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# Hemp *Cannabis sativa* L Seed as a Functional Food Source: A Survey

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## Abstract

Hemp seeds (*Cannabis sativa* L.) are increasingly recognized as a nutrient-dense food source, rich in bioactive compounds such as polyphenols and antioxidants. This survey paper provides a comprehensive analysis of hemp seeds as a functional food, emphasizing their nutritional composition, bioactive compounds, and potential health benefits. Hemp seeds are notable for their high-quality protein content, including essential amino acids, and a balanced ratio of omega-3 to omega-6 fatty acids, which support cardiovascular health and reduce inflammation. The bioactive compounds, particularly polyphenols, confer significant antioxidant and anti-inflammatory properties, contributing to the prevention of chronic diseases like cardiovascular disease, diabetes, and cancer. The paper highlights the variability in nutritional and phytochemical profiles due to genetic and environmental factors, emphasizing the need for standardized benchmarks. It also explores advanced processing techniques like nanoencapsulation and electrospinning, which enhance the stability and bioavailability of bioactive compounds in hemp seeds. As consumer demand for natural and functional foods rises, hemp seeds are poised to play a pivotal role in the food industry, offering sustainable and health-promoting alternatives to traditional food sources. Future research should focus on optimizing cultivation and processing methods to fully exploit the potential of hemp seeds as a functional food ingredient, addressing challenges related to bioavailability and stability of bioactive compounds.

## 1 Introduction

### 1.1 Hemp Seeds as a Nutrient-Dense Food Source

Hemp seeds (*Cannabis sativa* L.) are recognized as a nutrient-dense food source, primarily due to their rich nutritional profile and bioactive compounds [1, 2]. Historically valued for fiber, these seeds are increasingly acknowledged for their nutritional benefits, being abundant in proteins, lipids, and dietary fiber—essential for balanced diets, particularly for vegan and vegetarian populations seeking plant-based protein sources.

The growing interest in hemp seeds is driven by their health benefits and the rising consumer demand for natural, functional foods [2]. Their nutritional value is enhanced by bioactive compounds, including polyphenols and antioxidants, which promote health by improving vascular function and reducing oxidative stress. These compounds are also being investigated for their potential in preventing age-related neurodegenerative diseases, expanding the role of hemp seeds in modern nutrition [3].

Research on hemp proteins highlights their significant nutritional and functional properties, reinforcing the seeds' status as a nutrient-dense food source [4]. As research continues to reveal the diverse benefits of hemp seeds, their contribution to health and wellness is expected to increase, solidifying their importance in contemporary dietary practices and the development of functional foods [5].

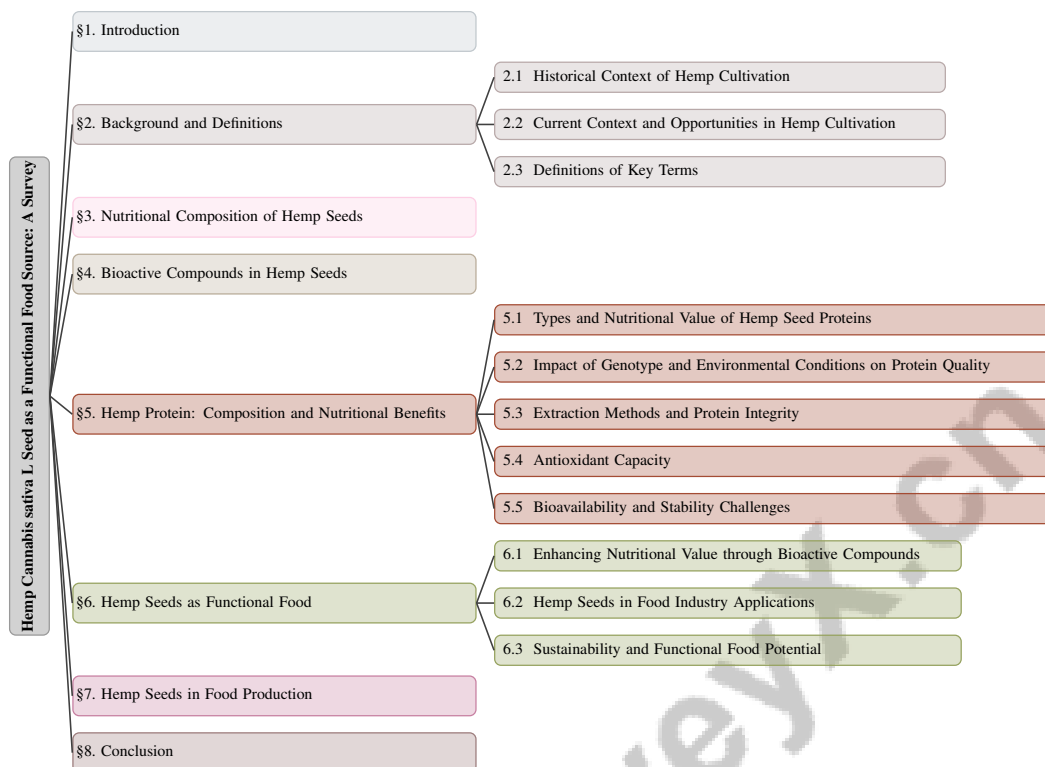


Figure 1: chapter structure

## 1.2 Growing Interest in Hemp Seeds

The increasing interest in hemp seeds stems from their nutritional and phytochemical properties, which vary by cultivar and growing conditions [2]. This variability underscores the need for standardized benchmarks to assess and compare the nutritional quality of hemp seeds, accounting for environmental factors, cultivation practices, and genetic diversity [6]. The global market for hemp seeds is poised for significant growth, driven by the rising demand for high-protein, plant-based foods, with hemp seeds acknowledged for their substantial protein content and associated benefits [7, 8].

