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A review of pumpkin seeds as a nutritional boost in innovations and fortifying flavors

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Abstract
Pumpkin seeds (*Cucurbita* spp.) have evolved from agricultural by-products into prized ingredients in functional food innovation and nutrition. This review examines their botanical background, nutritional composition, and bioactive phytochemicals, highlighting roles in cardiovascular, metabolic, bone, immune, and prostate health. We detail advances in processing—roasting, germination, dehulling, oil and protein extraction—and show how these enhance nutrient bioavailability and sensory appeal. Key applications in bakery, spreads, plant-based meat analogues, and gluten-free foods are surveyed alongside sensory evaluation and consumer acceptance trends. Finally, we discuss technical and commercial barriers—extraction efficiency, protein solubility, flavor optimization, and agronomic limitations—and propose future directions for scalable, sustainable utilization. Integrating the latest research and market insights, this review underscores pumpkin seeds' potential as a versatile, health-promoting ingredient in modern food systems.

Keywords: Pumpkin seeds, functional foods, bioactive compounds, processing techniques, nutritional composition, health benefits

1. Introduction

Pumpkin (*Cucurbita* spp.), a member of the Cucurbitaceae family, is widely cultivated in tropical and subtropical regions as a vegetable crop. It shares botanical lineage with cucumbers, melons, and squashes. Globally, three major species dominate cultivation: Cucurbita pepo, Cucurbita maxima, and Cucurbita moschata Lee *et al.* (2003) [33]. Historically, pumpkins were primarily cultivated for their seeds, as the flesh of wild Cucurbita species was bitter and inedible Whitaker and Bemis (1964) [56] Over time, both the pulp and seeds have gained recognition for their nutritional and therapeutic value.

Pumpkin pulp is consumed in various forms-soups, pies, bread, curry, and preserves-while pumpkin flakes and powders are used in the culinary industry to enhance flavor, texture, and color (Norfezah *et al.*, 2011, El-Adawy and Taha, 2001) [41, 17]. The seeds, once discarded as agro-industrial waste, are now considered nutraceuticals due to their rich content of proteins, oils, sterols, polyamines, antioxidants, and dietary fiber (Yadav *et al.*, 2010; Nyam *et al.*, 2013) [57, 42]. Pumpkin seed oil, particularly from C. pepo var. styriaca, has gained global attention for its cardioprotective, anti-inflammatory, and antioxidant properties Montesano *et al.* (2018) [39]

Retail trends further reflect this shift: major U.S. food chains such as Walmart, Costco, and Trader Joe's now market pumpkin-seed-based products including granola, quinoa salad, cookies, and tortilla chips. Countries like Australia, Hungary, Serbia, and Slovenia are leading producers of pumpkin seed oil, and its popularity continues to grow steadily across global markets Patel, (2013) [45].

1.1 Background

The rising interest in functional foods and natural bioactive ingredients has positioned seeds as key contributors to health and nutrition. Pumpkin seeds, in particular, are rich in unsaturated fatty acids, high-quality protein, dietary fiber, and essential minerals such as magnesium, zinc, and iron (Syed *et al.*, 2019; Gavril *et al.*, 2024) [54, 21]. Their phytochemical profile includes tocopherols, phytosterols, cucurbitacins, and polyphenols-compounds associated with antioxidant, anti-inflammatory, antidiabetic, and anticancer activities (Dhakad *et al.*, 2023; Gavril *et al.*, 2024) [15, 21]. Pumpkin seeds have also demonstrated therapeutic potential in managing benign prostatic hyperplasia, hyperlipidemia, and postmenopausal bone health, owing to their phytoestrogen content (Montesano *et al.*, 2018; Dhakad *et al.*, 2023) [39, 15]. Their inclusion in traditional medicine systems and modern nutraceutical formulations reflects a convergence of ethnobotanical knowledge and clinical validation.

1.2 Purpose of the Review

This review aims to explore the nutritional composition, bioactive constituents, and therapeutic relevance of pumpkin seeds, with emphasis on their role in food product innovation. It synthesizes current research on:

- Functional properties of pumpkin seed flour and protein isolates
- Applications in bakery, spreads, meat analogues, and gluten-free formulations
- Processing techniques that enhance nutrient bioavailability and sensory quality

Additionally, the review highlights market trends, sustainability aspects, and technical challenges in seed valorization. By integrating findings from recent studies, it underscores the potential of pumpkin seeds as a versatile and health-promoting ingredient in modern food systems.

2. Botanical and Nutritional Profile of Pumpkin Seeds

Pumpkin (*Cucurbita spp.*), a member of the Cucurbitaceae family, is widely cultivated in tropical and subtropical regions. It shares botanical lineage with cucumbers, squashes, and melons. The three major cultivated species—Cucurbita pepo, Cucurbita maxima, and Cucurbita moschata—are globally recognized for their agronomic and nutritional value Lee *et al.* (2003) [33]. Historically, pumpkins were primarily grown for their seeds, as the flesh of wild varieties was bitter and inedible Whitaker and Bemis (1964) [56]. Today, both the pulp and seeds are valued for their culinary versatility and therapeutic potential.

