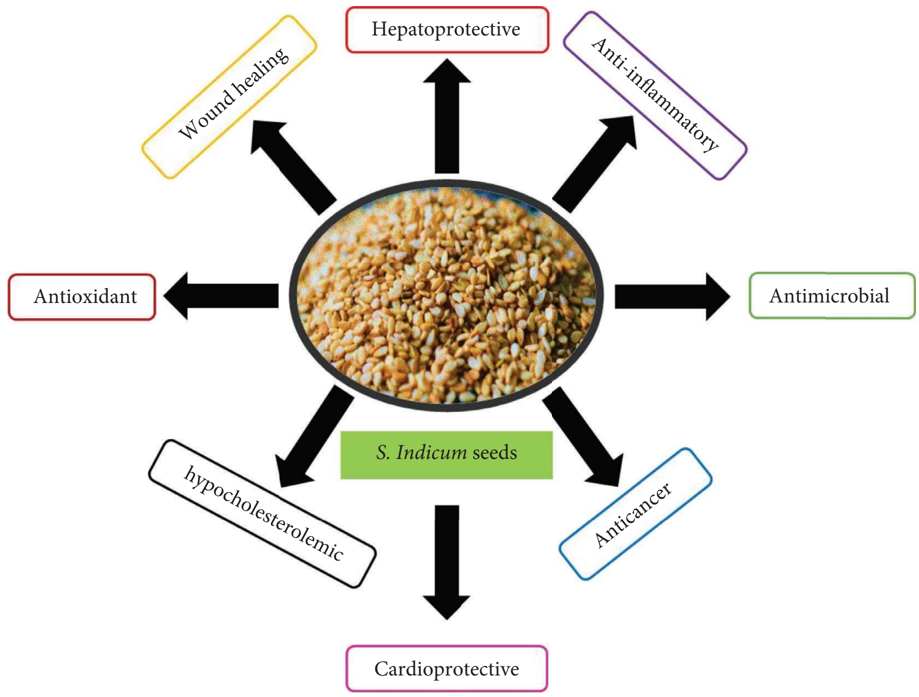

Figure 3: Schematic illustration of the therapeutic potential of *S. indicum.*

per os (p.o.) or sesame oil at doses of 100, 200, or 400 mg/kg p.o., were effective against paw edema and reduced edema volume after 4 h of carrageenan application (0.1 mL 1%) and the antiedema effect was dose-dependent. Accordingly, at doses of 200 and 400 mg/kg of body mass, the sesame oil inhibited, respectively, 18.36% and 27.54% of total leucocytes. Sesamin also caused significant inhibition of total leucocytes at 12.55% and 23.26% at doses of 100 or 200 mg/kg, respectively. In addition to sesamin, sesame contains many other bioactive compounds including luteolin. In fact, luteolin, a flavonoid component present in many functional products, has been proven to downregulate proinflammatory mediators/factors, such as cytokines, inducible nitric oxide synthase (iNOS), tumor necrosis factor-α (TNF-α), interleukin-β (IL-β), and interleukin-6 (IL-6) [60]. Other studies have established that sesame has anti-inflammatory potential [61–63]. In fact, sesame oil can increase concentrations of the anti-inflammatory cytokine interleukin-10 (IL-10). Similarly, concentrations of two major mediators of inflammation, the proinflammatory cytokines TNF-α and prostaglandin E2 (PGE2) were significantly lower after the introduction of sesame into the diet [61].

3.2.2. Antidiabetic Properties. Diabetes is a pathologic state manifested by dysregulation of glycemia accompanied by several long-term complications. The antidiabetic/antihyperglycemic action of sesame seed extracts and sesame oil has been previously studied [64–66]. Furthermore, sesame seeds exhibited a potent antihyperglycemic action in patients with insulin-independent diabetes mellitus (T2DM) [64]. When the antidiabetic effect of sesame seeds extract (SSE) on type 2 diabetic patients was studied, it was observed that SSE improved fasting blood glucose (177.27 vs. 161.03 mg/dL, $p^{‹}0.001$), triglyceride (283.5 *vs.* 203.13, $p^{‹}0.001$), cholesterol (230.10 vs. 2 00.57 mg/dL, $p^{‹}0.001$), glycosylated hemoglobin (7.11 *vs.* 6.52, $p^{‹}0.001$), and reduced, but not significantly, alkaline phosphatase (198.3 *vs.* 187.80 IU/L) and alanine aminotransferase (25.60 *vs.* 23.07 IU/L). Due to its bioactive constituents, sesame exerts its antihyperglycemic effect by modulating glucose uptake and inhibiting α-amylase and β-glucosidase activities, leading to the management of diabetes and its serious complications [67].

