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REVIEW ARTICLE

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Hemp seed as an emerging source of nutritious functional ingredients

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ABSTRACT
Industrial hemp (*Cannabis sativa* L.), cultivated for its low THC content (<0.3%), is increasingly valued for its nutrient-rich seeds and broad applications in human nutrition. This review offers a holistic analysis of hemp seed utilization, covering agronomic, nutritional, processing, and economic aspects. Agronomic practices and environmental factors considerably influence the seed's nutritional profile, which includes high levels of complete proteins, essential fatty acids with an optimal ω-6 to ω-3 ratio, dietary fiber, and micronutrients. Hemp seeds also contain bioactive compounds with antioxidant and anti-inflammatory properties providing further health benefits and economic value. Advancements in processing methods, such as germination, fermentation, and cold pressing have enhanced nutrient bioavailability and reduced antinutritional factors, supporting the development of functional foods. Economically, the hemp seed market shows strong growth potential, driven by consumer demand for plant-based, sustainable food sources. However, challenges persist in scaling production and standardizing quality across supply chains. Hemp seeds represent a sustainable, nutrient-dense food ingredient with momentous potential to support health and diversify agricultural economies. Continued interdisciplinary research and supportive policy frameworks are essential to unlock their full value in the human diet.

KEYWORDS
Industrial hemp; plant proteins; bioactive compounds; nutrition; dietary fiber

1. Introduction

Hemp, which belongs to the *Cannabaceae* family, is a sustainable, versatile, high-yielding, and environmentally friendly crop that can provide raw materials for many applications (Carus et al. 2013). Hemp is usually grown as a crop to produce grain (commonly known as a seed) or fiber. Different parts of the hemp plant are useful for different applications, such as hemp stalk fiber, which can be used in the textile industry, and hemp seeds, which can be used in the food industry. Hemp oil, flowers, and leaves are useful in the pharmaceutical industry. Hemp, as a plant, is gaining attention because of the lessening of some regulations for hemp cultivation. Therefore, researchers are focusing more on how this plant material can be optimized for various applications.

The global industrial hemp market size was 9.24 billion USD in 2024 and is projected to reach 26.44 billion USD by 2031, at a compound annual growth rate (CAGR) of 14.05% from 2024 to 2031 (VMR 2024). Legalizing industrial hemp cultivation in different countries is expected to be a key driver of market growth. Globally, the North American region is expected to grow faster, especially in the United States and Canada (Mordor Intelligence 2022). The North American hemp market experienced a large growth period from 2015 to 2020. The North American hemp market is expected to grow at a CAGR of 15.67% between 2024 and 2032 (imarc 2024). The key factors behind North America's industrial hemp market growth are the nutritional value of hemp-based food, consumer inclination toward protein-rich food, adoption of vegan foods, and awareness of biobased food packaging (Mehwish and Muzamail 2023). According to the literature on cannabidiol (CBD) hemp production in Connecticut, the total production cost per acre is 19,289 USD where two-third of the cost varies depending on the level of production. Total revenues are 24,375 USD per acre, considering local price of 1.50 USD and 6.5% CBD, which leads to a profit of 5,086 USD per acre (Jelliffe, Lopez, and Ghimire 2020).

As the popularity of hemp products continues to grow, several studies have been conducted on the economic feasibility of crops. The total cost of production for fiber and grain (seed) crops has been estimated at USD 1155–1005 per metric ton and 2911–3566 per metric ton, respectively. Field production costs are highly impacted by the cost of fertilizer and seed, while the main factors for fiber processing costs are facilities and labor (Khanal and Shah 2024). Studies show that there is a high potential for profit for farmers; however, the price of hemp products needs to trend upward without severe price fluctuations (Khanal and Shah 2024; Kumar, Mazhar, and Nawaz 2024; Odiase 2022; Patalee, Jeong, and Mark 2024). Spent hemp seed is a possible alternative to alfalfa legume and grass hay; thus, there are some opportunities for the hemp market if its approval for use in

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animal feed continues. Overall, there is likely to be more return on investment at later stages of value addition for the hemp market, and it will be critical to create more uses of industrial hemp to increase demand and stabilize the market for growers (Odiase 2022). While hemp fiber utilization has some potential for market development, there is a lot further to go to increase hemp seed in food products to develop a stable market for growers.

Recent studies have investigated the application of hemp seeds in various food products, including pasta (Bonacci et al. 2023), bread (Sciacca et al. 2023), gluten-free cakes (Hayit et al. 2024), yogurts (Nakov et al. 2023), and plant-based meat analogs (Amagliani et al. 2023; Zahari et al. 2023), and many others. Studies have investigated the functionality of hemp cake and its impact on end-product quality and nutritional profile (Bonacci et al. 2023). Other research has focused on how the fortification of foods with hemp cake affects sensory properties in addition to overall nutrition and quality (Sciacca et al. 2023).

In addition to the fortification of products, significant work has been conducted on the utilization of meat and dairy alternatives. Thus far, researchers have found that hemp proteins must be co-extruded with other protein sources, such as wheat, pea, or soy, to produce meat-like textures (Amagliani et al. 2023; Zahari et al. 2023). Amagliani et al. (2023) proposed that the reason that hemp seed protein does not extrude on its own is the high amount of edestin (11S globulin) macromolecular complexes. The edestin complex inhibits the formation of the desired fibrous texture. However, hemp protein has been shown to improve texture when incorporated into soy or pea protein concentrates (Amagliani et al. 2023). The desire to utilize hemp seed products in various food products may stem from the copious amount of research showing the superior nutritional value of hemp seed and its products (Cai et al. 2023; Miguel-Albarreal et al. 2024; Nissen et al. 2023; van Klinken, D'Adamo, et al. 2024; van Klinken, Stewart, et al. 2024). Thus, the agronomic and economic potential, combined with the functional and nutritional value of hemp seeds, illustrates its potential.

This review aims to provide an overview of hemp seed nutritional value and how it can be fractionated into separate components and utilized in various food products. Hemp seeds have traditionally been used as a food source because of their high nutritional value (Matthäus and Brühl 2008). Hemp seeds have also been used as medicine in China for at least 3000 years. In North America, hemp seeds are used as human food, paint, varnish, and bird food (Callaway 2004). With the renewed legalization of industrial hemp cultivation in the U.S. and the ever-increasing interest in the utilization of hemp seeds for human food, it is important to understand the key nutritional contributions of this crop to the human diet. In this study, we focused on hemp seed nutritional facts, the specific locations of specific nutritional benefits, and how these can be used for various applications. This review presents a novel holistic farm-to-fork approach to provide a compendium of agronomic and processing effects on hemp seed nutritional composition, and how this relates to the functionality and utilization of hemp seed and its components for food and human nutrition.

2. Brief history of industrial hemp cultivation

Hemp is thought to have originated in Central Asia (De Candolle 1883; Vavilov 1951), and traces of hemp fruit were found at 8260 BC in Okinoshima, central Japan (Okazaki et al. 2011). According to archaeological findings and ancient records, hemp cultivation in China dates back to at least 6000 years ago (Yang 1991). Hemp was introduced to Europe somewhere between 1000 and 2000 BCE, followed by widespread cultivation after 500 BCE (Small and Marcus 2002). Hemp textile remains have been found in grave mounds in Gordion, Turkey, since the seventeenth century BC (Dhondt and Muthu 2021). During the twentieth century, hemp production in Europe declined progressively owing to increasing labor costs and the continuing diffusion of synthetic fibers (Allavena 1962).

Hemp was first brought to North and South America in 1545 and 1606, respectively, when it was mainly grown for fiber production (Cherney and Small 2016; Miller 1991; Pretot, Collet, and Garnier 2014). Hemp was first imported to North America in New England (Dhondt and Muthu 2021), where it was grown as a commodity fiber crop from the mid-eighteenth century until the 1930s (Rupasinghe et al. 2020). Subsequently, hemp production ceased, following the Marihuana (SIC) Tax Act of 1937 (Deitch 2003). During WWII, the production of hemp was encouraged due to the unavailability of other fibers (Callaway 2004). However, the prohibition resumed after WWII when hemp production in North America ceased (Deitch 2003). Commercial hemp production was legalized by Farm Bill in 2018 (Mark et al. 2020). A brief history of hemp is presented in Figure 1.

More than 30 countries are involved in industrial hemp production owing to their high potential (Rachel Jacob et al. 2022). Canada, Europe, and China are the three major hemp-producing regions by production area. Canada has the highest hemp production area of ~138,000 acres, followed by Europe at more than 70,000 acres, and China at ~30,000 acres (Zhao, Wang, et al. 2022). While industrial hemp has been cultivated since early in human history, modern prohibition, regulation, and stigmatization have caused major setbacks in its production and utilization. These setbacks require work in some of the most basic and fundamental areas of industrial hemp seed cultivation and use in food. Thus, producers and processors must understand how to develop a consistent supply of hemp seeds by maintaining the agronomic, nutritional, and functional qualities of the seeds. The following sections outline the nutritional value of hemp seed macro- and micronutrient components in relation to agronomic practices and food processing.