Pumpkin seeds, often discarded as agro-industrial waste, are now considered a nutritional powerhouse. They are rich in essential minerals such as zinc, phosphorus, magnesium, potassium, and selenium, which contribute to immune function, bone health, and antioxidant defense (Maheshwari *et al.*, 2015; Devi *et al.*, 2018) [34, 14]. These seeds are also a source of bioactive compounds including phytosterols, tocopherols, polyamines, and phenolic acids, which exhibit anti-inflammatory, anticancer, and cardioprotective properties (Amin *et al.*, 2019; Syed *et al.*, 2019) [2, 54].

2.1 Botanical Description

Pumpkin plants are herbaceous vines with large leaves and yellow flowers, producing fruits that vary in size, shape, and color. The seeds are typically flat, oval, and encased in a fibrous endocarp. Cultivars are classified into hulled and hull-less types, with the latter preferred for oil extraction due to ease of processing and higher oil yield Montesano *et al.* (2018) [39]. The Styrian pumpkin (C. pepo var. styriaca) is a notable hull-less variety cultivated for its high-quality oil and protein-rich seeds.

2.2 Nutritional Composition

Pumpkin seeds contain a dense array of macronutrients, including protein (24-39%), oil (28-43%), fiber (2-16%), and carbohydrates (25-28%) (Alfawaz, 2004; Elinge *et al.*, 2012; Milovanovic *et al.*, 2014) [1, 18, 37]. The lipid profile is dominated by unsaturated fatty acids, with linoleic acid (52.69%) and oleic acid (18.14%) being the most abundant. Saturated fats such as palmitic (16.41%) and stearic acid (11.14%) are present in smaller proportions, contributing to the oil's oxidative stability and health benefits Ardabili *et al.* (2019) [4].

In a case study Pumpkin seeds of the Cucurbita pepo subsp. pepo var. Styriaka grown in Iran exhibit a favorable nutritional and physicochemical profile, making them a promising source of edible oil and protein. The seeds contain approximately 41.59% oil and 25.4% protein, along with notable levels of crude fiber (5.34%), ash (2.49%), and carbohydrates (25.19%). The extracted oil demonstrates high oxidative stability, with a tocopherol content of 882.65 mg/kg, total phenolics at 66.27 mg gallic acid/kg, and a balanced fatty acid composition dominated by linoleic (39.84%), oleic (38.42%), palmitic (10.68%), and stearic (8.67%) acids. These attributes, combined with favorable physicochemical parameters such as specific gravity (0.915) and refractive index (1.4662), underscore the potential of Styriaka pumpkin seeds as a high-quality oilseed crop suitable for functional food applications Gohari *et al.* (2011) [22].

The amino acid profile of pumpkin seed kernels reveals high levels of arginine, glutamic acid, and aspartic acid, while methionine and tryptophan are limiting. This makes pumpkin seed protein suitable for fortification and development of protein isolates Alfawaz, (2004) [1]. Recent studies have also confirmed the presence of all essential amino acids, supporting its use in plant-based diets and meat analogues Habib *et al.* (2025) [24].

In terms of micronutrients, pumpkin seeds are particularly rich in magnesium (up to 592 mg/100g), zinc (7.81-14.14 mg/100g), iron (3.75-8.8 mg/100g), and vitamin E (up to 882.65 mg/kg oil) (Nyam *et al.*, 2013; Ardabili *et al.*, 2019; Syed *et al.*, 2019) [42, 4, 54]. These nutrients play critical roles in enzymatic function, antioxidant defense, and metabolic regulation.

Pumpkin seeds also contain potent phytochemicals such as phenolic compounds (e.g., ferulic acid, vanillic acid), phytosterols (e.g., β-sitosterol), tocopherols (α-and γ-forms), and carotenoids. These compounds contribute to the seeds' antioxidant capacity and therapeutic effects, including anti-inflammatory, antidiabetic, and anticancer activities (Gavril *et al.*, 2024; Dhakad *et al.*, 2023) [21, 15].

Recent innovations have explored the use of pumpkin seed flour and protein isolates in functional food development, including spreads, bakery products, and meat substitutes. Studies have demonstrated improved sensory attributes, protein digestibility, and oxidative stability in products enriched with pumpkin seed derivatives (Das *et al.*, 2021; Bashir *et al.*, 2025) [13, 8].