Antidiabetic properties of various individual phenolic components present in sesame have been investigated. Cinnamic acid administered orally at a dose of 50 mg/kg/day for 5 weeks, stimulates insulin and adiponectin secretions, increases hepatic glycolysis, improves glucose uptake, potentiates pancreatic β-cell functionality, and decreases protein glycation [68]. Ellagic acid and protocatechuic acid were found to be useful in managing diabetes via inhibition of gluconeogenesis and improving insulin sensitivity [69]. Rutin regulates glycemia and ensures its antidiabetic effect through the inhibition of the polyol signaling pathway as well as via the modulation of lipid metabolism and the prevention of lipid peroxidation [70]. Apigenin facilitates and enhances the translocation of glucose transporter type 4 (GLUT4) in skeletal muscles, either by upregulating the AMP-activated protein kinase pathway or by activating the insulin signaling pathway, either of which results in the uptake of glucose and thus hypoglycemia [71]. Recently, when the antidiabetic effects of kaempferol against streptozotocin-induced diabetes were investigated in rats, it was found that chronic administration of 50 mg kaempferol/kg-b.w reduced production of glucose in the liver, increased hexokinase activity, decreased hepatic pyruvate carboxylase activity, and inhibited the gluconeogenesis pathway [72].

3.2.3. Antioxidant Properties. Oxidative stress is recognized as an imbalance between the production of free radicals and antioxidant defense mechanisms, which leads to excessive reactive oxygen species (ROS) [73]. In turn, these ROS interact with different cytoplasmic molecules, such as proteins, membrane lipids, and DNA, and thus induce serious cell damage and participate in the development of many chronic illnesses such as diabetes and associated complications, arthritis, Parkinson's, and Alzheimer [74–76]. Sesame is one of the most popular antioxidant-rich product largely used against oxidative stress and related pathologies. In this context and owing to its antioxidative properties, sesame oil is known for its preservative power. Indeed, its antioxidant potential has been demonstrated in several studies [77, 78]. Being soluble in the oil fraction, vitamin E (tocopherol) has shown strong antioxidant activity [79]. The lignan family is also known for its capacity to trap free radicals due to its numerous demethylenedeoxide groups and to promote the activities of catalase and superoxide dismutase, both of which are enzymes involved in the detoxification of ROS in cells [80]. In addition to sesame oil, sesame seed extracts contain several bioantioxidant molecules including caffeic acid, cinnamic acids, and quercetin (Table 1). *In vivo* investigations documented the antioxidative potential of these bio-valuable compounds. Subchronic administration of 6 mg caffeic acid/kg b.w reduced oxidative stress caused by alcohol-induced toxicity in rats by increasing nonenzymic antioxidant system defense and by preventing lipid peroxidation [81]. Likewise, cinnamic acid intervenes in the antioxidative process by modulating lipid metabolism and boosting glutathione (GSH), superoxide dismutase (SOD), and catalase (CAT) activities, as well as scavenging and decreasing ROS production [82]. In addition, results of a recent study showed that quercetin improved oxidative stress status and decreased expressions of TNF-α, IL-1β, and IL-6 in alcohol-induced liver and lymphoid tissue injuries in rats [83].

3.2.4. Antimicrobial Properties. Discovering new effective and lesser side-effect drugs for human treatment is mandatory. Microbial infections constitute significant threats to the health of humans because of their ability to resist multiple antibiotics [84, 85]. Sesame has been shown to have promising antimicrobial ability against numerous microbial strains including *Pseudomonas aeruginosa*, *Bacillus cereus*, and *Staphylococcus aureus* [86]. The antibacterial effect of sesame extracts was attributed to sesamol and other active ingredients.