This interest aligns with a broader trend towards functional foods, sought for their health-promoting properties [9]. The antioxidant potential of hemp seeds presents a natural alternative to synthetic antioxidants, which have raised health concerns [10]. Additionally, the popularity of polyphenols, known for enhancing athletic performance, further positions hemp seeds as a valuable source of these micronutrients [11]. Despite their high nutritional value and potential health benefits, hemp seeds remain underutilized in food production, highlighting opportunities for expanded applications and market development [5]. The exploration of endophytic bacteria in hemp cultivation may also enhance the production of bioactive compounds, increasing the seeds' appeal [12].

## 1.3 Significance in Functional Foods

Hemp seeds are central to the development of functional foods due to their composition of bioactive compounds, particularly polyphenols and antioxidants, which offer substantial health benefits. These compounds play a critical role in mitigating chronic conditions such as cardiovascular diseases, diabetes, and cancer through their anti-inflammatory and antioxidant actions. Notably, polyphenolic compounds in hemp seeds contribute to cardiovascular health by regulating blood pressure [13].

Integrating hemp seeds into diets meets the growing consumer demand for natural, health-promoting products [14]. They serve as a source of bioactive peptides, highlighting their potential as nutraceuticals. The antioxidant properties of hemp seed extracts are significant for enhancing cognitive health and delaying neurodegenerative processes, further establishing their role in functional foods.

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Research indicates that the bioactive components in hemp seeds positively influence skin health by improving hydration, elasticity, and reducing signs of aging [15]. The essential fatty acids, phytosterols, and antioxidants found in hemp seeds, oil, and flour underscore their utility in functional food applications [16]. The interaction between polyphenols and the gut microbiome is crucial, affecting the bioavailability and effectiveness of these compounds in vivo.

Establishing nutritional quality benchmarks for hemp seeds is vital for their application in nutrition and health, facilitating their incorporation into functional foods [6]. As ongoing research uncovers the diverse benefits of hemp seeds, their role in enhancing the nutritional profiles of food products and promoting overall health is increasingly recognized, positioning them as essential in functional food development. The therapeutic potential of these bioactive compounds in disease prevention and management further emphasizes the importance of hemp seeds in functional food applications.

## 1.4 Structure of the Survey

This survey is systematically organized to provide an in-depth understanding of hemp seeds (*Cannabis sativa* L.) as a functional food source. The paper begins with the **Introduction**, setting the stage by discussing hemp seeds as a nutrient-dense food source, highlighting their bioactive compounds, and elucidating their significance in the context of functional foods. This is followed by a detailed exploration of the **Background and Definitions**, offering an overview of historical and contemporary cultivation practices, while defining key terms essential for comprehending subsequent sections.

The **Nutritional Composition of Hemp Seeds** section examines the macro and micronutrient profiles of hemp seeds, emphasizing their rich content of proteins, dietary fibers, lipids, and essential fatty acids, along with the impact of processing methods on their nutritional composition. In the **Bioactive Compounds in Hemp Seeds** section, we analyze the presence and health implications of polyphenols and antioxidants, including challenges related to their bioavailability and stability.

The survey further investigates **Hemp Protein: Composition and Nutritional Benefits**, focusing on the types of proteins present, their nutritional value, and factors affecting protein quality, as well as discussing extraction methods and their impact on protein integrity. The review titled **Hemp Seeds as Functional Food** explores the multifaceted potential of hemp seeds (*Cannabis sativa* L.) as a valuable ingredient in the functional foods sector, thoroughly examining their exceptional nutritional profile—rich in high-quality proteins, essential fatty acids, vitamins, and bioactive compounds—while highlighting applications in food product development and their role in promoting sustainability within the food industry. This review aims to illuminate how incorporating hemp seeds can enhance the nutritional value of various food products, thereby contributing to healthier dietary options and supporting a balanced diet [7, 8, 17, 5, 4].

In the **Hemp Seeds in Food Production** section, we discuss technological advancements in hemp-based food products, their health benefits, consumer acceptance, and potential applications in functional foods and nutraceuticals. The paper concludes with a **Conclusion**, summarizing key points and emphasizing the importance of hemp seeds as a nutrient-dense food source, while outlining challenges and future research directions in the field. The following sections are organized as shown in Figure 1.

## 2 Background and Definitions

### 2.1 Historical Context of Hemp Cultivation

Hemp (*Cannabis sativa* L.) has a long history, primarily due to its versatile applications and evolving cultivation techniques. Historically, hemp was crucial for textiles, ropes, and sails, reflecting its economic importance [18]. Although hemp seeds have been consumed for their nutritional value, their potential as a food source has only recently been acknowledged [16]. The resurgence of hemp cultivation in the United States is linked to legislative changes that have redefined its legal status, facilitating agricultural advancements and research into its applications [18]. This shift has led to a reassessment of hemp's agricultural significance, spurring research aimed at optimizing cultivation methods to enhance the nutritional and phytochemical profiles of hemp seeds [2]. Variability in hemp seeds' nutritional composition, influenced by genotype and environment, underscores the need for standardized benchmarks to improve product quality [6]. The lack of comprehensive biochemical data on cultivars like Fedora has historically limited their use in functional foods and nutraceuticals [16].

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Research organized into stages—covering cultivation, nutritional analysis, therapeutic applications, and food processing technologies—illustrates a systematic approach to harnessing hemp’s potential as a functional food [5]. Such efforts are essential for advancing hemp’s agricultural and nutritional applications, ensuring its sustainable integration into modern food systems.