3. Health Benefits of Pumpkin Seeds

Pumpkin seeds have gained attention for their medicinal and nutritional properties, contributing to multiple aspects of human health. They are rich in minerals, antioxidants, polyunsaturated fatty acids, phytosterols, and bioactive peptides, all of which offer therapeutic benefits in the prevention and management of chronic conditions, including cardiovascular diseases, prostate disorders, diabetes, and inflammatory diseases Syed *et al.* (2019) [54]. Pumpkin has long been recognized in traditional medicine systems for its diverse pharmacological activities, including antidiabetic, antihypertensive, antitumor, immunomodulatory, antibacterial, antihypercholesterolemic, antiparasitic, anti-inflammatory, and analgesic effects Caili *et al.* (2006) [9]. Their broad applications in metabolic regulation, immune enhancement, and anti-inflammatory support have further been emphasized in recent studies Dhakad *et al.* (2023) [15]. The anti-inflammatory properties of specific fatty acid esters from pumpkin seeds have also shown potential in modulating cytokine activity Dong *et al.* (2021) [16].

3.1 Cardiovascular Health

Pumpkin seed oil contains high levels of monounsaturated (MUFA) and polyunsaturated fatty acids (PUFA), especially linoleic and oleic acids, which help lower blood pressure, reduce LDL cholesterol, and promote vascular elasticity Montesano *et al.* (2018) [39]. Phytosterols in the seeds—such as β-sitosterol—modulate lipid profiles and contribute to anti-atherosclerotic activity Bashir *et al.* (2025) [8]. The magnesium content, up to 592 mg/100g, also supports cardiac rhythm and blood pressure regulation Syed *et al.* (2019) [54].

3.2 Antioxidant and Anti-inflammatory Properties

Pumpkin seed extracts are a rich source of phenolic compounds, including vanillic acid, tyrosol, luteolin, and sinapic acid, which scavenge free radicals and reduce oxidative stress Andjelkovic *et al.* (2009) [3]. Protein isolates from pumpkin seeds demonstrate strong chelating activity, inhibit xanthine oxidase, and lower lipid peroxidation in liver and kidney tissues (Nkosi *et al.*, 2005, Dong *et al.* 2021) [40, 16] further reported that oleic acid esters derived from pumpkin seeds suppress inflammatory cytokines like TNF-α and IL-1β in adipose tissue, underscoring their anti-inflammatory potential.

3.3 Prostate Health

Pumpkin seed oil has shown efficacy in reducing testosterone-induced prostate hyperplasia in rats. In a controlled study, administration of pumpkin seed oil at 2 mg/100g body weight for 20 days significantly reduced prostate size compared to controls, indicating its potential for managing benign prostatic hyperplasia Gossell-Williams *et al.* (2006) [23]. This is attributed to the presence of sterols and phytoestrogens that inhibit androgenic activity and reduce prostate inflammation.

3.4 Bone Density and Skeletal Support

Magnesium from pumpkin seeds supports bone mineralization and creates an alkaline environment favorable for skeletal health, which has been positively associated with improved bone density, particularly among elderly populations Ryder *et al.* (2005) [50]. The presence of trace minerals such as zinc and manganese further contributes to osteoblast activity, collagen synthesis, and the maintenance of overall bone integrity.

3.5 Diabetes Management and Glycemic Control

Pumpkin seeds aid in the regulation of blood glucose levels and enhance insulin sensitivity. Supplementation with pumpkin seed oil and protein has been shown to improve antioxidant enzyme activity—such as superoxide dismutase (SOD), glutathione (GSH), and catalase (CAT)—while reducing malondialdehyde (MDA) levels and normalizing plasma glucose and hepatic enzyme concentrations, including alanine aminotransferase (ALT) and aspartate aminotransferase (AST) (Makni *et al.*, 2010; Makni *et al.*, 2011) [36, 35]. Amino acids such as tryptophan and glutamic acid, found abundantly in pumpkin seeds, support pancreatic function and glucose metabolism.

3.6 Immune Modulation and Antimicrobial Action

High levels of zinc, vitamin E (tocopherols), and phytoestrogens in pumpkin seeds contribute to immune system support and hormonal regulation Dhakad *et al.* (2023) [15]. These nutrients enhance both innate and adaptive immune responses, including post-infection recovery Hussain *et al.* (2023) [28]. Furthermore, antimicrobial peptides such as MAP2 and MAP11, derived from pumpkin seeds, exhibit inhibitory effects against fungal and bacterial strains, highlighting their potential role in food safety and immunotherapy applications Syed *et al.*, 2019) [54].

4 Processing of pumpkin seeds for food applications

Pumpkin seeds have gained recognition in food technology due to their dense nutritional profile and versatile functional attributes. Before being incorporated into food products, seeds undergo pre-processing steps such as mechanical cleaning, sorting, and dehulling, which help to eliminate impurities, reduce bitterness, and improve textural characteristics Polyzos *et al.* (2024) [46]. Hull-less pumpkin seed varieties are often preferred for food applications because they possess superior organoleptic and nutritional qualities compared to hulled counterparts Syed *et al.* (2019) [54].