3. Nutritional components of hemp seed

Hemp seeds are considered one of the most nutritionally complete food sources because of their high nutritional value. It can be consumed in various forms, such as hulled

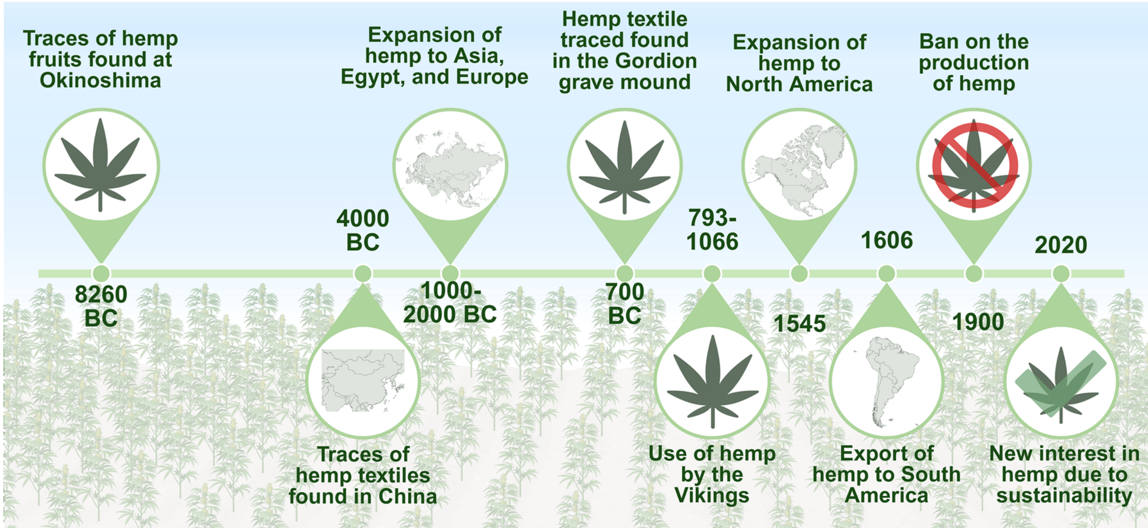

Figure 1. Brief history of hemp adapted from Dhondt and Muthu (2021) (created in BioRender).

(whole seed), dehulled (kernel) seed, or processed products, such as oil, flour, or protein powder (Farinon et al. 2020). Hemp seed composition can vary depending on genotype and environmental factors (Campbell et al. 2019; Galasso et al. 2016; Lan et al. 2019; Lančaričová et al. 2021; Mihoc et al. 2012). Campbell et al. (2019) determined that growing environment has a strong effect on traits, such as yield, plant height, and water usage. The study determined that variety is more closely linked to traits, such as days to maturity, THC, and CBD production (Campbell et al. 2019). Lan et al. (2019) found that the growing year impacted the mineral content of the hemp seed but not the proximate composition for hemp seed varieties grown in North Dakota, USA. On the other hand, a study conducted in Slovakia resulted in significant ($p < 0.05$) differences in the lipids, fatty acids, the ratio saturated:polyunsaturated fatty acids, total dietary fiber, and protein. The growing year was also found to impact the lipid and dietary fiber content of the hemp seeds. It was determined that increased precipitation generally results in lower oil content (Lančaričová et al. 2021). While there are many studies showing composition of several varieties of hemp seed at a single location, additional work should be done to compare the same sets of varieties across different locations. It is evident that certain varieties perform better in specific environments, while other varieties are stable across different environments (Campbell et al. 2019).

Table 1 shows the typical ranges of hemp seed nutrients in the different parts of the seed. Whole hemp seeds contains ~21–28% protein with essential amino acids, 24–36% lipid with a balanced fatty acid composition, and 28–34% fiber with a high percentage of insoluble fibers, along with vitamins and minerals. In addition, hemp seeds contain minor components, including phenolic compounds, tocopherols, carotenoids, and phytosterols, which are mainly affected by environmental and agronomic factors (Irakli et al. 2019). Due to the high oil content and lack of starch hemp seeds, it is considered to be in the classification of oil seeds rather than being classified as cereal grains or legumes.

Table 1. Nutritional value of different parts of hemp seed (Rizzo, Storz, and Calapai 2023).

Nutrient	Fraction	Whole	Dehulled	Meal	Hull	Oil
Protein	Total (%)	21–28	36	41	13	
	Arginine (%)	2.28–3.10	4.55	3.91	0.94	
Lipids	Total (%)	24–36	47	10	10	100
	PUFA (%)					72–84
	LA (%)					52–59
	ALA (%)					10–22
	SDA (%)					0.2–2
	n6:n3					2.5–5.5
Fiber	Total (%)	28–34	8	30	65	
	Insoluble (%)	22–31				
	Soluble (%)	3–5				
Sterols	Total (mg/100 g)	124				279
	B-Sitosterol	54–80				190
Tocopherols	Total (mg/100 g)	61–135				14–97
	γ-Tocopherol (mg/100 g)	1–295				15–89
Minerals	Ca (mg/100 g)	90–255				
	Fe (mg/100 g)	4–240				

However, hemp seeds are also high in protein and dietary fiber, which provides additional nutritional value to this crop. As fat and protein are the two energy sources provided by hemp grain, the quality and functionality of these two components are of great concern in the food industry.

Galasso et al. (2016) reported that, in a study of several cultivars grown in Italy, the variability of traits, such as total protein, oil content, and α-linolenic acid (ALA) content seemed to be higher in hemp seed accessions than in hemp cultivars. The variability of macronutrients among different cultivars could drive the need to target specific cultivars for a particular end use. For example, cultivars with higher protein content could be diverted to the production of meat analogs, whereas those with higher lipid content should be utilized for oil production. Lan et al. (2019) determined that the crop year did not affect the macronutrient composition of hemp seed but had a significant ($p < 0.05$) impact on the nutritional minerals of hemp seeds. According to Mihoc et al. (2012), drought during the growth period results in a

Table 2. Mineral element content for different hemp seed vaireties (Alonso-Esteban, Torija-Isasa, et al. 2022).

	Bialobrzeskie	Carmagnola	Fedora 17	Felina 32	KC Dora	Kompolti	Santhica 27	Tiborszallasi	Average
	Whole hemp seed								
Na	2.96	4.16	2.78	3.67	2.99	1.45	1.30	2.70	2.75
K	311.5	616.7	709.3	551.9	656.4	713.6	582.0	415.1	569.6
Mg	381.8	394.9	410.9	367.1	365.9	375.5	360.8	410.6	383.4
Ca	205.1	211.9	189.0	181.7	161.3	137.3	146.3	172.0	175.6
P	835.4	810.3	876.4	870.4	874.5	880.5	893.8	928.1	871.2
Mn	8.81	9.71	6.47	7.41	7.34	5.55	6.07	8.46	7.48
Fe	10.11	10.65	6.45	7.72	6.39	6.05	7.26	9.70	8.04
Cu	1.77	2.20	2.76	2.67	1.63	2.82	2.79	1.76	2.30
Zn	8.81	9.71	6.69	7.02	7.11	7.84	7.88	8.46	7.94
Ca/P	0.19	0.20	0.17	0.16	0.14	0.12	0.13	0.14	0.16
					Hulled hemp seed				
Na	1.33	1.43	1.33	0.97	1.13	1.79	1.43	1.86	1.41
K	792.5	1067.7	990.4	899.9	991.6	866.9	968.4	778.8	919.5
Mg	518.8	934.2	786.5	578.3	868.4	482.3	821.0	585.4	696.9
Ca	87.86	91.99	76.73	74.06	94.00	65.01	81.71	81.00	81.55
P	1156.1	1145.3	1122.8	1003.9	1114.0	1201.7	1042.5	1009.3	1099.5
Mn	9.14	5.48	5.15	3.53	5.90	3.74	4.49	4.00	5.18
Fe	10.89	9.60	6.57	5.10	9.78	5.87	6.83	7.33	7.83
Cu	1.89	1.81	1.30	1.62	1.45	1.45	1.31	1.02	1.48
Zn	9.14	9.45	11.20	8.18	12.74	8.78	10.27	8.74	9.81
Ca/P	0.06	0.06	0.05	0.06	0.07	0.04	0.06	0.06	0.06

decreased oil content in hemp seeds. Genetic differences and growing conditions have also been linked to significant ($p < 0.05$) differences in phenolic content and antioxidant activity among hemp seed cultivars (Irakli et al. 2019). It is important to consider how genetic and environmental factors affect the nutritional profiles of hemp seeds. Producers may want to select cultivars that are well-suited to their growing region for both agronomic traits and nutritional value.