## 2.2 Current Context and Opportunities in Hemp Cultivation

The current landscape of hemp cultivation is characterized by the interplay of challenges and opportunities following its historical prohibition and recent legalization [18]. This legal shift has revitalized interest in hemp’s agricultural and industrial applications, fostering advancements in cultivation practices and research. Current efforts focus on optimizing the plant’s nutritional and phytochemical profiles for diverse sectors, including food and animal nutrition. Hemp seeds, hempseed cake, and hemp oil are increasingly used in animal feed, offering a sustainable alternative to conventional components [19]. This integration benefits livestock, such as dairy ruminants, and supports a circular economy by utilizing hemp coproducts [17]. The nutritional value of these products is attributed to their proteins, essential fatty acids, and bioactive compounds, enhancing animal health and productivity. In the food industry, there is a shift towards natural alternatives, with plant-based antioxidants preferred as preservatives and in packaging systems [10]. Hemp, rich in antioxidants, is a viable option for this transition, expanding its applications beyond traditional uses. Exploring hemp protein’s potential in food product development is promising, despite challenges from anti-nutritional factors that require innovative processing techniques [4]. As research continues to reveal hemp’s multifaceted benefits, the industry is poised for growth, driven by consumer demand for natural, sustainable, and health-promoting products. Continuous innovation in hemp-based products and advancements in cultivation techniques are expected to enhance hemp’s economic viability and environmental sustainability, positioning it as a versatile crop with a low environmental impact. Its ability to absorb heavy metals and act as a carbon sink further underscores its appeal as a sustainable agricultural option [17, 18, 5, 7].

## 2.3 Definitions of Key Terms

Understanding essential concepts is crucial for investigating hemp (\**Cannabis sativa*\* L.) as a functional food, particularly regarding the nutritional benefits and health implications of hemp seeds, known for their high-quality proteins, balanced fatty acids, and bioactive compounds that contribute to their potential as valuable ingredients in functional foods [5, 7].

Naturally occurring chemical substances in foods, especially plant-based sources, bioactive compounds modulate metabolic processes and are linked to health benefits, including chronic disease prevention and treatment, such as cancer, cardiovascular issues, and metabolic disorders. They include phytochemicals, polyphenols, and bioactive peptides, with antioxidative, anti-inflammatory, and immunomodulatory properties that enhance immune function, improve gut health, and mitigate oxidative damage [20, 21, 15, 22].

A class of bioactive compounds, polyphenols are micronutrients with antioxidant properties found in hemp seeds. They are categorized into flavonoids, phenolic acids, stilbenes, and lignans, associated with health benefits such as neuroprotection, vascular health, and chronic disease management, including Type 2 diabetes and certain cancers [23].

Compounds that inhibit oxidation, antioxidants prevent cell damage from free radicals. In hemp seeds, polyphenols act as antioxidants, reducing oxidative stress and contributing to chronic disease prevention [22]. The distinction between natural and synthetic antioxidants is significant in food applications, with natural antioxidants preferred for their health benefits [10].

Foods offering health benefits beyond basic nutrition due to bioactive compounds, hemp seeds are classified as functional foods due to their rich composition of bioactive peptides and other health-promoting substances [24]. The role of natural antioxidants and polyphenols in functional foods is crucial for enhancing health outcomes [25].

Referring to the health advantages of nutrient-dense foods like hemp seeds, which are rich in proteins, essential fatty acids, and bioactive compounds that support overall health and wellness [17].

A high-quality plant-based protein source derived from hemp seeds, hemp protein contains all essential amino acids and is noted for its digestibility and nutritional value, making it a valuable component of vegan and vegetarian diets [17].

### 3 Nutritional Composition of Hemp Seeds

Understanding the nutritional composition of hemp seeds is crucial due to their significant health benefits, primarily derived from their macronutrient profile. Hemp seeds are rich in proteins, dietary fibers, and lipids, featuring a balanced fatty acid composition, including essential omega-3 and omega-6 fatty acids, as well as vitamins and bioactive compounds. This composition supports their classification as functional foods with potential health-enhancing properties [7, 8, 6, 5, 4].

Figure 2 further elucidates this topic by illustrating the hierarchical structure of the nutritional composition of hemp seeds. The figure highlights the macronutrient profile, which includes proteins, dietary fibers, and fatty acids, while also showcasing comparative nutritional benefits that emphasize hemp seeds' advantages over other food sources in terms of protein, fatty acids, and micronutrients. Additionally, it addresses the impact of processing methods, covering traditional techniques, innovative technologies, and nutrient interactions. This comprehensive visual representation reinforces the significance of hemp seeds in nutritional science and their potential contributions to health.