Bakery products such as bread, buns, biscuits, and cakes have been formulated by partially substituting wheat flour with pumpkin seed flour at levels of 10%, 20%, and 30%. This incorporation improved the nutritional profile—particularly protein and mineral content—while maintaining consumer acceptability across taste, texture, and appearance. Products with up to 30% substitution were well-received, supporting the use of pumpkin seed flour in functional baked goods Revathy and Sabitha, (2013) [48].

4.1 Roasting and Germination

Roasting is a common thermal treatment applied to pumpkin seeds to enhance flavor, reduce moisture content, and improve antioxidant potential. The process promotes the formation of Maillard reaction products—such as pyrazines and furans—which are responsible for the characteristic nutty and caramel-like aroma and taste of roasted seeds Aziz *et al.* (2023) [5]. In addition to improving flavor, roasting also reduces phytic acid levels, leading to better mineral bioavailability Patel *et al.* (2023) [44]. This technique has also been shown to increase functional properties such as water and fat absorption capacity by 17.26% and 21.3%, respectively, while decreasing least gelation concentration by 6%. However, foaming and emulsification capacities may be compromised after roasting Fagbemi *et al.* (2005) [19]. Historically, pumpkin seeds were consumed after roasting and salting, particularly in traditional food cultures Cirrilli (1971) [11].

Germination serves as another effective pre-treatment that enhances the nutritional and functional quality of seeds. It results in elevated levels of free amino acids—including glutamic acid, arginine, and phenylalanine—and significantly boosts antioxidant activity and digestibility compared to raw seeds Dar *et al.* (2017) [12].

4.2 Protein Isolation and Flour Production
After oil extraction, the remaining defatted pumpkin seed cake—containing approximately 50-60% protein—serves as a rich source for protein isolate production. Pumpkin seed protein isolate (PSPI) is typically extracted using alkaline solubilization (pH 10-12) followed by isoelectric precipitation at pH 4.5, yielding a high-functionality protein concentrate suitable for emulsifying, gelling, and foaming applications (Hadidi *et al.*, 2025; Polyzos *et al.*, 2024) [25, 46].
Pumpkin seed flour, produced from roasted or germinated seeds, is valued for its high protein, zinc, and dietary fiber content. In one study, cookies made using 25-30% pumpkin seed flour received favorable sensory evaluations, scoring above 7 on a 9-point hedonic scale and maintaining antioxidant stability for up to 30 days Sharma and Lakhawat (2017) [52].

4.3 Spread and Butter Formulation
Pumpkin seed butter is created by finely grinding dehulled seeds, which naturally contain about 30% oil. These butters are often blended with ingredients such as salt, honey, or natural emulsifiers to improve spreadability and flavor. On average, a 30-gram serving delivers 9 grams of protein and 10 grams of unsaturated fat, making it nutritionally comparable to popular nut-based spreads like peanut or almond butter Mishra *et al.* (2019) [38]. Furthermore, these seed-based spreads have been shown to remain microbiologically safe and sensorially acceptable for up to 7 days under refrigerated storage conditions Das *et al.* (2021) [13].

4.4 Processing Effects on Nutrients
The method of processing significantly influences the nutritional properties of pumpkin seed derivatives. Roasting has been observed to improve the extractability of minerals such as calcium and potassium while simultaneously lowering the concentration of anti-nutritional factors Aziz *et al.* (2023) [5]. Germination enhances the availability of micronutrients like magnesium, zinc, and iron, and improves overall protein digestibility Syed *et al.* (2019) [54].
Shelf-life assessments reveal that cookies prepared with pumpkin seed flour maintain acceptable texture and sensory quality for up to 60 days under ambient conditions. Conversely, high-moisture products such as muffins tend to remain fresh for only 2 to 3 days at room temperature, underscoring the importance of product-specific formulation and packaging considerations Patel *et al.* (2023) [44].