Alonso-Esteban, Torija-Isasa, et al. (2022) quantified the mineral content of hemp seeds from different cultivars. Table 2 shows the mineral contents of the different varieties of hemp seeds. The most abundant mineral found is phosphorus, with an average value of 871.2 mg/100 g whole seeds. Potassium and magnesium contents are higher in hulled seeds, with an average value of 919.5 mg/100 g seeds and 696.9 mg/100 g seeds, respectively. On the other hand, calcium content is higher in whole seeds (175.6 mg/100 g seeds) than in hulled seeds (81.55 mg/100 g seeds). Besides that, microelements are abundant in the whole seed with a higher amount of iron (8.04 mg/100 g), copper (2.30 mg/100 g), and manganese (7.48 mg/100 g) (Alonso-Esteban, Torija-Isasa, et al. 2022). In general, the mineral content is greatly affected by soil conditions and growing locations. The mineral composition of the soil at an individual growing location dictates the amount and type of minerals that can be taken up by the hemp plant.

According to the nutrient reference values (NRVs) set by the European Union (CFR 1977), both whole and hulled hemp seeds can be considered high in Mn, Mg, P, Cu, and Zn, as their percentage is higher than the set value of 30%. Figure 2(a) shows the percentage of minerals in whole and hulled hemp seeds (100 g serving size) and their contributions to NRVs. Figure 2(b) shows the same percentage, but with a 30 g serving size. Overall, hemp seeds contain highly valuable macronutrients, a plethora of micronutrients, and bioactive compounds. The nutritional properties of specific components of hemp seeds are discussed in the following sections.

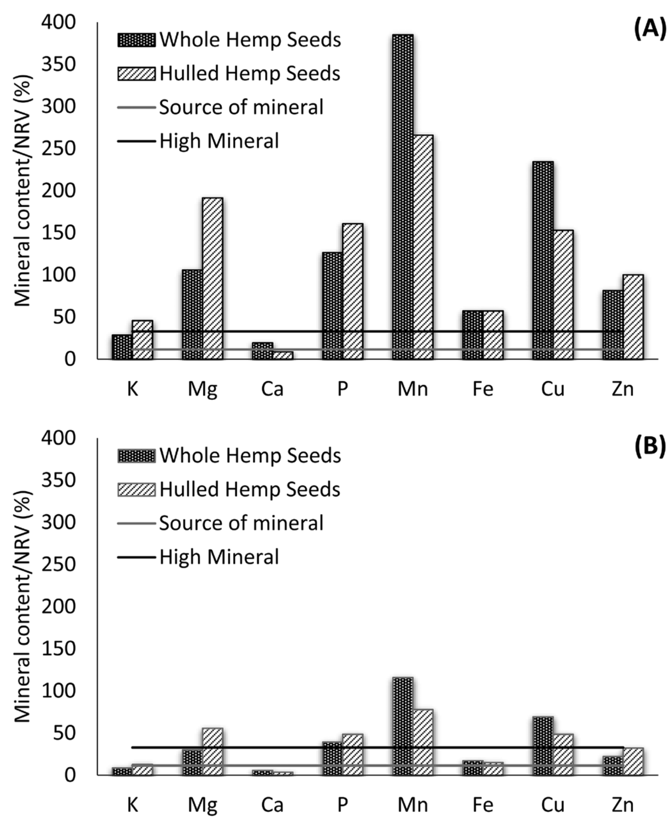

Figure 2. Contribution (%) to the nutrient reference values (NRV) of 100 g (a) and 30 g (habitual serving size) (b) of whole and hulled hemp seeds. In (a), lines represent the minimum level that allows nutritional claims in food labeling, according to EU Regulations No 1924/2006 and No 1169/2011*Data and graph adapted from Alonso-Esteban, Torija-Isasa, et al. (2022).

3.1. Hemp seed oil

Hemp seed oil (HSO) is an excellent source of nutrients and bioactive compounds. It has a very high content of essential fatty acids consisting of around 80% of polyunsaturated fatty acids (PUFA) (Porto, Decorti, and Natolino 2015). Essential fatty acids maintain the cell membrane structure and skin

Table 3. Fatty acid profile of hemp seed oil quantified by gas chromatography (Montserrat-de la Paz et al. 2014).

Fatty acid	Percentage (%)
Palmitic acid (16:0)	5.62
Palmitoleic acid (16:1)	0.31
Stearic acid (18:1)	2.68
Oleic acid (18:1)	11.90
Linoleic acid (18:2, ω-6)	55.05
Eicosanoic acid (20:0)	2.50
α-Linolenic acid (18:3, ω-3)	16.70
γ-Linolenic acid (18:3, ω-6)	3.40
Eicosenoic acid (20:1)	1.44
Docosanoic acid (22:0)	0.40
Saturated fatty acids	11.20
Monounsaturated fatty acids	13.34
Polyunsaturated fatty acids	75.46
P/S ratio	6.7
ω-6/ω-3 ratio	3.5

integrity (Faugno et al. 2019) making them critical for a healthy diet. Table 3 shows the detailed fatty acid profiles of the hemp seed oil. The major unsaturated fatty acids are linoleic acid (C18:2 ω-6; 50–60%) and α-linoleic acid (C18:3 ω-3; 20–25%), which are usually in the optimal ratio for human nutrition of 3:1 for ω6 and ω3 (Dunford 2015; Hazekamp et al. 2010). However, this ratio can vary depending on climate, farming, fertilization, light conditions, cultivar type, and processing conditions (Arango et al. 2024; Devi and Khanam 2020; Przybylska-Balcerek et al. 2024). The ω6/ω3 ratio of commercial Italian hemp oils varied between 1.71 to 2.27 (Izzo et al. 2020). Abdollahi et al. (2020) studied hemp varieties cultivated in three different regions of Iran and found that the ω6/ω3 ratio varied between 2.59 and 7.88. Iranian indigenous cultivars had lower ω6/ω3 ratios than the ω6/ω3 ratio of the French cultivar when grown in three regions of Iran (Abdollahi et al. 2020). This indicates that it is important to select cultivars that are well-suited to individual growing regions to produce high-quality oil with better nutritional properties. Additionally, the ω6/ω3 ratio of hemp seed oil is better than that of soybean oil, which has higher ratios due to the lack of α-linolenic acid (Arango et al. 2024). Hemp seed oil contains a desirable ω6/ω3 ratio, because lower ratio values are linked to better health outcomes and decreased total mortality. Hemp seed oil is one of the best plant sources of ω3 fatty acids and is important for meeting the dietary requirements of people consuming plant-based diets. Additionally, hemp seed oil could be an important source of vegan dietary supplements of ω3 fatty acids.

Hemp seed oil is most often extracted using cold pressing to produce high-quality oil that does not undergo thermal damage. Cold pressing is one of the least efficient oil extraction methods. Cold pressing leaves much of the oil in the hemp cake after oil extraction, and thus, work has been done to find extraction methods with higher yields. Researchers have used different oil extraction methods and found that the Soxhlet extraction method provides the optimum ratio of ω6/ω3 in hemp oil. The Soxhlet extraction (70 °C for 8 h with a solvent to solid ratio of 8:1 v/w) method is relatively low cost a high oil yield (Da Porto, Decorti, and Tubaro 2012; Rezvankhah et al. 2019). The yield of oil was ~30 g oil per 100 g hemp seed, resulting in 100% recovery of the oil through Soxhlet extraction (Da Porto, Decorti, and Tubaro 2012). However, Soxhlet extraction involves hazardous chemicals, and the extraction process is time-consuming. Moving forward, greener technologies for hemp oil extraction should be employed to maintain quality while maximizing the yield.

Techniques, such as supercritical carbon dioxide extraction and microwave-assisted extraction have the potential to improve the Hemp oil extraction process. One study tested supercritical carbon dioxide extraction at temperatures of 40,60, or 80 °C; 300 or 400 bar of pressure; 10 kg/h flow rate; and 30, 45, or 60 kg CO_2/kg feed. The ω6/ω3 values for hemp seed oil extracted with supercritical carbon dioxide were similar to those extracted using the Soxhlet method. However, supercritical carbon dioxide extraction led to lower yields under all conditions and lower oil quality under many of the extraction conditions when compared to Soxhlet extraction (Da Porto, Decorti, and Tubaro 2012). Additionally, Allay, Benkirane, Ben Moumen, et al. (2025) found that modifying the carbon dioxide for super critical fluid extraction (SFE) with 10% ethanol resulted in the best oil yield (30.13%) and highest total phenolic content (294 GAE mg/kg). Muangrat and Kaikonjanat (2025) determined that supercritical carbon dioxide resulted in higher yield than screw press methods. The oil obtained with SFE also had higher antioxidant capacity than that obtained by screw press (Muangrat and Kaikonjanat 2025)

Rezvankhah et al. (2019) used microwave-assisted extraction with 300, 450, or 600 W of power for 5, 10, or 15 min. Microwave-assisted extraction had slightly lower yields than the traditional Soxhlet method; however, the oil quality was significantly improved. Microwave-assisted extraction significantly ($p < 0.05$) improved oxidative stability and maintained a ω6/ω3 ratio similar to that of Soxhlet extraction. The optimized microwave-assisted extraction conditions (450 W for 7.13 min) resulted in a significantly ($p < 0.05$) lower peroxide value and significantly (P.05) higher radicle (DPPH) scavenging activity than the oil obtained from Soxhlet extraction (Rezvankhah et al. 2019). Thus, the oil obtained by microwave-assisted extraction could have better oxidative stability and longer shelf life than that obtained by Soxhlet extraction. Allay, Benkirane, Moumen, et al. (2025) found that the ethanol percentage and microwave power have large impacts on the oil quality and specifically on the phenolic content. A maximum oil yield of 30.69% was achieved with 800 W of microwave power, using 7.5% ethanol for 13.60 min (Allay, Benkirane, Moumen, et al. 2025). These studies show the benefits of employing a green extraction technique, especially when the goal is to generate a biologically active oil.