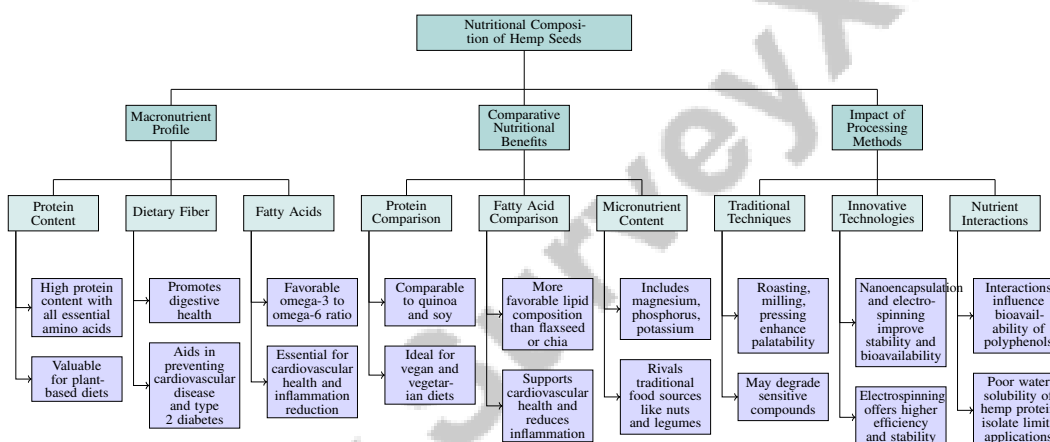


Figure 2: This figure illustrates the hierarchical structure of the nutritional composition of hemp seeds, highlighting the macronutrient profile, comparative nutritional benefits, and the impact of processing methods. The macronutrient profile includes proteins, dietary fibers, and fatty acids. Comparative benefits showcase hemp seeds' advantages over other food sources in terms of protein, fatty acids, and micronutrients. The impact of processing methods covers traditional techniques, innovative technologies, and nutrient interactions.

#### 3.1 Macronutrient Profile

Hemp seeds (*Cannabis sativa* L.) boast a robust macronutrient profile, characterized by high protein content with all essential amino acids, making them valuable for plant-based diets [8]. Their rich dietary fiber promotes digestive health and aids in preventing chronic diseases like cardiovascular disease and type 2 diabetes [8]. The favorable omega-3 to omega-6 fatty acid ratio in hemp seeds is essential for cardiovascular health and inflammation reduction. However, the nutritional quality of these macronutrients can vary significantly with cultivation conditions, necessitating standardized benchmarks to ensure consistent quality [6]. Optimizing cultivation practices through research can enhance the nutritional profile of hemp seeds for functional food applications.

#### 3.2 Comparative Nutritional Benefits

Hemp seeds (*Cannabis sativa* L.) stand out in the nutritional landscape due to their exceptional macronutrient profile, offering advantages over other plant-based and animal-derived foods. Their complete protein content, comparable to quinoa and soy, makes them ideal for vegan and vegetarian

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diets [8]. Hemp seeds provide a balanced profile of essential fatty acids, particularly omega-3 and omega-6, which supports cardiovascular health and reduces inflammation [17]. This lipid composition is often more favorable than that of seeds like flaxseed or chia. Additionally, their dietary fiber enhances digestive health and prevents chronic diseases, making them superior to refined grains and processed foods [8]. The micronutrient content, including vitamins and minerals like magnesium, phosphorus, and potassium, enriches their nutritional profile, offering benefits that rival traditional food sources like nuts and legumes. These attributes underscore hemp seeds' potential as functional food ingredients, enhancing nutritional quality while meeting the demand for health-promoting, natural options [5].

### 3.3 Impact of Processing Methods

Processing methods significantly influence the nutritional composition of hemp seeds (*Cannabis sativa* L.), affecting the bioavailability and stability of bioactive compounds. Traditional techniques like roasting, milling, and pressing enhance palatability and facilitate the extraction of oils and proteins but may degrade sensitive compounds, impacting nutritional quality [8]. Innovative processing technologies, such as nanoencapsulation and electrospinning, are being explored to improve the stability and bioavailability of bioactive compounds, although safety concerns persist. Electrospinning, in particular, offers higher efficiency and stability for bioactive compounds compared to traditional methods, preserving nutritional integrity [26]. Extraction methods are crucial for maximizing antioxidant potential and preserving nutritional quality [27]. The interactions between polyphenols and other macronutrients during processing can influence the bioavailability of polyphenols and their health-promoting effects. The poor water solubility of hemp protein isolate (HPI) limits its functional applications, highlighting the need for advanced processing techniques to enhance its solubility and nutritional benefits [1]. By leveraging advanced processing methods and understanding nutrient interactions, the nutritional profile of hemp seeds can be preserved and enhanced for effective use in functional foods and nutraceuticals.

## 4 Bioactive Compounds in Hemp Seeds

Hemp seeds (*Cannabis sativa* L.) have garnered significant attention for their bioactive compounds, which offer numerous health benefits. This section explores the polyphenolic content of hemp seeds and their health implications, underscoring their role in enhancing the seeds' nutritional profile and establishing them as functional foods. The following subsection delves into the specific polyphenol content, highlighting their antioxidant properties and therapeutic potential in various health domains.

### 4.1 Polyphenol Content and Health Implications

Rich in polyphenols, hemp seeds (*Cannabis sativa* L.) contain flavonoids and non-flavonoids like quercetin, which exhibit potent antioxidant properties. These antioxidants are crucial in mitigating oxidative stress, thereby reducing the risk of chronic diseases such as cardiovascular diseases, diabetes, and certain cancers through the modulation of inflammatory pathways and enhancement of insulin sensitivity [23, 28, 29, 30]. Flavonoids and phenolic acids in hemp seeds are noted for their anti-inflammatory effects, beneficial in managing inflammatory conditions [13, 20]. They also contribute to skin health by improving hydration, elasticity, and reducing aging signs [28], and exhibit neuroprotective effects, potentially preventing neurodegenerative diseases [1].

Polyphenol content varies across cultivars and environmental conditions, necessitating standardized benchmarks for consistent nutritional and antioxidant properties [20]. As consumers increasingly prefer natural antioxidants over synthetic ones, polyphenols play a vital role in developing functional foods and serve as preservatives and active ingredients in food products, enhancing both nutritional value and economic viability. Studies emphasize the importance of extracting and stabilizing polyphenols from natural sources, affirming their significance in food technology and therapeutic potential in modulating metabolic processes [31, 32, 10, 22]. With growing recognition of polyphenols' benefits, including their impact on athletic performance and skin health, hemp seeds are increasingly valued in functional food formulations. Future research should focus on polyphenol bioavailability and their interactions with macronutrients during digestion and food processing to maximize their health-promoting efficacy.