5. Chronological development of pumpkin seeds
Pumpkin seeds have a rich legacy tracing back to 7000-5500 BCE in Mesoamerican civilizations, where they were cultivated for their therapeutic properties and nutrient density. Indigenous cultures utilized them in traditional medicine to treat urinary disorders, parasitic infections, and digestive ailments, highlighting their early value beyond basic nutrition (Yadav *et al.*, 2010; Whitaker and Bemis, 1964) [57, 56].
The seeds' utility expanded during the 16th century following the Columbian Exchange, enabling their global dissemination into European, African, and Asian cultures. Once introduced, they were incorporated into folk medicine and food traditions for their digestive, diuretic, and immunomodulatory effects (Dhakad *et al.*, 2023) [15].
In the mid-to-late 20th century, scientific interest in pumpkin seeds intensified as researchers began investigating their nutritional profile, confirming high levels of polyunsaturated fatty acids, protein, minerals such as magnesium and zinc, and beneficial phytochemicals like phytosterols and tocopherols (Alfawaz, 2004, Syed *et al.*, 2019) [1, 54].
Agronomic breeding advancements led to the development of hull-less varieties such as Cucurbita pepo var. styriaca, which simplified oil extraction and improved functional processing efficiency Chahal *et al.* (2022) [10]. These cultivars became widely studied for their superior bioactive yield and ease of integration into food formulations.
A comprehensive genomic analysis of 321 Cucurbita accessions, including C. pepo, C. moschata, and C. maxima, to investigate seed trait variation. Using genotyping-by-sequencing (GBS), they identified 15 significant loci associated with seed dimensions such as length, width, and area. Importantly, 32 candidate genes previously linked to seed development in model species like Arabidopsis and Oryza sativa were located within key genomic regions, providing strong targets for molecular breeding programs aimed at improving seed quality and yield in pumpkins Lee *et al.* (2023) [32].
Over the past decade, pumpkin seed derivatives—including flours, protein isolates, spreads, and oils—have found widespread use in functional foods such as bakery items, plant-based meat analogues, and dairy alternatives, backed by favorable sensory evaluations and nutritional improvements (Mishra *et al.*, 2019; Bashir *et al.*, 2025) [38, 8]. Their documented antioxidant, anti-inflammatory, antidiabetic, and antimicrobial activities have propelled their relevance in nutraceuticals and food safety applications (Dong *et al.*, 2021; Gavril *et.*, 2024; Habib *et al.*, 2025) [16, 21, 24]. Today, pumpkin seeds are positioned as sustainable, health-promoting ingredients, with evolving roles in personalized nutrition, food innovation, and therapeutic formulations.

5.1 Historical and Scientific Evolution
The domestication of pumpkin species can be traced back to early Mesoamerican civilizations, dating between 7000 and 5500 BCE, where Cucurbita pepo was among the first cultivated plants used for both its edible flesh and nutrient-rich seeds Hosen *et al.* (2021) [26]. Indigenous populations valued pumpkin seeds not only as a food source but also for their therapeutic applications, employing them in treatments for urinary disorders and intestinal parasites due to their bioactive compounds Yadav *et al.* (2010) [57]. The global distribution of pumpkin seeds expanded following the Columbian exchange in the 16th century, enabling their adaptation across varied agro-climatic regions in Europe and Asia. This dispersion gave rise to species diversity, including C. maxima, C. moschata, and specialized cultivars such as hull-less varieties like the Styrian pumpkin. These hull-less seeds—resulting from a recessive mutation affecting lignin deposition—simplified post-harvest processing and increased oil recovery efficiency (Chahal *et*

al., 2022; Faturoti and Ogidi, 2025) [10, 20]. By the 20th century, pumpkin seeds garnered scientific interest due to their high concentrations of unsaturated fatty acids, essential minerals such as zinc and magnesium, phytosterols, tocopherols, and cucurbitacins. These constituents positioned pumpkin seeds as valuable in preventive nutrition and functional food development (Yadav *et al.*, 2010; Syed *et al.*, 2019) [57, 54]. Technological advancements, including single nucleotide polymorphism (SNP) mapping and marker-assisted selection, have accelerated breeding efforts focused on enhancing protein content, seed size, and oil quality (Lee *et al.*, 2023; Wang *et al.*, 2019) [33, 55].

5.2 Commercial and Global Adoption

In contemporary food markets, pumpkin seeds have achieved significant commercial traction due to their nutritional versatility and alignment with consumer wellness trends. Their incorporation into everyday food products—such as granola bars, trail mixes, cookies, and ready-to-eat snacks—is now commonplace in large-scale retail chains like Walmart, Costco, and Trader Joe's Patel (2013) [45]. These products are marketed primarily for their plant-based protein, healthy fat composition, and functional fiber content. Countries in Central Europe, including Austria, Hungary, Slovenia, and Serbia, are prominent producers of pumpkin seed oil, especially from Styrian cultivars known for their high levels of polyunsaturated fatty acids and phytosterols. These oils are widely consumed both for culinary purposes and as nutraceutical supplements Patel (2013) [45]. Consumer demand continues to rise for gluten-free, high-protein, and clean-label food options—trends that have created opportunities for pumpkin seed ingredients in diverse sectors such as bakery, dairy alternatives, and plant-based meat products (Aziz *et al.*, 2023; Gavril *et al.*, 2024) [5, 21]. Their adaptability, nutrient density, and compatibility with sustainable agricultural practices position pumpkin seeds as a key driver in personalized nutrition and future-forward food innovation.

6. Functional and Technological Properties in Food Systems

The successful incorporation of pumpkin seed components into food formulations relies on a comprehensive understanding of their functional contributions—particularly how proteins, fibers, and lipids interact to influence texture, stability, and sensory attributes. Pumpkin seed proteins, known for their ability to form structured gels, also exhibit substantial water-and oil-binding capacities, making them well-suited for use in bakery applications and plant-based meat analogues Polyzos *et al.* (2024) [46].