In a study of commercial cold-pressed hemp seed oils, the nutritional quality varied widely. Oxidative stability varied among the samples, and some did not meet the Codex standards for cold-pressed oils. Among commercially available hemp seed oils, the free acidity ranged from 0.89 to 4.58 mg KOH/g, and peroxide values ranged from 3.97 to 23.89 $mEqO_2$/kg. The ω6/ω3 ratios of commercial cold-pressed oils ranged from 2.60 to 3.67 (Tura et al. 2023). Owing to their lower oxidative stability, it is important to consider appropriate storage to maintain the quality of cold-pressed oils. Enzyme treatments have also been used to increase the yield of cold-pressed hemp seed oil. Various commercial carbohydrase cocktails and one commercial protease were used to extract oil from hemp seeds. The use of all enzymes resulted in significantly ($p < 0.05$) more oil (28.4–32.8%) being obtained after extraction as compared to the control (26.7%). Enzyme-aided extraction did not affect the oxidative stability of hemp seed oil, with peroxide values being similar among the samples. Additionally, the total tocopherol content was significantly ($p < 0.05$) higher for many oil samples obtained by enzyme-aided extraction (Latif and Anwar 2009). The addition of enzymes can open up the fibrous structure of hemp seeds, allowing for a more complete extraction of high-quality oil from hemp seeds. In general, variations in cold-press processing parameters can significantly affect the yield and quality of hemp seed oil (Golimowski et al. 2023; Latif and Anwar 2009; Tura et al. 2023). These studies, along with the fatty acid composition of hemp seed oil, indicate that there is substantial benefit in developing novel processes for the extraction of high-quality hemp seed oils.

Hemp seed oil also contains other beneficial compounds, such as tocopherols (Vit. E), carotenoids (Vit. A), phytosterols, and phenolic compounds. Hemp seeds and oil are valuable sources of vitamin E, and serving (30 g) can contribute substantially to meeting the daily average intake (AI) requirements (Farinon et al. 2022). A study by Tura et al. (2023) indicated that differences in production methods affect the quality and nutritional value of cold-pressed hemp seed oils. γ-Tocopherol ranged from 594 to 967 mg/kg. Additionally, the chlorophyll content ranged from 0.78 to 75.7 mg/kg, and the carotene content ranged from 2.53 to 33.9 mg/kg (Tura et al. 2023). These results highlight the need to control agronomic practices and process parameters to maintain high-quality oils with the best nutritional properties. Additionally, processing conditions could be tailored to maximize the amount of these beneficial compounds in hemp seed oil, resulting in an abundance of natural antioxidants to maintain oil quality.

Farinon et al. (2022) found that the total tocopherol content of the cultivars F75 and Sj was similar (28.57 and 25.00 mg/100 g dry weight, respectively), yet there were small significant ($p < 0.05$) differences in the α-tocopherol content between the two cultivars. This study also found that malting did not affect the total tocopherol content in one cultivar, but increased the total tocopherol content in the other cultivar. The study proposed that α-tocopherol might be more susceptible to heat, as the α-tocopherol content decreased in samples malted at 70 °C *versus* those malted at 50 °C (Farinon et al. 2022). A study on roasted hemp seeds confirms the finding that heating results in decreased tocopherol content in hemp seed oil. The total tocopherol content decreased significantly ($p < 0.05$) in hemp seed oil obtained from seeds roasted at 140, 160, and 180 °C for up to 60 min (Özdemir, Bakkalbaşı, and Javidipour 2021). Another study on enzyme-assisted extraction of hemp seed oil showed a significant ($p < 0.05$) increase in total tocopherol content in oil obtained by enzyme-assisted extraction methods compared to that of the control oil (Latif and Anwar 2009). In general, processing greatly impacts the vitamin content of hemp seed oil, and gentler processing methods may be better for maintaining the levels of fat-soluble vitamins.

Frankowski et al. (2023) conducted a study on the effect of mineral fertilization during plant growth on the bioactive compound content of hemp seeds and oil. The hemp variety Henola was grown with various fertilization regimens, and it was determined that the total oil content was not affected, with minor impacts on the fatty acid profile. These authors also reported differences in phenolic compounds, carotenoids, phytosterols, and tocopherols when different fertilization regimes were used (Frankowski et al. 2023). These compounds contribute to the nutritional quality of oil by acting as antioxidants and key vitamins. Additionally, many bioactive compounds in hemp seed oil have antioxidant and radical-scavenging activities that enhance the stability and overall quality of these oils.

Other studies have shown that processes, such as bleaching also affect the fatty acid profile of hemp seed oil (Golimowski et al. 2023). Although the type of bleaching agent did not have significant ($p < 0.05$) effects on the oil, the bleaching process, in general, produced beneficial effects. Bleaching of hemp seed oils reduces the saturated fatty acid content and, in turn, increases the amount of polyunsaturated fatty acids (Golimowski et al. 2023). Studies have also shown the impact of enzyme-assisted cold pressing (Latif and Anwar 2009) and roasting (Özdemir, Bakkalbaşı, and Javidipour 2021) on the quality and nutritional value of hemp seed oil. Overall, additional studies are needed to determine the best agronomic and processing practices to maintain the highest nutritional value and quality of hemp seed oil. In addition, the high content of bioactive compounds in hemp seed oil requires additional work and evaluation to determine the possible treatment of various health conditions and chronic diseases.

3.2. Hemp seed protein

Hemp seeds contain proteins with high biological value and an amino acid profile that is comparable to or, in some cases, superior to those of casein and soybean meal (Callaway 2004; Tang et al. 2006; Wang and Xiong 2019). The two main storage proteins in hemp are edestin (globulin) and albumin. The edestin typically accounts for 60–80% of the total protein, with the remainder being albumin. Hemp edestin has a structure similar to that of hexameric soy glycinin, comprising of six identical subunits. Each subunit is further composed of an acidic and basic subunit linked by one disulfide bond. Albumin in hemp contains fewer disulfide-bonded proteins and is more flexible with a less compact structure than edestin (Wang and Xiong 2019).

Soy protein isolate (SPI) is highly refined, containing at least 90% protein by weight. SPI is produced through a multi-step process involving extraction, separation, and drying. The main extraction technique is alkaline extraction and acid precipitation. The extraction of proteins and separation of fibers are done by the alkaline extraction process prior to obtaining the protein isolate through acid precipitation. On the other hand, hemp protein isolate (HPI) is a concentrated form of protein originating from hemp seeds that have been defatted to remove most of the oil. Then, the extraction of the HPI is conducted using alkali extraction and acid precipitation, similarly to the SPI. Hemp meal protein content can be higher than that of soy meal, while the protein contents of hemp protein isolate (HPI) and SPI may be similar. Additionally, HPI contains protein subunits in the range of 18–46 kDa. SPI has similar bands with the addition of two higher-molecular-weight subunits (α and α′). However, HPI was found to have a low solubility under neutral conditions. However, the solubility of HPI under acidic conditions is similar to that of SPI (Tang et al. 2006).

However, it is important to note that the extraction conditions affect the composition and structure of the proteins in HPIs. These differences alter the quality and functionality of HPI. When comparing alkali extraction with isoelectric precipitation to salt-extracted proteins, salt extraction resulted in significant ($p < 0.05$) extraction yield, protein recovery yield, and crude protein content. The alkali-extracted-isoelectric point precipitated proteins had significantly ($p < 0.05$) higher contamination with lipids and carbohydrates (Fang et al. 2023). Thus, when high-purity HPI is desired, salt extraction may be preferable. Salt extraction also resulted in changes in the protein secondary structure, with a larger proportion of α-helix and random coil conformations and a lower proportion of β-sheets. Salt extraction also improves foaming capacity and emulsifying activity at pH 3 (Fang et al. 2023). Considering the differences in the molecular structure and functionality of HPI compared to SPI, alterations in formulation and processing technologies may be needed to utilize HPI. However, there could be specific applications where the functionality of HPI is considered superior to that of SPI. In addition to hemp seeds with high protein content, the protein has a good amino acid profile and nutritional value.