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## 4.2 Antioxidant Capacity

Hemp seeds (*Cannabis sativa* L.) are renowned for their strong antioxidant properties, largely due to their high content of polyphenols and bioactive compounds [33]. Antioxidant capacity is assessed through spectrophotometric tests measuring total phenolic content (TPC) and various activities like TAC, DPPH, ABTS, FRAP, and CUPRAC [33], demonstrating their ability to neutralize free radicals and prevent oxidative stress-induced cellular damage.

The antioxidant capacity of hemp seed polyphenols compares favorably with major antioxidants like vitamins E and C, crucial in managing chronic conditions such as obesity and diabetes where oxidative stress plays a significant role [20]. Additionally, the anti-inflammatory effects of polyphenols can alleviate oxidative stress and inflammation, improving skin health and reducing aging impacts [28].

The antioxidant activity of hemp seeds is attributed to mechanisms such as free radical scavenging, metal ion chelation, and modulation of antioxidant enzyme activities. These processes are influenced by the seeds' phytochemical composition, including polyphenols and terpenoids with antimicrobial and anti-inflammatory properties. Factors like genotype and growing conditions significantly alter the nutritional and phytochemical profiles of hemp seeds, enhancing their potential as functional foods and dietary supplements [2, 7]. As consumer preferences shift towards natural antioxidants, hemp seeds' role in functional food development grows, offering a natural alternative to synthetic antioxidants. Continued research into optimizing the antioxidant potential of hemp seeds and exploring their applications in health-promoting food products is essential.

## 4.3 Bioavailability and Stability Challenges

The bioavailability and stability of bioactive compounds in hemp seeds, particularly polyphenols and antioxidants, are crucial for their health benefits [25]. While polyphenols are known for their antioxidant properties, their bioavailability is often limited by interactions with dietary components and gut microbiota, affecting absorption and metabolism.

Ensuring the stability and bioavailability of polyphenols and other bioactive compounds in hemp seeds is challenging [25]. These compounds are susceptible to degradation by environmental factors like light, temperature, and oxygen, which can compromise their efficacy [25]. Moreover, interactions between polyphenols and gut microbiota can lead to variability in individual responses, complicating health benefit predictions [34].

Encapsulation technologies offer a promising solution to enhance the stability and bioavailability of bioactive compounds in hemp seeds. By encapsulating these compounds within protective matrices, they can be shielded from environmental degradation, preserving their health-promoting properties during processing and storage [35]. However, optimizing encapsulation techniques to maximize bioavailability and stability remains a challenge [25].

The limited bioavailability of polyphenols, especially in pure form, poses a barrier to their therapeutic potential, particularly in cancer prevention and treatment [23]. Research is increasingly focused on developing advanced delivery systems to enhance the absorption and efficacy of polyphenols in the body [23]. Understanding the interactions between polyphenols and the gut microbiome is also essential, as these interactions significantly influence bioavailability and effectiveness [34].

Innovative methods, such as nanoencapsulation, are being explored to improve the solubility and stability of polyphenols and other bioactive compounds, addressing challenges related to low bioavailability and degradation. Recent advancements in both synthetic and natural methods aim to enhance the solubility and stability of hydrophobic bioactive compounds, crucial for their effectiveness in food and pharmaceutical applications. Synthetic approaches, including nanoencapsulation using various nanocarriers, show promise in enhancing bioavailability by protecting compounds from degradation and improving release profiles. However, natural methods are increasingly favored for enhancing bioavailability while preserving the integrity and functional properties of bioactive compounds, aligning with consumer demands for natural, health-promoting food products [14, 36, 37, 22]. As the demand for functional foods rises, addressing these challenges is essential for maximizing the health benefits of hemp-derived bioactives and their applications across various industries.

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## 5 Hemp Protein: Composition and Nutritional Benefits

### 5.1 Types and Nutritional Value of Hemp Seed Proteins

Hemp seeds (*Cannabis sativa* L.) are valued for their high-quality protein content, consisting of approximately 25-30% protein, primarily edestin and albumin. Edestin, which accounts for 60-80% of hemp protein, is a highly digestible globular protein rich in essential amino acids necessary for cellular repair and immune function [4]. Albumin complements this with a well-balanced amino acid profile, beneficial for both human and animal nutrition [8].

The digestibility and bioavailability of hemp proteins enhance their appeal as a superior plant-based protein source [8], particularly due to high arginine levels, which support cardiovascular health and muscle repair [4]. Innovative processing techniques can optimize the functional properties of hemp proteins, such as solubility and emulsifying capacity, broadening their application in food development [4]. As demand for plant-based proteins grows, especially among vegan and vegetarian consumers, incorporating hemp proteins into food products not only improves nutritional profiles but also supports sustainable dietary practices [8].

Hemp proteins also enhance animal nutrition by improving feed quality, with studies showing that hemp seeds and by-products can be incorporated into livestock diets to promote health and productivity [19]. This versatility highlights hemp seed proteins as a key ingredient in both human and animal nutrition.

### 5.2 Impact of Genotype and Environmental Conditions on Protein Quality

The protein quality of hemp seeds is significantly influenced by genetic and environmental factors. Genetic variations among *Cannabis sativa* L. cultivars lead to differences in protein content, amino acid profiles, and digestibility [38]. Environmental conditions, such as soil quality, climate, and agricultural practices, also critically impact protein synthesis and accumulation [6]. Factors like soil nutrients and water availability affect levels of essential amino acids, including arginine, vital for cardiovascular health [4].