The seed's lipid fraction, predominantly composed of linoleic and oleic acids, is naturally rich in tocopherols and phytosterols, which contribute to enhanced oxidative stability and emulsion integrity in formulations such as salad dressings and non-dairy beverages (Aziz *et al.*, 2023). Additionally, residual seed proteins and polysaccharides support foam formation and moisture retention, which are critical for maintaining desirable mouthfeel and extending shelf life in products like snack bars and whipped desserts Patel *et al.* (2023) [44].

From a sensory perspective, thermal processing—especially roasting—generates key flavor compounds, including pyrazines and furans, that impart appealing nutty and caramel-like notes. At the same time, antioxidant constituents inherent in the seeds help delay lipid oxidation, thereby preserving freshness and prolonging product shelf life (Syed *et al.* 2019; Dar *et al.* 2017) [54, 12].

6.1 Protein Functionality and Oil Properties

Proteins derived from pumpkin seeds mainly include albumins, globulins, and prolamins, each contributing uniquely to the functional behavior of food systems Polyzos *et al.* (2024) [46]. These proteins exhibit the lowest solubility near their isoelectric point (pH 4-6), but solubility significantly improves under alkaline conditions, making them suitable for use in products like beverages, emulsified dressings, and plant-based meat alternatives (Patel *et al.* 2023) [44]. Their water absorption capacities range from 2 to 4 grams per gram of protein, and they can bind 2 to 3 grams of oil per gram, qualities that support their application in bakery and meat analogue formulations Aziz *et al.* (2023) [5]. Thermal gelation typically begins at approximately 70 °C due to the denaturation of 11S globulins, resulting in firm gels that melt slightly above 75 °C. These properties can be further optimized through interventions such as pH-shift treatment or ultrasonication Dar *et al.* (2017) [12]. Cold-pressed pumpkin seed oil, composed mainly of linoleic (50-55%) and oleic acids (15-20%), is notable for its oxidative stability, attributed to its high content of γ-tocopherol and phytosterols Syed *et al.* (2019) [54].

6.2 Emulsification, Foaming, and Water-Holding Capacity

Residue-rich defatted pumpkin seed meals retain proteins and carbohydrates that contribute to favorable emulsifying and hydrating properties Polyzos *et al.* (2024) [46].The emulsifying activity index (EAI) of isolated pumpkin seed protein can reach 40-80 m^2/g, and treatments that shift the pH to acidic (pH 2) or highly alkaline (pH 12) can enhance EAI by up to 300% (Patel *et al.* 2023) [44]. Emulsions exhibit over 60% stability after 30 minutes, especially in mildly acidic conditions (pH 4-6), where disulfide linkages enhance droplet stability Aziz *et al.* (2023) [5]. Foaming ability is best at lower pH levels (2-4), although the presence of high salt concentrations (above 0.5 M NaCl) can rapidly reduce foam integrity Dar *et al.* (2017) [12]. Water-holding capacity of raw defatted pumpkin flour ranges between 1.5-2.5 g/g, but enzymatic or microbial treatments that increase exposure of polar groups can raise this above 3 g/g Syed *et al.* (2019) [54].

6.3 Flavor Profile and Sensory Characteristics

Unprocessed pumpkin seed flour has a mildly grassy and sweet-beany aroma, which can be altered or refined through various processing methods Polyzos *et al.* (2024) [46]. Roasting induces the formation of Maillard reaction compounds such as pyrazines and furans, contributing to appealing roasted and caramel-like aromas (Patel *et al.* 2023) [44]. Bitterness from cucurbitacins and astringency from polyphenols may be minimized through dehulling or the application of specific enzymatic treatments Aziz *et al.* (2023) [5]. Consumer sensory panels report favorable responses to products containing 5-15% pumpkin seed flour, with scores ranging from 7 to 8 on a 9-point scale for attributes like nuttiness, texture, and visual appeal Dar *et al.* (2017) [12]. Finer flour fractions (<150 µm) deliver a smooth mouthfeel, while coarser particles offer a desirable texture in applications such as snack bars Syed *et al.* (2019) [54].

6.4 Shelf Stability and Storage Considerations
The naturally high γ-tocopherol content in pumpkin seed oil serves as an internal antioxidant, helping to prevent lipid oxidation during storage Syed *et al.* (2019) [54]. Shelf stability of seed flour is maintained by keeping water activity below 0.40, which inhibits microbial growth and enzymatic spoilage Polyzos *et al.* (2024) [46]. Packaging solutions like PET/EVOH multilayer films or HDPE jars with nitrogen flushing have proven effective in extending product shelf life to 12-18 months under ambient conditions Aziz *et al.* (2023) [5].

Storage environments maintained at 10-20 °C and relative humidity between 30-50% are ideal, as elevated temperatures increase the risk of hydroperoxide formation (Patel *et al.* 2023) [44]. Furthermore, mild heat treatments such as thermal pasteurization of seed-based spreads ensure microbiological safety without degrading flavor or texture Dar *et al.* (2017) [12].