Sesame contains numerous bioactive constituents, especially flavonoid compounds, known for their ability to eradicate different pathogenic microbes (Table 1). Flavonoids exert their action on various molecular targets, including fatty acid synthase type II (FAS-II), DNA gyrase, dihydrofolate reductase-epigallocatechin-3-gallate (DHFR-EGCG) helicase, and virulence enzymes [87–89]. The combination of antioxidant-rich plant extracts with antibiotics boosts antibacterial efficacy against multidrug-resistant microbes including *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa* [90–92]. This synergistic effect is most often due to the positive interaction between its active molecules and antibiotics. Luteolin, the most abundant flavonoid component present in sesame, exhibited antibacterial properties, destroying cell membranes of *Staphylococcus aureus* and *Listeria monocytogenes* and sabotaging the biofilm formation of both strains [93]. Moreover, luteolin derivatives were stated to be the most active components against bacterial strains including *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Enterococcus faecalis*, *Micrococcus luteus*, *Bacillus subtilis*, *Bacillus cereus*, *Salmonella typhimurium*, *Escherichia coli*, *Proteus mirabilis*, *Klebsiella pneumonia*, *Pseudomonas aeruginosa*, and *Helicobacter pylori*, and fungi including *Candida albicans*, *Candida parapsilosis*, and *Candida glabrata*. In general, flavonoids exert their antimicrobial effects without a specific mechanism by binding with various extracellular proteins or destroying the membranes of cells during their penetration of bacterial cells. In addition, once inside, they interact with numerous microbial constituents such as adhesins, metabolic enzymes, replication and transcription enzymes, proteins, and polysaccharides [94, 95].

It has been demonstrated that sesame oil is useful in treating some diseases related to oxidative stress such as chronic renal failure, atherosclerosis, rheumatoid arthritis, and neurodegenerative disorders [96]. Furthermore, sesame oil and sesamol possess a significant antimicrobial activity due to their phenol-rich compounds [97]. Nephroprotective effects of the ethanolic extract of *S. indicum* seeds were observed in streptozotocin-induced diabetic male albino rats [98]. Ethanolic extract of *S. indicum* leaves possesses *in vitro* antioxidant and anticolon cancer activities, and its major compound pedaliin contributes to these activities [99]. Other studies have reported the anticancer activity of *S. indicum* [100–103].

S. indicum has also been reported for wound healing [104, 105], as cardioprotective [106, 107], and as hepatoprotective [108].

4. Effects of Processing *S. indicum* Seeds on Nutritional and Biological Value

Food transformation is a process that improves the organoleptic and nutritional quality of food products. From a qualitative point of view, transformation is subject to several complex reactions to obtain an appreciated final product. For their properties and benefits, sesame seeds are highly wanted by the food industry. In this sense, the endosperm can be extracted, roasted, and ground to give a white paste marketed under the name "Tahini." An industrial transformation process adapted to the sesame seeds is proposed in Figure 4. It comprises two key stages: dehulling and roasting.

4.1. Effects of Dehulled Seeds Relative to Raw Seeds. After harvesting, the removal of the seed coat and separation of the endosperm are the primary processes during the production of sesame paste. The basic steps in the process are soaking, mechanical rubbing, and separation of the hulled seeds (Figure 5). Implementation of such a protocol is not easy