Hemp seeds contain a very high amount of arginine (12% of hemp seed protein), which is higher than potato, maize, wheat, rice, egg white, soy, rapeseed, and whey (Callaway 2004). Arginine is an integral component of mammalian proteins and acts as an intermediate in the urea cycle as a free amino acid. Arginine indirectly aids in immunity by acting as a substrate for various nitrogen-containing compounds (Nieves and Langkamp-Henken 2002). Hemp seed protein contains nearly double the amount of arginine compared to proteins from other staple foods, such as potato, wheat, maize, rice, soy, egg white, and whey. The arginine/lysine ratio of hemp protein is 3.0–5.5, which is higher than that of soy protein isolate (1.41) or casein (0.46). This remarkably high arginine/lysine ratio makes hemp seed a valuable ingredient in the development of functional foods that promote cardiovascular health. High arginine/lysine ratios make hemp protein a valuable ingredient for foods to promote cardiovascular health. This is partly due to arginine's role as a precursor to nitric oxide, which acts as a vasodilator that enhances blood flow and maintains normal blood pressure (Wang and Xiong 2019). In addition, it contains a high amount of glutamic acid and a substantial amount of sulfur-containing amino acids. When compared to SPI, HPI had lower isoleucine, lysine, and phenylalanine levels, but other essential amino acids were higher in HPI than in SPI. Overall, the ratio of essential to total amino acids was significantly ($p < 0.05$) higher for HPI than SPI. Hemp seed protein has a very balanced amino acid profile and meets the FAO/WHO requirements for many essential amino acids (Wang et al. 2008).

Amino acid scores, determined by the completeness of the hemp seed protein, vary due to differences in the raw material source. Tang et al. (2006) found that the sulfur-containing amino acids methionine and cysteine were the first limiting amino acids, followed by lysine. In a different study, House, Neufeld, and Leson (2010) found that lysine (with an amino acid core of 0.62) was the first limiting amino acid, followed by tryptophan (with an amino acid score of 0.87) and leucine (with an amino acid score of 0.94). The hemp seed heart has comparatively higher amino acids than the hull, resulting in a higher amino acid profile in hemp meal after dehulling because of the removal of protein lacking the outside layer. In comparison to other plant protein dietary sources, hemp protein is in the same range as cereal grains (corn 0.54 and wheat 0.44) with regard to lysine limitation. Other oil seeds contained a higher proportion of lysine, resulting in higher relative amino acid scores (soy meal 1.05 and canola meal 1.01). However, the amino acid score is only a single measure of protein quality, and the ability of a protein to be digested and utilized by the body must be considered (House, Neufeld, and Leson 2010). Hemp seed is one of the few plant protein sources that contain all nine essential amino acids and does not have allergy concerns associated with soybeans. As the desire for plant proteins continues to rise owing to consumers shifting to increasingly plant-based diets, finding sources of complete proteins from plants is of utmost importance. Hemp seed and hemp heart proteins have the potential to fulfill this requirement.

Trypsin inhibitors and oligosaccharides present in soybean protein are responsible for the reduced digestibility of gastrointestinal disorders, but hemp cake protein is free of these compounds, showing its superiority over soybean protein (Wang and Xiong 2019). Hemp proteins have excellent digestibility. The whole seeds, hemp meal, and dehulled hemp seeds have in vivo protein digestibility of 85, 87, and 95%, respectively (House, Neufeld, and Leson 2010; Malomo and Aluko 2015). Dehulled hemp seeds have higher in vivo protein digestibility only slightly lower than that of animal proteins (94% for egg and 98% for beef) and comparable or better than other vegetable proteins (80% for kidney beans and 95% for soy protein) (Rutherfurd et al. 2015; Schaafsma 2000). Dehulling and other processing methods could be beneficial for increasing the digestibility of hemp seed proteins. Malomo and Aluko (2015) increased the digestibility of hemp seed proteins through membrane ultrafiltration. The increased digestibility of the membrane-filtered protein may be related to its increased solubility, allowing the protein to be more accessible to the enzymes. Additionally, the membrane-filtered protein underwent pre-digestion to reduce the polysaccharide and phytate content of the sample, further enabling digestibility of the protein (Malomo and Aluko 2015). Hemp seed protein has excellent digestibility, making it an ideal source of dietary protein. Additionally, it may be advantageous to focus on the utilization of hemp hearts for the production of HPI and other protein ingredients. The hulls can then be utilized for animal feed, or to produce value added ingredients, such as dietary fibers, or other bioactive compounds (Sooksawat et al. 2024) which will be discussed further in Sections 3.3 and 3.4.

Treatments that alter the secondary structure of hemp proteins may also increase their digestibility. Karabulut et al. (2024) found that treatments involving manothermosonication, high-pressure homogenization, and pH shifting could increase the digestibility of HPI. Manothermosonication, a technique involving sonication with heat and pressure, increased protein digestibility by 10%, while high-pressure homogenization increased digestibility by ~5% (Karabulut et al. 2024). While hemp seed protein has a high nutritional value, there are some limitations in terms of price fluctuations, color issues, low solubility, and lack of consumer knowledge, as shown in Figure 3. However, all of these limitations can be overcome by utilizing the available opportunities and developing value-added functional foods with a unique combination of active ingredients. There is an extensive amount of current research on improving functional and sensorial quality, and as demand rises and stabilizes, the price will also flatten. Additionally, consumers are becoming more aware of industrial hemp seeds as more products are released on the market. As with other plant proteins, there must be continued work to improve extraction efficiency. The nutritional quality and functionality of plant proteins must be maintained after extraction. Additionally, the extraction of plant proteins is a resource- and energy-intensive process that needs to be improved to increase sustainability and reduce the impact on the environment.

3.3. Hemp seed carbohydrate and dietary fiber

Hemp seed carbohydrates consist of cellulose, xylose, arabinose, galactose, sucrose, raffinose, glucose, and fructose (Schultz et al. 2020). Their percentages differed in whole

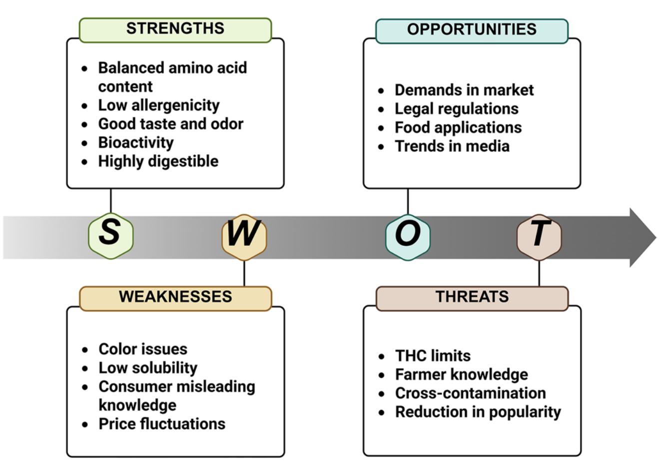

Figure 3. The SWOT analysis of hemp seed protein for food industry adapted from Karabulut et al. (2023) (created in BioRender).

and dehulled hemp seeds. Whole hemp seeds contain 9.5/100 g of available carbohydrates (comprised primarily of free sugars and starch), whereas the dehulled seeds contain 5.03/100 g (Alonso-Esteban, Pinela, et al. 2022). Cellulose and hemicellulose percentages of different varieties are between 16.5–18.1 and 8.0–9.4%, respectively (Vonapartis et al. 2015). Cellulose is present only in the hull and not in hemp hearts. Overall, the carbohydrate content of the heart was much lower than that of the hulls. However, the hearts contained a greater amount of sucrose (1.5–3.8%) compared to the hull (0.17–0.71%). Most of the hemicellulose components are also likely to be mostly contained in the hull fraction, as the hull contains much more xylose (5.7–17.1%) compared to the heart (0.56%) (Schultz et al. 2020). On the other hand, starch is concentrated in the heart and represents a minor component of the hemp seed. Starch percentage in hemp seed ranges between 1.5 and 2.0% in different varieties (Schultz et al. 2020; Xu, Li, et al. 2021; Xu, Zhao, et al. 2021). While most starch is non-resistant and the content of free sugars is low, the majority of carbohydrates found in hemp seeds are classified as dietary fiber. Clear separation of macromolecules in the hemp seed should be considered when utilizing the seed as a food ingredient. Processors may choose to utilize each portion of the hemp seed separately, depending on the dietary fraction being utilized.