7. Application of Pumpkin Seeds in Innovative Food Products
Pumpkin-seed ingredients have been successfully applied across diverse food categories. In bakery applications, substituting up to 30% wheat flour with pumpkin-seed powder raised cookie protein by over 20% and β-carotene by 40% while maintaining sensory scores above 7/9 on a 9-point hedonic scale. Defatted pumpkin-seed cake incorporated at 10-20% in extruded snack formulations boosted protein content by 25% and improved crispness, benefits attributed to the high water-and oil-binding capacities of residual seed proteins (Mishra *et al.* 2019) [38].

In plant-based analogues, adding 5-10% pumpkin-seed protein isolate enhanced emulsion stability by 35%, increased foam volume in dairy alternatives by 20%, and reduced cooking losses in meat analogues by up to 20% compared to soy controls Baig *et al.* (2023) [6]. As emulsion stabilizers in functional beverages, 3% pumpkin-seed protein isolate maintained uniformity for 14 days, driven by its interfacial proteins and intrinsic antioxidants Aziz *et al.* (2023) [5]. Beyond foods, ultrasound-assisted extraction followed by cold plasma treatment of pumpkin-seed protein isolates yielded edible films with tensile strengths of 7-10 MPa and a 30% reduction in swelling, highlighting their promise for sustainable, bio-based packaging Zenasni *et al.* (2025) [58].

8. Sensory Evaluation and Consumer Acceptance
The successful integration of pumpkin seed components into food products depends not only on their nutritional value but also on their influence on sensory perception and consumer satisfaction Roy and Datta (2015) [49]. Sensory evaluation—encompassing visual appeal, aroma, flavor, mouthfeel, and aftertaste—plays a decisive role in determining the market acceptance of fortified foods (Silva *et al.*, 2014; Roy and Datta, 2015; Mishra *et al.* 2019) [53, 49, 38]. This section explores how the incorporation of pumpkin seed ingredients alters sensory attributes, summarizes findings from consumer acceptability studies, and reviews emerging consumer trends influencing demand for pumpkin seed-fortified products (Aziz *et al.*, 2023; Polyzos *et al.*, 2024) [5, 46].

8.1 Sensory Modifications with Pumpkin Seed Fortification
Research indicates that incorporating moderate levels (10-25%) of pumpkin seed flour or meal can enhance the sensory attributes of baked products. In one study, cereal bars prepared with 12.5-25% medium to coarse pumpkin seed flour were rated highly for their enriched color and intensified nutty aroma, without a reduction in textural appeal Silva *et al.* (2014) [53]. Similarly, cookies formulated with 15-30% defatted pumpkin seed flour replacement achieved hedonic scores above 7 out of 9, with improved flavor, acceptable changes in moisture content, and deeper crust coloration Mishra *et al.* (2019) [38]. Additionally, sponge cakes containing up to 20% pumpkin seed flour showed improved crumb softness and no negative flavor development even after four days of storage, suggesting stable sensory characteristics over time Ike *et al.* (2020) [29].

8.2 Consumer Acceptability of Fortified Products
Consumer acceptance of pumpkin seed-enriched foods remain consistently favorable when formulations are optimized for taste and texture. A sensory study involving 100 panelists aged 10-50 evaluated five different pumpkin seed-based products, including sugar-and molasses-coated roasted seeds, biscuits, barfi, and spiced tikia. Among these, the sweet items—particularly biscuits and barfi—received the highest scores, ranging from “liked very much” to “extremely liked” Roy and Datta (2015) [49]. Savory snacks such as mathri and halwa, enriched with pumpkin seed flour, demonstrated improved nutritional values—reaching protein levels of about 20% and fat content near 31%—without diminishing consumer satisfaction, which remained in the “good” category Mishra *et al.* (2019) [38]. In another study, cereal bars fortified with 12.5-25% pumpkin seed flour received average taste and texture ratings above 7.5 on a 9-point hedonic scale, affirming the feasibility of combining enhanced nutrition with sensory appeal Silva *et al.* (2014) [53].

8.3 Market Trends and Consumer Preferences
Current market trends reflect a growing inclination toward nutrient-dense, plant-based, and clean-label foods. Pumpkin seeds—once considered agro-industrial by-products—are now being reimagined as premium functional ingredients. Their inclusion in products such as snack bars, biscuits, and ready-to-drink nutritional beverages aligns with consumer preferences for gluten-free, high-protein, and minimally processed foods Aziz *et al.* (2023) [5]. Scientific literature supporting the nutritional density of pumpkin seeds—including their richness in unsaturated fats, tocopherols, and essential minerals—has contributed to their growing popularity among health-conscious consumers Polyzos *et al.* (2024) [46]. Retail data from specialty stores and e-commerce platforms suggest a year-on-year increase in pumpkin seed product offerings, fueled by consumer interest in clean nutrition and functional food innovations (Aziz *et al.*, 2023; Polyzos *et al.*, 2024) [5, 46]. This momentum underscores the robust commercial potential of pumpkin seed-fortified food products.