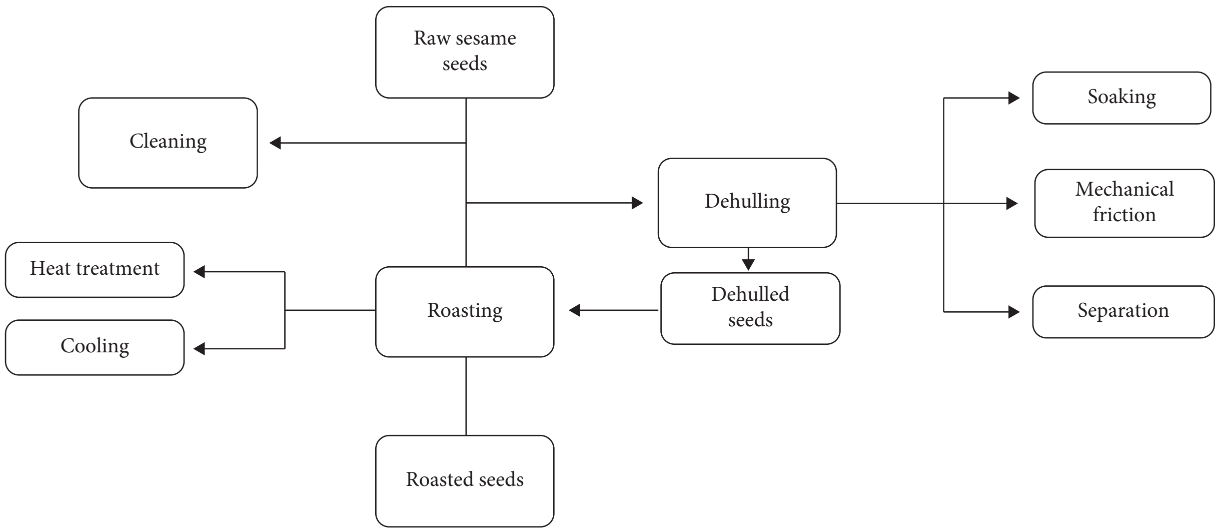

Figure 4: Schematic diagram of the preparation of sesame seeds.

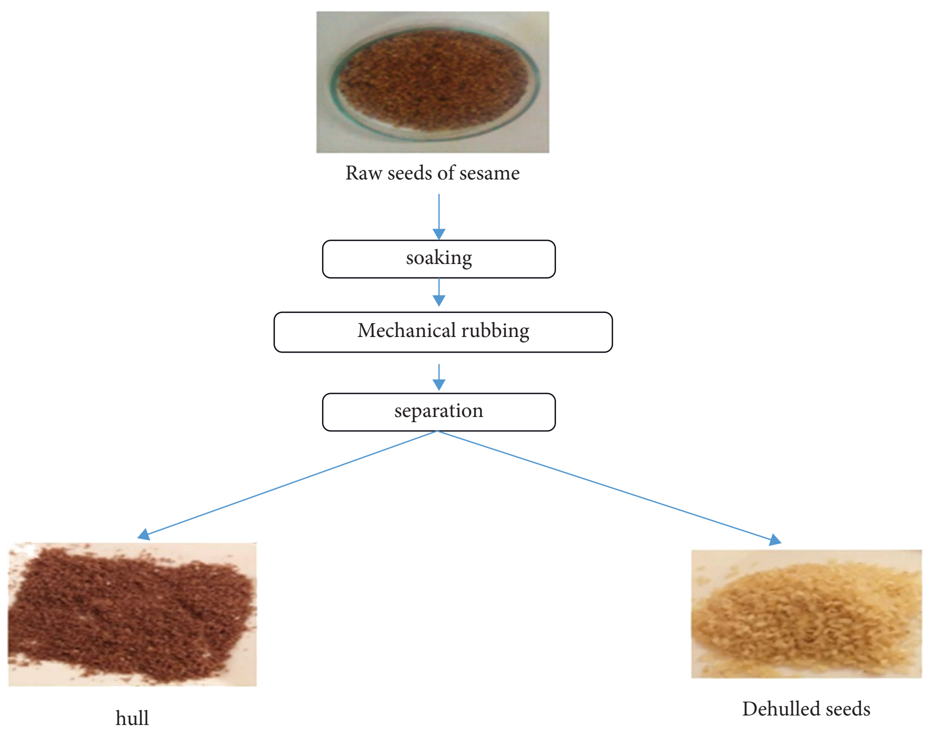

Figure 5: Dehulling process.