Post-harvest processing methods further influence the integrity and bioavailability of hemp proteins [4]. Techniques such as mechanical pressing and solvent extraction can alter protein structures and functional properties [38]. Understanding the genetic and environmental determinants of hemp seed quality is essential for optimizing their nutritional and functional use, given their potential health benefits and applications in food and feed industries [6, 7, 5, 4].

### 5.3 Extraction Methods and Protein Integrity

Protein extraction from hemp seeds is crucial for determining product quality and functionality. Traditional methods like mechanical pressing and solvent extraction can compromise protein integrity due to denaturation [4]. Recent advancements, including ultrafiltration and enzymatic hydrolysis, aim to enhance protein yield while preserving nutritional quality [4]. Ultrafiltration improves purity by separating proteins based on molecular size, while enzymatic hydrolysis increases amino acid bioavailability by breaking proteins into smaller peptides [4].

The emulsifying properties of hemp proteins are vital for functional food development, as stable emulsions rely on protein solubility and interactions with other food components, influenced by extraction methods [38]. Optimizing these techniques is essential to maximize the nutritional benefits of hemp proteins and their applications in diverse food products.

### 5.4 Antioxidant Capacity

Hemp seeds possess significant antioxidant properties, crucial for combating oxidative stress and reducing chronic disease risk. Polyphenols and other bioactive compounds enhance their antioxidant capacity, neutralizing free radicals and protecting cells from oxidative damage. Key phenolic compounds, such as hydroxycinnamic acid amides and lignanamides, contribute to these properties [8, 33, 7]. Optimized extraction methods effectively harness these compounds, positioning hemp seeds as a promising source of natural antioxidants for pharmaceutical and cosmetic applications.



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The antioxidant activity is primarily due to phenolic compounds like flavonoids and phenolic acids, known for scavenging free radicals and preventing lipid peroxidation [3]. Tocopherols and phytosterols in hemp seeds further reduce oxidative stress and inflammation, with tocopherols protecting cell membranes and phytosterols supporting cardiovascular health [39, 16].

Polyphenols also modulate antioxidant enzyme activity, enhancing the body's defenses against oxidative stress [22]. As the role of polyphenols in functional food development gains recognition, their natural antioxidant properties offer a safer alternative to synthetic counterparts, which may pose health risks [10]. Continued research into hemp seed antioxidants will likely expand their applications in functional foods and nutraceuticals [25].

The bioavailability of these antioxidants is crucial for their health benefits, as effective absorption and utilization are necessary for protective effects [25]. Interactions with dietary components and gut microbiota influence absorption and metabolism [34]. As demand for natural health-promoting products rises, hemp seeds are positioned to play a significant role in developing functional foods that enhance overall health and well-being.

## 5.5 Bioavailability and Stability Challenges

Ensuring the bioavailability and stability of hemp seed bioactive compounds, such as polyphenols and antioxidants, is essential for their health benefits [25]. These compounds are susceptible to degradation from environmental factors like light, temperature, and oxygen, which can compromise their efficacy [25]. Complex interactions with dietary components and gut microbiota also influence their absorption and metabolism [34].

Research focuses on advanced delivery systems and processing techniques to enhance bioavailability and stability [35]. Encapsulation technologies, such as nanoencapsulation and electrospinning, protect sensitive compounds from degradation during processing and storage, improving their efficacy [37]. Understanding interactions between polyphenols and the gut microbiome is essential, as these interactions significantly influence the bioavailability and effectiveness of polyphenols in vivo [34].

Innovative methods like nanoencapsulation are being explored to improve the solubility and stability of hydrophobic bioactive compounds, addressing challenges related to low bioavailability and degradation. Recent advancements in synthetic and natural methods aim to enhance the solubility and stability of these compounds, crucial for their effectiveness in food and pharmaceutical applications [14, 36, 37, 22]. As demand for functional foods continues to rise, addressing these challenges is essential for maximizing the health benefits of hemp-derived bioactives and their applications across various industries.

## 6 Hemp Seeds as Functional Food

### 6.1 Enhancing Nutritional Value through Bioactive Compounds

Hemp seeds (*Cannabis sativa* L.) are increasingly valued for enhancing food products' nutritional value through their rich bioactive compounds, notably polyphenols and antioxidants [8]. These compounds offer significant health benefits by combating oxidative stress and inflammation, which are linked to chronic diseases like cardiovascular disorders and cancer. Polyphenols, a key bioactive class in hemp seeds, possess strong antioxidant properties, effectively neutralizing free radicals and reducing oxidative damage [1, 22]. Their interactions with polysaccharides enhance stability and bioavailability, beneficial in food processing for improving nutritional profiles, such as in baked goods [40]. Beyond antioxidants, hemp seeds provide dietary fiber and high-quality proteins, essential for health [8]. Incorporating hemp flour into foods like pasta increases protein and fiber, meeting the demand for plant-based, high-protein foods and functional foods with health benefits beyond basic nutrition [20]. The food industry's interest in hemp seeds as functional ingredients is driven by the demand for natural, health-promoting products [35]. Innovative processing techniques, including nanoencapsulation and electrospinning, are expected to enhance the stability and bioavailability of hemp's bioactive compounds, ensuring their efficacy in health promotion. By leveraging hemp seeds' nutritional attributes, the food industry can create novel products that meet the growing demand for functional foods with enhanced nutritional profiles [5].