Dietary fiber is an edible part of plant materials that contains polysaccharides, oligosaccharides, lignin, and some plant substances. Dietary fiber can be classified as soluble dietary fiber (SDF) or insoluble dietary fiber (IDF), and in hemp seeds, the majority of dietary fiber is insoluble (Zhao, Wei, et al. 2022). The ratio of water-insoluble and -soluble fibers in the hemp seed is typically 80:20 (Callaway 2004). High-protein diets that lack dietary fiber can cause constipation, and due to hemp seeds, high IDF may act to prevent undesirable effects, such as constipation in those on a high-protein diet. According to a study by Mattila et al. (2018), the total dietary fiber constitutes 98% of the total carbohydrates in the hemp seed. Crude fiber of hemp seeds has been reported to be 28.78–36.55% among 13 Hemp seed varieties (Xu, Zhao, et al. 2021). The dietary fiber content of hemp hulls has been reported to be in the range of 77–84% (Leonard et al. 2022). Lignin is a non-carbohydrate component that constitutes a substantial amount of dietary fiber in hemp seeds. One study found lignin content of hemp seeds ranged from 10.5–11.8% (Vonapartis et al. 2015). However, there is very little information about the content and composition of lignin in hemp seeds, and this requires additional study. The high dietary fiber content of hemp seeds makes them incredibly valuable from a nutritional standpoint because most people do not consume sufficient dietary fiber. Since the dietary fiber is concentrated in the hull, with very little in the heart processors developing dietary fiber ingredients should consider sourcing hulls that have been separated from the hemp seed.

However, very few studies have been conducted on the dietary fiber components of hemp seeds. To fully utilize the dietary fiber in hemp seeds, it is critical to conduct in-depth studies on its composition, structure, and functionality.

Regarding functionality, both nutritional and technological functions must be investigated. Agbana et al. (2024) conducted an in-depth study on the cell wall polysaccharides of a single commercial sample of hemp seeds. Cell wall polysaccharides, such as cellulose and hemicelluloses, are the main contributors to dietary fiber in hemp seeds. Although, a small amount of starch (<2%) present, more than 50% of that is resistant starch, which contributes to dietary fiber (Agbana et al. 2024). Cell wall polysaccharide content and structure analysis revealed that hemp seeds contain diverse polysaccharides with varying structures. The composition was similar to that of other dicots but with a prevalence of linear xylans and xyloglucans with low substitution rates. The structural aspects of hemp seed cell wall components provide enhanced interactions between cellulose and hemicellulose. These interactions strengthen the cell walls and impact the rate of fermentation in the gut after consumption (Agbana et al. 2024). The high degree of insolubility makes it difficult to study hemp seed fibers. Investigations utilizing various fractionation methods along with advanced analytical methodologies will need to be conducted to understand the composition and structure of hemp seed dietary fiber.

Studies have also shown that processing affects the solubility of dietary fiber in hemp seeds. The extrusion of hemp hulls improved the functional characteristics and increased the water solubility of dietary fiber. The extrusion catalyzed the breakdown of the fiber and converted the IDF to the SDF. Monosaccharide and linkage analyses of the fiber from extruded hemp seeds confirmed the heterogeneous nature of the dietary fiber components, with the majority being xylose with smaller amounts of rhamnose and glucose. Linkage analysis also revealed several sugar residues that were unique to samples with higher IDF (Leonard et al. 2022). Thus, there are structural elements present in hemp dietary fiber which reduce its solubility. In order to increase the solubility of dietary fiber from hemp seeds, treatments that result in structural changes to the carbohydrates are needed. Another study by Feng, Sun, and Fang (2022) indicated that hemp seed cake can be added to foods, such as potato chips to increase dietary fiber content. The addition of hemp seed cake also resulted in a significant ($p<0.05$) reduction in oil uptake from the frying oil (Feng, Sun, and Fang 2022). This is beneficial for producing healthier snacks with higher fiber content and lower fat content. Overall, the high proportion of dietary fiber in hemp seeds can be exploited to produce new dietary fiber supplements and functional foods containing high dietary fiber.

3.4. Hemp seed phenolic compounds

Most polyphenols are found in hemp seed hulls, followed by seed cake and oil (Leonard et al. 2020). Hemp seeds contain two types of phenolics: bound and free. Hemp seed-bound phenolics are usually present at higher concentrations than free phenolics (Nasrollahzadeh et al. 2022). Free phenolics are easy to extract, whereas bound phenolics are difficult to extract owing to their covalent bonding with the cell wall (Shahidi and Yeo 2016). Bound phenolics can be extracted by alkaline, acidic, or enzymatic hydrolysis (Bagheri et al. 2024; Tang et al. 2016). The abundance of bound phenolic compounds could be beneficial for the utilization of hemp seeds as a bioactive ingredient in functional foods. Bound phenolics are often covalently attached to dietary fiber, making them more stable and highly potent than free phenolic compounds. Thus, hemp seeds have a high proportion of phenolic compounds that are stabilized but may be released in the gut during digestion to provide health-promoting benefits.

Hemp seeds are rich in phenolic compounds, and their types and concentrations can vary depending on the cultivar, harvest, cultivation climate, and extraction methods. Phenolic compounds, such as N-trans-caffeoyltyramine, canabisin A, protocatechuic acid, p-hydroxybenzoic acid, and cinnamic acid have been found in free phenolic extracts of hemp seeds (Irakli et al. 2019). Przybylska-Balcerek et al. (2024) found the presence of p-hydroxybenzoic acid, vanillic acid, caffeic acid, p-coumaric acid, sinapic acid, ferulic acid, syringic acid, benzoic acid, and catechins in bound polyphenolics extracted by alkaline and acid hydrolysis. According to a previous study, the total phenolic content of defatted Moroccan hemp seeds varied from 6.86 to 50.19 mg GAE/g extracts when using different extraction methods by varying the solvent mixtures. The best solvent mixture was determined by quantifying the phenolic content using both HPLC-DAD and Folin-Ciocalteu methods. The best binary mixture was found to be acetone:water = 2:1, and the best ternary mixture was found to be water:acetone:methanol = 1:1:1. The extraction method also affected the antioxidant activity of the phenolic compound extracts. The total antioxidant activity (TAC) was the highest for the solvent system containing water:acetone (1:2), followed by water:methanol:acetone (1:1:1). Hemp seed extracts have been found to contain a variety of phenolic acids, hydroxycinnamic acid amides, lignanamides, and cannabinoids, which vary in composition depending on the solvent system used for extraction (Benkirane et al. 2022). Ultrasonic treatment was found to be more beneficial for hemp seed phenolic extraction than the conventional method. Different combinations of ultrasonic parameters were used, and the optimized parameters showed a 2-fold increase in phenolic content compared to the conventional non-heated method (Teh and Birch 2014). These studies illustrate the importance of understanding how the composition of phenolic compounds changes with different extraction solvents and methods. Further work should be done to determine appropriate methods for recovering bound phenolic compounds while maintaining their activity for use in functional foods.

Phenolic compounds have been found in different macromolecular components of hemp seeds, such as oil and protein. Phenolic acids, such as vanillic, ferulic, (−) epicatechin, and kaempferol have been found in hemp seed oil after extraction with various solvent systems. Simple liquid-liquid extractions of the free phenolic compounds from hemp seed oil were performed with methanol, ethanol, and 80% aqueous methanol. The simple extraction with methanol was able to extract vanillic acid, ferulic acid, (−) epicatechin, and kaempferol. The simple extraction with ethanol obtained vanillic acid and kaempferol, and the simple extraction with 80%

methanol only obtained (−) epicatechin. Additionally, solid-phase extraction (SPE) was used to extract free phenolics from hemp seed oil. The oil mixed with hexane was loaded onto C-18 SPE columns, and the nonpolar lipid fraction was removed with hexane before eluting the phenolics with methanol or 80% aqueous ethanol. Methanol (0.154 mgGAE/g oil total phenolics) was the best solvent for liquid-liquid extraction of phenolics, while 80% aqueous ethanol (0.011 mgGAE/g oil total phenolics) was able to recover more phenolics from the SPE method compared to the methanol extract (0.004 mgGAE/g oil) (Kalinowska et al. 2022). Smeriglio et al. (2016) also identified several free phenolic acids (gallic acid, protocatechuic acid, 4-hydroxybenzoic acid, vanillic acid, chlorogenic acid, and trans-p-coumaric acid), flavanones, flavanols, isoflavones, flavones, and flavanols in hemp seed oil after extraction with methanol/water (8:2 v/v). Nasrollahzadeh et al. (2022) reported the presence of phenolics and proanthocyanidins in several hemp seed protein isolates. Extractable phenolic compounds were extracted from hemp protein concentrates using 50% aqueous methanol and 70% aqueous acetone. The hydrolyzable phenolic compounds were extracted using methanol/sulfuric acid (90:10 v/v) at 85 °C for 22 h. There were significant ($p < 0.05$) differences in the amounts of extractable polyphenols (79–328 mg GAE/100g), non-extractable hydrolyzable polyphenols (1592–2315 mg GAE/100g), and non-extractable proanthocyanidins (83–409 mg/100g) among hemp protein isolates obtained using various methods. The total phenolic content ranged from 1983 to 2727 mg/100 g dry basis (Nasrollahzadeh et al. 2022). It is evident that there is a considerable amount of phenolics and bioactive compounds that remain in hemp seed oils and protein isolates that could have beneficial effects. These components can enhance oil stability by acting as antioxidants or by exerting anti-inflammatory activities in the human body.