because of the morphometric characteristics of the sesame seed; indeed, it is a small seed whose sphere and surface are respectively about 1.56 mm^2 and 7.8 mm^2. Soaking consists of immersing the seeds in water for various durations, depending on the operational conditions, variety of seeds, and temperature of the water. To reduce costs and speed up the process, the use of pretreatment can be used by industries [109]. Several techniques have been proposed for bibliographic review, whether by chemical, physical, or even biological means. A commonality among these methods is the lysis of lignocellulosic cells that constitute the basic unit of the integument. Pretreatment in the presence of a dilute acid allows the hydrolysis of lignin and hemicellulose by breaking the "lignin-xylan" bonds [110]. However, this treatment can alter the physical and chemical characteristics of the endosperm [111]. Contact time can be reduced, so as not to attack the sugars that are soluble in acidic substances. After soaking, the next step is to separate the shell from the endosperm. In practice, after removing the excess of the soaking solution, a cylindrical peeler equipped with an agitator with a speed of rotation of about 80 cycles per minute is used, which allows the seeds to rub against each other, thus causing dehulling. Subsequently, the dehulled seeds and their coats are placed in a saline solution (20%). Differences in density between the seed coat (>1.0) and the endosperm (<1.0) allow separation. Dehulled seeds floating at the top are collected for washing. The dehulling process increased the protein, oil, and soluble sugar content in the dehulled seeds compared to the coats (Table 2) [112]. These results have been confirmed in another study, which suggests that the difference between shelled seeds and their husks is probably due to the location of these elements in the inner layers of the endosperm [29].

In addition, dehulling allows removal of the tegument formed mainly of precisely hemicellulosic fibers A and B [113]; hemicellulose A contains galacturonic acid and glucose in a ratio of 1 : 12.9, while hemicellulose B contains galacturonic acid, glucose, arabinose, and xylose in a ratio of 1 : 3.8 : 3.1. In addition, identification of bioactive molecules from industrial plant residues has been the subject of numerous studies, which explains that polyphenols are extremely associated with seed coat fibers and that dehulling may cause a reduction of the polyphenolic content of the seeds [29]. The same observation was also reported for several fruits such as peanuts [114], wheat [115], beans [116], and chickpeas [117]. It is important to note that oxalic acid, localized in the seed coat, is among the antinutrients found in plants. In the case of sesame seeds, dehulling allows their elimination. The coat of sesame seeds can contain up to 35 mg oxalic acid/100 g, which forms with calcium oxalate salts [118]. Thus, bioavailable calcium has been estimated at less than 25% of the total calcium of sesame seeds [119], and the rest is intimately linked to oxalic acid. These insoluble salts are considered irritants for certain tissues (kidneys, digestive system, etc.).

4.1.1. Importance and Mechanism of Dehulling. The seed hull is the layer that surrounds the endosperm and cotyledons and plays a crucial role in the development of the embryo, since it protects against potentially dangerous environmental elements. To increase the seed's nutritional and organoleptic properties, the seed hull must often be removed. Typically, the biochemical composition of the seed hull contains relatively very low-rate protein and a lot of fiber, largely indigestible fiber, such as cellulose and lignin. Its proportion varies among various seed oils (Table 3). For the following reasons, it is advantageous to remove the seed coat: (1) it decreases the amount of antinutritional elements including insoluble fiber and tannins, and the nutritional quality, including the digestion of proteins, improves; (2) by removing the astringent flavor brought on by tannins, it enhances texture and palatability; and (3) it enhances the final appearance, given that the end products are lighter in color (white seeds).

The seed coat can be removed manually or with a mortar. There are two key activities involved: (1) loosening the seed coat from the cotyledons and (2) removing the seed coat and splitting the cotyledons. The genotype and physical attributes of the seed may have an impact on the variability in the dehulling. Because certain hulls are fibrous or hard, grain is typically preconditioned in order to make the removal of hulls easier. Pretreatments are typically used to remove seed hulls. Heat treatment, prolonged soaking in water, or a chemical solution (alkaline and acid substances) can be used to soften the seed coat [121].

Table 2: Comparison between the composition of dehulled sesame seeds and their coats after dehulling [29].

Compounds	Dehulled seeds	Seeds coat
Oil	52.24%	12.21%
Sugars	2.48%	0.97%
Protein	25.77%	10.23%
Fibers	19.33%	42.03%
Polyphenols	87.77 mg/100 g	598.2 mg/100 g

Table 3: Proportions of kernels and hulls in various oil seeds [120].