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## 6.2 Hemp Seeds in Food Industry Applications

The food industry recognizes hemp seeds (*Cannabis sativa* L.) for their rich nutritional profile and functional properties, making them versatile ingredients in various applications [8]. The rising consumer demand for natural, health-promoting products has led to hemp seeds' integration into diverse items like baked goods, beverages, snacks, and dairy alternatives [5]. Hemp seeds are primarily used in plant-based protein products due to their complete protein profile and high digestibility, appealing to those seeking plant-based options [8]. Incorporating hemp protein enhances food products' nutritional value, aligning with the plant-based diet trend among health-conscious consumers [17]. Additionally, hemp oil, rich in omega-3 and omega-6 fatty acids, supports cardiovascular health and is popular in salad dressings, smoothies, and cooking [16]. Hemp seeds' functional properties, such as emulsification and water-binding capacity, further enhance their appeal in novel food product development [4]. Using hemp flour in baked goods boosts fiber and protein content, delivering desirable texture and flavor [8]. This has led to various hemp-based products, including bread and snack bars, meeting the demand for functional foods [5]. Hemp seeds also serve as a natural antioxidant source, preferred over synthetic alternatives for health reasons [10]. Their polyphenol content enhances food products' shelf life and nutritional profile, offering a natural solution to oxidative stability challenges. As the food industry innovates to meet health-conscious consumer demands, hemp seeds emerge as versatile ingredients. Their exceptional nutritional profile, including high-quality proteins, polyunsaturated fatty acids, and vitamins, positions them as valuable components for functional foods. Hemp seeds' bioactive compounds, such as polyphenols and terpenoids, provide antimicrobial, antioxidant, and anti-inflammatory benefits, enhancing their appeal in health-promoting products. This interest in hemp seeds highlights their potential to transform ordinary foods into nutritionally superior options supporting a balanced, sustainable diet [8, 7]. Continued exploration of hemp seeds' potential in food applications is expected to drive their adoption in the industry, contributing to sustainable, nutritious food options that meet modern consumer demands.

## 6.3 Sustainability and Functional Food Potential

Hemp seeds (*Cannabis sativa* L.) are recognized for their nutritional profile and sustainability, making them promising for functional food applications [26]. Hemp cultivation has minimal environmental impact, requiring low water and pesticide inputs and thriving in diverse climates [14]. Its environmental resilience and soil health improvement through phytoremediation position hemp as a sustainable crop aligning with eco-friendly agricultural practices [26]. Hemp seeds' incorporation into functional foods is driven by their high bioactive compound content, including polyphenols and antioxidants, which offer health benefits [14]. These compounds' antioxidant and anti-inflammatory properties aid in preventing chronic diseases like cardiovascular diseases, diabetes, and cancer. Innovative processing, such as nanoencapsulation and electrospinning, enhances hemp seeds' antioxidant potential by improving bioactive compounds' stability and bioavailability, ensuring efficacy in functional food applications. Hemp seeds' unique nutritional profile, featuring a balanced omega-3 to omega-6 fatty acid ratio, high protein, and dietary fiber, makes them a nutritious food source enhancing various products' nutritional value, addressing the demand for natural, health-promoting options [5]. Developing hemp-based functional foods aligns with the trend towards sustainable, health-oriented food systems, offering viable alternatives to traditional food sources requiring higher environmental inputs [5]. As the functional food industry evolves, hemp seeds' recognition as sustainable, health-promoting ingredients grows [14]. Ongoing exploration of novel extraction and processing methods, such as electrospinning, is expected to enhance hemp seeds' nutritional value and functional properties, facilitating their integration into diverse food products [26]. By leveraging hemp seeds' unique attributes, the food industry can develop innovative products meeting the increasing demand for sustainable, nutritious options, positioning hemp seeds as key players in functional food development [27].

## 7 Hemp Seeds in Food Production

### 7.1 Technological Advancements in Hemp Food Products

Recent innovations in the processing of hemp (*Cannabis sativa* L.)-based food products have notably enhanced the nutritional and functional attributes of hemp seeds. Techniques like ultrafiltration and enzymatic hydrolysis have optimized the extraction of hemp proteins and oils, preserving

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their nutritional integrity while improving solubility and bioavailability for various applications [4]. These advancements enhance the functional properties of hemp proteins, including emulsification, facilitating their incorporation into functional foods that provide additional health benefits [7, 38]. The food industry has seen a rise in hemp-based products, driven by consumer demand for natural, health-enhancing options [5]. Hemp seeds are increasingly used in diverse products like baked goods, beverages, snacks, and dairy alternatives, leveraging their rich nutritional profile [5]. Hemp oil, with its favorable fatty acid composition, is popular in culinary applications such as dressings and spreads [17]. The emulsification and water-binding capacities of hemp seeds improve texture and stability across various food applications [4]. Continued research into innovative processing techniques is crucial for maximizing the nutritional and functional benefits of hemp-based products, which are recognized for their high-quality proteins, essential fatty acids, and bioactive compounds. By optimizing these processes, the food industry can develop functional foods that contribute to a balanced and sustainable diet [5, 7]. Ongoing advancements in hemp food technology are expected to drive industry growth, offering consumers a diverse range of health-promoting and sustainable food options aligned with modern dietary preferences and environmental considerations.