In another study, phenolic content was found to be dependent on geographic location and genotype factors. They studied the phenolic compounds in non-industrial hemp seed varieties collected from different Moroccan regions. The phenolic profile consists of phenolic acids, hydroxycinnamic acid amides, lignanamides, and cannabinoids. The primary phenolic compound found in the hemp seeds was N-trans-caffeoyltyramine. High amounts of phenolic compounds have been found in hemp seeds collected from the Jebha and Galaz regions (Benkirane et al. 2023). The main phenolic compounds found in different studies are ferulic acid, vanillic acid, p-coumaric acid, catechin, epicatechin, kaempferol, quercetin, and procyanidin B2 (Kalinowska et al. 2022; Smeriglio et al. 2016). Irakli et al. (2019) also found that genotype and environmental factors affected the phenolic content of hemp seeds. There was a significant ($p < 0.001$) variation in the total phenolic content (TPC) between cultivars and growing years. The primary factor in TPC was the growing year (58.9%), with the secondary factor being genotype (27.3%). In general, there was a trend of increased TPC for years with reduced rainfall (Irakli et al. 2019).

These compounds have high antioxidant properties and several health benefits. Owing to their antioxidant properties, phenolic compounds prevent oil deterioration by quenching free radicals produced by lipid oxidation (Cantele et al. 2020). Several studies have been conducted on how to improve the phenolic content and antioxidant properties of hemp seeds. Babiker et al. (2021) determined that roasting hemp seeds can increase their phenolic content, and the amount of polyphenols increases with increasing roasting time. Roasting for 14 min resulted in the highest phenolic content. Increases in specific phenolic acids were also observed in the roasted hemp seeds. Gallic acid content increased from 4.98 to 22.04 mg/100 g after 14 min of roasting. In addition to phenolic content, the same study found that roasting also increased the flavonoid content of hemp seeds. Roasting conditions are likely to degrade the cellular structure of hemp seeds, which could release bound phenolic and flavonoid compounds (Babiker et al. 2021).

Additionally, malting increases the free polyphenol content of specific phenolic compounds. For the variety Futura 75, the amount of free *N-trans*-caffeoyltyramine increased significantly ($p < 0.05$) when malting at 70 °C, but at 50 °C, there was a significant ($p < 0.05$) decrease. There was a non-significant increase in free *N-trans*-caffeoyltyramine in the variety secuieni jubilee after malting at 70 °C. Malting at different temperatures also resulted in significant ($p < 0.05$) changes in cannabisin A, cannabisin B, and *p*-hydroxybenzoic acid. Thus, malting conditions affected the levels of free phenolics in hemp seeds. Based on the comparison of the two varieties, the impact of malting on the phenolic profile may be dependent on the variety (Farinon et al. 2022). Overall, Hemp seeds are a rich source of phenolic compounds with beneficial antioxidant properties. More work is needed to ascertain the activities of these compounds and how processing can affect their availability in the human body. There is currently a lack of in vivo and clinical studies on the effects of hemp seed phenolic compounds on human nutrition. It would be beneficial to fill this knowledge gap as a food source rich in these compounds.

4. Utilization of hemp seed

4.1. Processing hemp seed and its byproducts

To obtain nutritional and health benefits from consuming hemp seeds, they must be processed. Hemp seeds are most commonly processed through cold pressing or other extraction procedures to separate the hemp oil from the seeds, producing hemp seed oil and the byproduct hemp seed cake. Hemp seed cake is a by-product of cold-pressed seed extraction. It contains a high biological value protein, which makes it a valuable nutritional source for animal feed. Hemp seeds may also be dehulled to separate the heart from the hull. Hemp hearts are rich in oils and proteins. The hemp seed hull contains a higher amount of bioactive compounds than the inner core, resulting in a higher amount of essential compounds in the hemp cake after oil extraction (Chen et al. 2012; Siano et al. 2018). High levels of phytochemicals, such as antioxidants, phenolic compounds, and tocopherols, are advantageous for meat production (Arango et al. 2022; Chen et al. 2012). Hemp seed cake contains

33.72 mg γ-tocopherol/100 g cake (Antunović et al. 2021). Introducing hemp cake into the poultry diet can also increase meat quality with functional compounds as antioxidant components, which can increase the product's oxidative stability by preventing oil oxidation (Kanbur 2022; Konca et al. 2014; Mierliţă 2019; Mohamed and Hassan 2023; Rezvankhah et al. 2018). Various fractions of hemp seed can be utilized in various ways to produce a variety of ingredients and functional foods.

4.2. Hemp protein for meat analogs

There has been an increased demand for alternatives to animal-based foods; thus, there has been strong interest in plant-based meat analogs. Many of these products are produced from soy or pea proteins. Hemp protein could be another valuable source of plant-based proteins for the production of meat analogs. To produce high-quality meat analogs, the texture of the extruded protein must mimic the emulated meat product. Zahari et al. (2023) found that a 50:50 blend of hemp seed protein concentrates and wheat gluten resulted in a thin fibrous layered structure that was greatly improved compared with the 100% wheat gluten meat analog. The blend of hemp protein and gluten provides a visual texture similar to that of chicken breast meat, and could be a viable analog for chicken-like products.

In a study by Amagliani et al. (2023), hemp seed protein could not be extruded under high-moisture extrusion conditions. The hemp seed protein contained high amounts of edestin macromolecular complexes, which could impede the formation of extruded products with the required fibrous structure. However, as in a previous study, the addition of hemp seed protein to pea or soy protein isolates resulted in good textural quality (Amagliani et al. 2023). Hemp protein isolates can improve the texture of extruded meat analogs when combined with other protein sources. Additionally, producing meat analogs with blends of different plant proteins could allow the production of proteins with custom nutritional profiles.

One challenge regarding the production of plant-based meat analogs is the intensive extraction process to produce protein isolates of high enough quality to produce the desired end-product quality. Thus, Nasrollahzadeh et al. (2022) studied the prospect of producing hemp protein isolates using less intensive means. In this study, five commercially available hemp seed protein concentrates generated using either wet or dry fractionation technologies were evaluated. The protein content of the concentrates ranged from 56–76% protein (dry basis). The composition of the isolates and the structural properties of the proteins varied depending on the extraction procedure (Nasrollahzadeh et al. 2022).

The hemp protein sample with the hull removed resulted in a lighter colored powder, which would be more beneficial for many meat analog products. Furthermore, as discussed in Section 3.3, the hulls could be further processed to produce high value dietary fiber ingredients. The color of hemp seed protein is often seen as a barrier to its use in meat analogs. Each protein sample yielded extruded products with various textural properties. The hydrophobic nature of the hemp proteins in combination with the hydrophilic corn starch used in the extrudate formulation resulted in the creation of an ideal multiphasic system, with the dispersed phase being elongated owing to the tensile and shear stresses of the extruder. These stresses applied to the multiphasic mixture resulted in the formation of visible fibers. Ultimately, hemp proteins show promise when combined with the correct multicomponent formulation to produce meat analogs with good texture (Nasrollahzadeh et al. 2022).

Extrusion has also been used to produce texturized vegetable proteins (TVP) from hemp seed proteins. Texturized vegetable proteins can be used as plant-based protein ingredients in various products, and it is highly desirable to find protein sources with low allergenicity for this product. The hemp protein is an ideal candidate for producing allergen-friendly TVP, as it is currently not known to be an allergen for a significant portion of the population (Rajendra et al. 2023). Using different extrusion parameters with hemp seed protein, a range of products with expansion indexes ranging from 1.00 to 1.33 were produced (expansion ratio of 1.00 indicates no expansion of the diameter of the extrudate compared to the diameter of the die). Rajendra et al. (2023) found that extrusion parameters, such as feed moisture content and screw rotational speed had a substantial impact on the quality and functional properties of hemp protein extrudates. Overall, selecting the correct extrusion parameters can improve the quality of TVP and other products produced from hemp seed proteins. Additionally, different textural profiles can be targeted for a wide variety of products by adjusting the processing parameters. Current research on hemp proteins indicates that it is a highly beneficial ingredient in many plant-based protein and meat analog products.