Oilseeds	Kernel (%)	Hull (%)
Soybean	93	7
Sunflower	60–70	30–40
Safflower	50	50
Cottonseed	62	38
Sesamum	82–86	14–18
Linseed	57	43

4.2. Effects of Roasting on the Chemical Composition. Roasting is a process widely applied in the food industry. The use of this technique dates back to the 14th century [122], especially with coffee. This heat treatment, based on temperatures above 100°C, aims to develop the organoleptic and sensory parameters of seeds such as color, texture, and flavor. Thus, the resulting product is appreciated by the consumer compared to the raw seeds. During this operation, at first, the seeds lose their initial moisture; water, in its free form, evaporates at a temperature of 100°C [123, 124]. This level of heating depends on the size of the seeds, the initial humidity rate, and the temperature degree. The second level of heat treatment (100 and 200°C) allows for the evaporation of water and makes the volatile molecules more intimately attached to the constituents of the seeds. The last step consists of cooling these roasted seeds to stop the roasting process and preserve their aromatic richness.

During roasting, the color changes and the generation of aromas are mainly due to a series of nonenzymatic reactions [125]. Amino acids are precursors of aromas; aspartic acid, glutamic acid, phenylalanine, and histidine act directly to give volatile aromatic compounds, such as pyrazine, which are retained by the oil fraction of seeds [126]. In addition, under the effect of heat, the Maillard reaction favors the formation of aromatic compounds from reducing sugars or even from sucrose and starch after their hydrolysis [127].

Roasting causes several rheological and physicochemical changes, but it can also influence the nutritional quality of the seed. Indeed, its effect on proteins has been reported in several studies [128, 129]. The protein content of sesame seeds increases in the early stages of roasting [130], but can be denatured after a long roasting time, resulting in a degradation of nutritional quality [131]. Amino groups of proteins react with hydroperoxides, resulting in the formation of aldehydes.

The sugars in seeds are also affected by roasting. Caramelization, which starts at temperatures greater than 10°C for fructose and 160°C for glucose produces intermediate volatile compounds, such as ketones and acetic acid which, after cyclization, give rise to new aromatic compounds, such as 2-2-hydroxyacetyl-furan and maltol, which impart the aroma associated with roasted seeds. These reactions end with the condensation of these molecules, which also generates brown compounds of greater molecular mass [132]. The effect of roasting temperature on phenolic content has been studied several times [5, 133, 134]. After roasting at moderate temperatures, there is an increase in the level of phenolic compounds, which might be due to the synthesis of new types of phenolic compounds [135], but, roasting at greater temperatures, for a long time can result in a reduction of these compounds [136]. For instance, the roasting effects on the oxidation of roasted sesame oil depend on the balance created between the thermal degradation of antioxidants and the generation of new antioxidants, such as sesamol and sesamolin. However, when roasting at temperatures greater than 100°C, the quality of the oil can decrease significantly due to the reduction of certain physicochemical characteristics, thus degrading the quality of the roasted seed oil [29].

Lipids are stored in cellular compartments called oleosomes, which are protected from oxidation by a layer of phospholipids. After thermal treatment, the cell wall and intercellular junctions are damaged and the oleosomes are destroyed [137]. Therefore, oxygen can more easily penetrate and disrupt the oxidative stability of lipids [138]. Roasting results in the formation of fat-soluble hydroperoxides, which are essential elements for the production of aromatic compounds, such as furans and ketones, which are responsible for the smell of roasted seeds.

4.2.1. Changes in Sensorial Proprieties. Numerous researchers have examined the physicochemical characteristics of seeds and nuts after roasting [139–141]. Roasting serves as the fundamental operation for the production of some of the unique properties of sesame seed. Specifically, it is done to enhance flavor and bring about the necessary changes to produce a distinct aroma. One of the crucial visual characteristics of food products is color since it affects consumer acceptance and preference. In oil seeds, color is an important parameter used to control the roasting process, because the browning and caramelization reactions produce brown pigments. The purity of the brown color is represented by the browning index (BI). Sesame's BI value stayed essentially constant while roasting at 120°C. However, it remained stable between 150°C and 180°C for 90 minutes before BI increased significantly [142]. The main compounds used for the development of color in roasted sesame seeds were glucose and galacturonic acid. Also, condensation of carbonyls and amines (especially melanoidins) during the Maillard reactions is thought to be the cause of color development.