## 7.2 Health Benefits and Consumer Acceptance

The food industry increasingly recognizes hemp seeds (*Cannabis sativa* L.) for their rich nutritional profile and potential health benefits, enhancing consumer acceptance. With approximately 24.66% protein, 32.05% lipids, and 36.10% dietary fiber, hemp seeds are particularly rich in essential fatty acids, including linoleic acid (omega-6) and alpha-linolenic acid (omega-3), which constitute about 75% of their fatty acid content. They also contain bioactive compounds like polyphenols and terpenoids, known for antimicrobial, antioxidant, and anti-inflammatory properties, significantly contributing to overall health and wellness [7, 8, 2, 6, 4]. A key factor in consumer acceptance is the growing demand for natural and functional foods that offer health benefits beyond basic nutrition [14]. Hemp seeds are recognized for enhancing cardiovascular health, supporting immune function, and reducing chronic disease risks, including diabetes and cancer, through the anti-inflammatory and antioxidant effects of their bioactive compounds. Their nutritional attributes, including high-quality protein and favorable fatty acid profiles, further enhance their appeal as functional food ingredients [8]. As a complete protein source with all essential amino acids, they are ideal for those seeking plant-based protein alternatives [8]. Additionally, bioactive peptides in hemp seeds offer benefits like improved cardiovascular health and reduced chronic disease risk. Sustainability in hemp cultivation, requiring minimal water and pesticides, aligns with the growing preference for environmentally friendly food options [14]. This sustainability enhances consumer demand for products that are both health-promoting and environmentally responsible [5]. As research continues to reveal the extensive health benefits and nutritional value of hemp seeds, consumer acceptance is expected to rise, stimulating growth in the hemp food industry and facilitating the development of innovative functional foods, appealing to health-conscious consumers and modern dietary preferences [5, 8, 7].

## 7.3 Potential Applications in Functional Foods and Nutraceuticals

Hemp seeds (*Cannabis sativa* L.) are increasingly recognized for their potential in functional foods and nutraceuticals, attributed to their rich composition of bioactive compounds, proteins, and essential fatty acids. With a comprehensive nutritional profile, including high-quality proteins providing all essential amino acids, hemp seeds serve as an ideal plant-based protein source for vegan and vegetarian diets [8]. Their inclusion in food products significantly enhances nutritional value, addressing the growing consumer demand for health-promoting, plant-based alternatives [5]. Bioactive compounds in hemp seeds, particularly polyphenols and antioxidants, are crucial for their potential as functional food ingredients. Known for their antioxidant and anti-inflammatory properties, these compounds aid in preventing and managing chronic diseases, including cardiovascular diseases, diabetes, and certain cancers. The antioxidant capacity of hemp seeds, attributed to their polyphenol content, offers a natural alternative to synthetic antioxidants, which have raised health concerns [10]. Hemp seeds also provide essential fatty acids, including omega-3 and omega-6, in an optimal ratio supporting cardiovascular health and reducing inflammation [17]. These fatty acids are vital for maintaining healthy cell membranes and promoting heart health, making hemp seeds integral to developing functional foods aimed at promoting heart health [17]. The incorporation of hemp seeds into food products is facilitated by their functional properties, such as emulsification and water-binding capacity, enhancing texture and stability across various applications [4]. This versatility has led to

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a wide range of hemp-based food products, including baked goods, beverages, snacks, and dairy alternatives, catering to the increasing consumer preference for natural and sustainable options [5]. As demand for functional foods and nutraceuticals rises, hemp seeds are well-positioned as a sustainable and health-promoting alternative to traditional food sources. Ongoing exploration of advanced processing techniques, including nanoencapsulation and electrospinning, is expected to enhance the nutritional profile and functional characteristics of hemp seeds. These innovations aim to improve the bioavailability and stability of bioactive compounds, facilitating the effective incorporation of hemp seeds into novel food products that offer additional health benefits while supporting a balanced diet [7, 8, 26, 5, 4]. By leveraging the unique attributes of hemp seeds, the food industry can meet the evolving preferences of health-conscious consumers, contributing to the growth of the functional food and nutraceutical markets.

## 8 Conclusion

### 8.1 Challenges and Future Research Directions

Hemp seeds (*Cannabis sativa* L.) hold significant promise as a functional food source, yet several challenges must be addressed to fully realize their potential. The variability in nutritional composition due to genetic diversity, environmental conditions, and cultivation practices poses a major challenge. Establishing standardized benchmarks is crucial for ensuring consistent quality across hemp-derived products, facilitating reliable comparisons and consumer trust.

The bioavailability and stability of bioactive compounds, such as polyphenols and antioxidants, are critical for realizing the health benefits of hemp seeds. These compounds are susceptible to degradation by environmental factors, which can diminish their efficacy. Their interactions with dietary components and the gut microbiota further complicate their absorption and metabolic pathways, leading to variability in health outcomes.

Advancing processing techniques to enhance the stability and bioavailability of hemp seed bioactives is a priority for future research. Technologies like nanoencapsulation and electrospinning offer promising avenues for preserving the nutritional integrity of these compounds, ensuring their effective integration into functional foods and nutraceuticals. Additionally, refining extraction methods and exploring natural antioxidants are essential for improving consumer acceptance and addressing flavor and sensory challenges.

Exploring genetic variations among hemp cultivars and their impact on protein profiles presents another research opportunity. Understanding these genetic differences can inform breeding programs aimed at optimizing the nutritional and functional attributes of hemp seeds, enhancing their role as a sustainable, health-promoting food source.

Moreover, large-scale human trials are necessary to validate the therapeutic potential of hemp seed bioactives, such as polyphenols. These studies are vital for confirming the safety and efficacy of hemp-derived compounds in promoting health and wellness. Innovations in polyphenol formulations and delivery methods, such as nanoencapsulation, can further improve the solubility and stability of these compounds, maximizing their benefits in functional foods and nutraceuticals.

Understanding the interactions between polyphenols and the gut microbiome is also crucial, as these interactions significantly influence the bioavailability and effectiveness of polyphenols in vivo. Addressing these challenges is essential for unlocking the full potential of hemp-derived bioactives and ensuring their effective application in health promotion. By advancing research in these areas, the food industry can develop innovative hemp-based products that cater to the growing consumer demand for natural, health-enhancing food options, positioning hemp seeds as a pivotal component in the future of functional food development.

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