Diets rich in processed food and red meat can cause various health problems, including cardiovascular diseases, diabetes, and cancer. Additionally, food security, ethical considerations, and convenience factors promote the demand for alternative meat. Soy and wheat proteins are the most common sources of meat analogs or alternate proteins. However, they are neither allergen-friendly nor gluten-free. The advantage of using hemp seed cake is that it does not contain common allergens and hemp plants are inherently gluten-free. Hence, studies are focusing on improving the quality of hemp proteins by altering the extrusion parameters. Textural, color, and absorption properties are dependent on the extruder screw rotation speed and feed moisture content. It was found that 40% feed moisture content and 400 rpm screw rotation speed provided the optimal textural, functional, and appearance characteristics to be use in hemp protein extract as a meat analog in the food industry (Rajendra et al. 2023).

4.3. Potential applications of hemp seed in functional foods

Hemp seed cake has been added to various foods to improve their nutritional value and quality. Hemp seed cake based frankfurters showed quality improvement in 50% reduced phosphate frankfurters (Yuan et al. 2022). Phosphate is important for processed meats to maintain cooking quality and textural characteristics (Câmara et al. 2020). However, higher phosphate intake can alter the calcium-to-phosphorus ratio in the human body, resulting in possible bone diseases in the healthy population. Therefore, studies are being conducted on reducing phosphorus in processed meat and developing supplements that can replace phosphorus without compromising its quality. Cold-pressed hemp seed cake has high antioxidant properties, along with all essential amino acids, making it a strong candidate for the food industry. The main problem is the particle size of the hemp seed cake, which creates a rough or unlikable mouthful. This can be addressed by reducing the particle size of the hemp seed cake, which was recently achieved by micronization. The micronization of seeds is achieved by coarse grinding the material in a mill before utilizing an ultrafine grinder and sieving to produce a powder with micrometer level particles (Cao et al. 2022; Yuan et al. 2022). Yuan et al. (2022) showed that 2% micronized hemp seed cake is the optimal ratio for replacing 50% phosphorus in processed meat to maintain quality. The addition of 2% micronized hemp seed cake resulted in significantly ($p < 0.05$) less cooking loss than both the control and the reduced phosphate frankfurters. The addition of the hemp seed cake also affected the textural characteristics of the frankfurters, yet at 2% addition, the texture was more similar to that of the control than the reduced phosphate sample (Yuan et al. 2022). Overall, processing can improve the functionality of hemp seed cake for use in sausage products.

Julakanti et al. (2023) investigated how milling and extraction pH can improve the properties of hemp seed proteins. The extraction pH and ball milling can reduce the particle size, which in turn improves the functional properties. Ball milling significantly ($p < 0.05$) increased the protein concentration of samples extracted at pH 9 and 10. Protein yield was significantly ($p < 0.05$) increased by ball milling (Julakanti et al. 2023). The ability to increase protein yields could be beneficial and cost-effective for food manufacturers. Ball milling of proteins extracted at pH 8 significantly ($p < 0.05$) increases solubility. The water holding capacity increased as the extraction pH increased from 8 to 9 or 10 (Julakanti et al. 2023). Depending on the desired use of hemp seed protein, the extraction parameters can be varied to prepare proteins with the required functional properties.

Hemp seed flour can also be added to bakery products to enhance the nutritional properties of wheat flour. Bread fortified with 10% hemp seed flour was seen to have an increase in the omega-3 essential fatty acid and antioxidant properties compared to durum wheat bread. The total essential amino acid content of the hemp flour-fortified bread was 4.68 g/100 g compared to that of 1.71 g/100 g in durum wheat bread. The hemp seed flour contains residual oil after the cold pressing process. The residual oil impacted the ω-3 fatty acid content of the bread. The control bread contained 3.40% ω-3 fatty acids and the breads prepared with hemp seed flour contained between 6.70 and 9.99% ω-3 fatty acids (Sciacca et al. 2023). Hemp flour-enriched pasta showed a higher phenolic content and antioxidant activity than wheat flour pasta. In addition to having a high nutritional value, hemp-enriched pasta is well appreciated in sensory evaluation (Axentii, Stroe, and Codină 2023). In another study, hemp seed flour (≥10%)-enriched pasta had good nutritional value, textural properties, and less cooking loss and stickiness. However, because of the bitter taste and hemp odor, consumers do not like pasta in the sensory evaluation (Merlino et al. 2022). Hemp seed flour-incorporated chapati showed increased protein and fiber content and higher protein digestibility. A hemp seed flour concentration of 30/100 g showed a 5% increase in the in vitro protein digestibility compared to that of whole wheat chapati. The essential fatty acid ratio increased 4.6-fold. The main challenges of hemp seed flour chapati were poor water holding capacity of the dough and reduced pliability of chapati, which were improved by the addition of vital wheat gluten, resulting in a continuous network formation between starch and protein molecules, forming a stable dough (Sharma and Prabhasankar 2021).

Raw and roasted hemp flour was incorporated with wheat flour to prepare cookies with high protein, phenolic, and antioxidant content. The incorporation of hemp flour with wheat flour decreased the hardness of the cookies, resulting in softer cookies. Raw hemp flour up to 20% and roasted hemp flour up to 15% enriched with wheat flour were found more desirable by panelists in the sensory evaluation (Ertaş and Aslan 2020). Hemp flour was mixed with corn flour to prepare high-value cookies. Hemp flour (20%) mixed with corn flour showed high scores in the spider plot of the organoleptic properties. Adding corn flour to hemp flour improved the physicochemical and textural properties of the cookies (Lukin and Bitiutskikh 2017). These studies have shown that hemp seed cake, hemp protein, and hemp flour can be utilized in various food products to produce highly nutritional functional foods with high consumer acceptance. However, in some instances, additional work is needed to find processing parameters to improve some aspects of the sensory profiles of products utilizing hemp seeds.

5. Challenges and future perspectives

There are challenges in expanding the use of hemp seed in the food and pharmaceutical industries. However, there is tremendous potential for hemp seed products and utilization of industrial hemp as an emerging crop. Hemp seed properties can differ for different varieties, which we need to remember. Therefore, qualitative and quantitative analysis of different hemp seed varieties is essential for their use as a food or functional ingredient for "food as medicine" dietary approaches. Proper mapping of hemp seed varieties and extraction of the targeted compounds can lead to optimized products that are beneficial for different industries.

Hemp seeds have the potential for various applications in the food and pharmaceutical industries. The main challenge is to properly extract and process the targeted compound while maintaining a low cost. Using the byproduct in another processing application can be one way to minimize the cost. Secondly, hemp can be grown as a dual-purpose crop. Thus, farming and harvesting costs can be divided into different categories. However, expansion and development of processing facilities near key growing regions are required to minimize transport costs.

Consumers are becoming more accepting of industrial hemp seed products; however, more education is needed to increase consumer demand for this crop. In addition, there are regulatory and legal challenges to hemp seed production. Support is required from the state and federal governments to stimulate the production of industrial hemp. Farmers face additional risks for the industrial hemp surrounding the limits of tetrahydrocannabinol (THC) levels. Producers also need readily available access to reliable THC testing facilities. For the agricultural industry and farmers to increase hemp seed production, they need to know that their products will have a stable market and processing facilities.

Several market segments are excellent opportunities for increasing the utilization of hemp seeds in the food industry. Hemp seed producers should exploit the nutritional value and allergenicity of hemp proteins to increase market demand and profits. The plant-based protein market would benefit from access to a consistent supply of hemp seeds because of the high quality of hemp protein. Related to this, the sports nutrition segment is another high-value avenue to capture, especially products aimed at vegetarian or vegan athletes. Overall, there are many opportunities to increase the utilization of hemp seed in food products that can support human nutrition and health while boosting food and agricultural industries.

The economic feasibility of hemp seed products faces several challenges, including technological limitations, inconsistencies in raw materials, and scalability challenges. Currently, the processing infrastructure is a considerable bottleneck, as the industry lacks large-scale industrial facilities capable of efficiently processing hemp, leading to supply chain disruptions and discouraging investment. There is a particular need to develop processing facilities that will be local to the areas where hemp seed will be produced. However, this is slightly less critical than for the processor needs for hemp stalk fibers. Moreover, the absence of specialized harvesting equipment causes inefficiencies and increased labor costs. The availability of hemp seed is also affected by the risk of crops exceeding legal THC limits, necessitating their destruction, and variability in crop yields due to environmental factors. Scalability is hindered by high production costs, regulatory complexities, market saturation, and supply chain constraints, which can lead to price volatility and affect profit margins. Addressing these challenges requires a sizeable investment in processing infrastructure, the development of efficient harvesting technologies, and the stabilization of regulatory frameworks to enhance the economic potential of hemp seed products.

Author contributions

Laila Hossain conducted the database search, interpreted the results, and wrote the original draft of the manuscript. Kristin Whitney also conducted the database search and interpreted the results, and she revised the original draft. Senay Simsek conceptualized the focus of the manuscript, supervised and managed the team, and reviewed and revised the manuscript. All authors approved the final version for submission.

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