Various compounds, including alkenes, furans, alkanes, aldehydes, lipids, ketones alcohols, pyrazine, and acids contribute to the flavors of oil seeds [143]. In sesame seeds, more than 100 compounds have been identified [119]. These compounds were mainly responsible for aroma in raw sesame seeds: 2-furfurylthiol, furaneol, 2-thenylthiol, and 2-metoxy-4-vinylphenol [144]. However, the roasting temperature and time exposed affect the distinctive flavor, from the desirable aroma and mild sweetness to a scorching smell. When the temperature is too low, the synthesis of flavor compounds in sesame oil is not accelerated, but when the temperature is too high, the flavor elements in sesame seeds are destroyed [145]. The recovery of all sesame oil flavors increases with the duration and intensity (time and temperature) of roasting, and the rate of pyrazines reaches its maximum after roasting at 200°C for 30 min. As the intensity of roasting increases, the relative content of 2-furanmethylthiol, guaiacol, and thiazoles decreases, while the relative content of monoalkylpyrazine increases in deep-roasted sesame seeds [146].

In addition to the flavor and color, another crucial control factor for sesame roasting is texture. Texture can be enhanced by controlling the conditions of roasting [147]. Roasted seeds tend to become brittle and crumble, which are typical traits of roasted goods [142]. The texture of seeds is influenced by moisture content and the roasting technique [148, 149]. Roasting at higher temperatures results in seeds and, subsequently, paste with a fragile and brittle texture. Also, a very high roasting temperature (200°C) can rupture the molecular structures of polysaccharides and proteins, causing a loss of consistency.

4.2.2. Mechanism of Heat during Roasting. First-order kinetics can be used to describe changes in the characteristics of product quality. The three primary types of heat transfer are employed in roasting [150]. Convection is a heat-transfer mechanism where particles move as a result of density gradients created by temperature changes. Newton's law says that "the convective heat transfer rate is proportional to the heat transfer surface and the temperature differential between the surface and the fluid," as shown in following equation:

$$\mathrm{Q_{CV}} = \mathrm{hA}\,(\mathrm{Ts} - \mathrm{T}f), \tag{1}$$

where $\mathrm{Q_{CV}}$: heat transfer by convection, h: heat transfer coefficient, A: surface of the product, Ts: temperature of the product, and Tf: the temperature of the bulk fluid.

Conduction is a method of heat transfer that takes place inside things. It involves the direct transmission of heat through atoms or molecules, which interact with nearby particles to exchange kinetic and potential energies. Fourier's law says that the rate of heat transfer through a uniform object is proportional to the surface of *heat* transfer and the temperature gradient, as shown in following equation:

$$\frac{dQ}{dt} = -kA\frac{dT}{dx}, \quad (2)$$

where (dQ/dt): the rate of heat transfer, (dT/dx): temperature gradient, and K proportionality constant (thermal conductivity).

Radiation is a method of transferring energy that uses electromagnetic waves. Electromagnetic waves (with wavelengths between 0 and infinity) are emitted by all objects. Until it encounters a surface, when it is absorbed and transformed into heat, radiant energy travels unimpeded.

$$\mathrm{QR} = \varepsilon\sigma\mathrm{A}\left(\mathrm{T}_1 - \mathrm{T}_2\right), \quad (3)$$

where QR: heat transfer, E: Gray body emissivity, σ: Stefan-Boltzmann constant, A: area, T_1: temperature of the emitting body, and T_2: food temperature.

Roasting can be separated into four phases (Figure 6): (1) heating, during which grains lose their initial moisture. Water in its free form evaporates at a temperature of 100°C. This level of heating depends strongly on the size of the grains, the initial moisture content, and the degree of temperature; (2) drying, during which the bound moisture is eliminated, along with part of the light hydrocarbons; (3) roasting, which is isothermal heating, during which devolatilization, depolymerization, and carbonization reactions are established by the heat; and (4) cooling, during which the temperature returns to ambient, stopping the roasting process and retaining the aromatic richness.