9. Processing Challenges and Utilization Barriers of Pumpkin Seeds

Pumpkin seeds possess notable nutritional and therapeutic value; however, their widespread adoption in food systems faces several technical and practical barriers. Challenges related to extraction efficiency, protein solubility, sensory acceptability, and industrial scalability have limited their incorporation into mainstream functional foods and nutraceutical formulations. Additionally, agronomic constraints and a lack of standardized processing protocols further impede commercial viability (Sert *et al.*, 2024; Pandey *et al.*, 2024; Hu *et al.*, 2023; Faturoti and Ogidi, 2025) [51, 43, 27, 20]. Addressing these limitations through optimized processing techniques and improved supply chain integration is essential to unlock the full potential of pumpkin seeds in food science and technology.

9.1 Oil Extraction Efficiency and Limitations

Pumpkin seed oil is highly valued for its abundance of polyunsaturated fatty acids, tocopherols, and phytosterols. However, the yield and quality of extracted oil greatly depend on the extraction method. Mechanical pressing, though commonly used, yields lower oil recovery (32-36%) but retains higher concentrations of bioactives. In comparison, solvent extraction offers better oil yield (up to 47%) but raises environmental and safety concerns due to solvent residue retention and regulatory restrictions (Kumari *et al.*, 2025; Zhang *et al.*, 2024) [31, 59]. Supercritical CO_2 extraction is considered the gold standard for quality, yet its cost and equipment demand make it impractical for small processors Hu *et al.* (2023) [27]. Agronomic factors such as hull thickness, seed moisture, and particle size further influence extraction efficiency, with hull-less varieties like C. pepo var. styriaca offering improved oil recovery but limited cultivation due to agronomic requirements Kabutey *et al.* (2021) [30].

9.2 Protein Isolation Constraints and Solubility Issues

Pumpkin seed protein isolate (PSPI) is rich in essential amino acids and is an excellent candidate for plant-based product development. Nonetheless, its commercial application is hampered by poor solubility and limited functional properties. Conventional extraction methods such as alkaline extraction and isoelectric precipitation result in protein denaturation and moderate yields (~45-60%), constraining its utility in diverse food matrices Sert *et al.* (2024) [51]. Techniques like ultrasound-assisted processing and high-pressure homogenization have demonstrated improvements in emulsification, foaming, and solubility, though their scalability remains restricted (Ramondo *et al.*, 2023; Pandey *et al.*, 2024) [47, 43]. Additionally, PSPI has low solubility at acidic pH levels (4.5-5.5), which limits its applicability in beverages, yogurt, and other low-pH foods Habib *et al.* (2025) [24].

9.3 Sensory Acceptability and Product Formulation

Incorporating pumpkin seed components into formulated foods often introduces sensory limitations. High inclusion levels of seed flour can affect taste, appearance, and texture. Bitterness from phenolic compounds and green hues from chlorophyll impair overall acceptability, especially in bakery items (Aziz *et al.*, 2023; Bandyopadhyay *et al.*, 2024) [5, 7]. Moreover, the presence of fiber and coarse particles can impact dough elasticity and reduce spread factor in cookies and breads, necessitating precise formulation adjustments to balance sensory and nutritional qualities Das *et al.* (2021) [13].

9.4 Commercial Limitations and Agronomic Factors

Despite being nutritionally valuable, pumpkin seeds are frequently underutilized, particularly in regions where only the pulp is consumed. Post-harvest management and processing infrastructure for seed drying, cleaning, and grading are often inadequate Mishra *et al.* (2019) [38]. Hull-less cultivars, though ideal for oil and protein extraction, are not widely grown due to climate and soil limitations, restricting raw material availability for industrial use Faturoti and Ogidi (2025) [20]. Additionally, the absence of standardized regulations and insufficient consumer awareness around pumpkin seed-based products challenge large-scale commercialization and brand development.

10. Conclusion

Pumpkin seeds, once considered agro-industrial waste, have gained recognition as a nutrient-dense and versatile ingredient, rich in proteins, unsaturated fatty acids, essential minerals, and bioactive compounds that offer numerous health benefits including cardiovascular support, bone health, glycemic control, immune modulation, and prostate health. Advances in processing techniques—such as roasting, germination, and protein isolation—have improved the bioavailability and sensory qualities of pumpkin seed derivatives, facilitating their successful incorporation into a variety of food products like bakery goods, plant-based meat analogues, spreads, and beverages, all of which have been well-received by consumers when properly formulated. Despite their promise, challenges such as extraction efficiency, protein solubility, sensory acceptability, and commercial limitations remain, requiring further innovation in processing, supply chain management, and consumer education to fully realize their potential. Overall, pumpkin seeds represent a sustainable, health-promoting, and innovative ingredient that aligns with the growing demand for plant-based and functional nutrition.

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