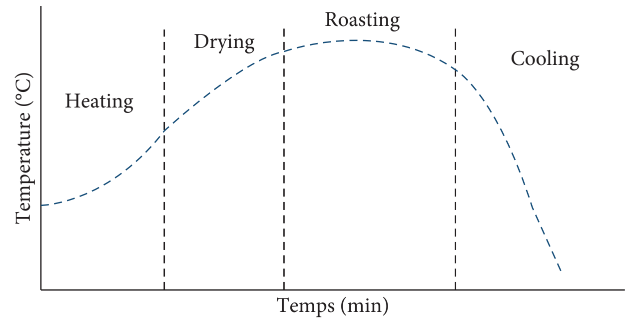

Figure 6: Phases of roasting.

4.2.3. Maillard Reaction: A Series of Steps Essential for Roasting. During roasting, the Maillard reaction is of great importance. The color of oilseeds changes during roasting and the generation of aromas are essentially due to a series of nonenzymatic reactions [125].

Also, amino acids are precursors of aromas of several oilseeds; aspartic acid, glutamic acid, phenylalanine, and histidine act directly to give aromatic compounds such as pyrazine [126, 151]. With the effect of heat, aromatic compounds are formed from reducing sugars or from sucrose and starch after their hydrolysis [127]. The Maillard reaction was described for the first time in 1912 by Lc, who studied the development of the brown color after the heat treatment of reducing sugars and amino acids [152]. This reaction is the succession of several complex reaction mechanisms which can be summarized in three capital steps: (1) glycation, which consists of the formation of an unstable glycosylamine based on a covalent bond between the carbonyl group of a reducing sugar and the amine group of an amino acid. Irreversible isomerization results in a more stable amadori product; (2) this step comprises three substeps: (i) Moderate dehydration, which is expressed by enolization between carbons 2 and 3 and accompanied by loss of the amino residue. The intermediate compound promotes the autocatalysis of the Maillard reaction by degrading it into several compounds (furanones, cyclopentanones, isomaltols); (ii) Severe dehydration, which promotes the degradation of ketosamines. An ene-diol is first formed between carbons 1 and 2 of N-glycosylamine. Then, a series of rearrangements lead to the formation of furfuraldehydes. These reactions are accompanied by decarboxylation of the amino acid (Strecker pathway) and release of aldehydes and pyrazines (aromatic compounds); (iii) a split: the last substep consists of a split of the aldose linked to the amine, releasing acids or carbonyl molecules. Thus, the condensation of these compounds makes it possible to obtain the odorous polymers which mark the Maillard reaction. The third and final stage is a series of interactions between the reaction intermediates of the second stage that lead to the obtaining of the Maillard products. These are mainly flavor compounds called "melanoidins" which are brown and have a high molecular mass [152].

Maillard reaction products were formed in sesame seeds as a result of the roasting process. These products include thermal process contaminants such as acrylamide, α-dicarbonyl compounds, and hydroxymethylfurfural, and contaminants, glycation markers such as furosine, N-ε-carboxymethyllysine, and N-ε-carboxyethyllysine [153].

5. Conclusions

This review is an essay to understand the botanical and phytochemical characteristics of sesame seeds and discuss the link between these characteristics and their biological activities. In fact, an inventory of the therapeutic properties of these seeds was first presented, and a biochemical analysis was reported concerning the effect of two transformation processes (dehulling and roasting) on the nutritional quality of sesame. In conclusion, *S. indicum* seeds are rich in phytochemicals, especially lignans, and these compounds are related to the biological properties of this plant. On the other hand, it appears that dehulled seeds are mainly rich in protein and oil. Dehulling allows the elimination of antinutrients like oxalic acid but also decreases the content of polyphenolic compounds. During roasting, the best results for chemical composition are achieved at moderate temperatures, in contrast to those at higher temperatures, which result in the lesser nutritional quality of the sesame seeds.

Data Availability

All data used are included within this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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