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Review Article

Defatted chia (*Salvia hispanica* L.) flour peptides: Exploring nutritional profiles, techno-functional and bio-functional properties, and future directions

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ABSTRACT

Chia (*Salvia hispanica* L.) is a summer-blooming herb from the mint family, known for its rich nutritional profile, including high-quality protein, fibre, and a balanced ratio of omega-3 and omega-6 fatty acids. With the rising demand for chia oil, defatted chia flour (DCF), a by-product of oil extraction, has gained attention as a valuable ingredient. DCF is rich in essential macronutrients and amino acids, offering a sustainable alternative to traditional protein sources and supporting global food sustainability and waste reduction efforts. Recent studies have highlighted the techno-functional properties of DCF peptides, showing excellent solubility, water- and oil-absorption capacities, as well as emulsifying, foaming, and gelling abilities. These properties enhance their application in diverse food systems, making DCF an important ingredient in the development of nutritious, innovative, and appealing food products. Beyond their functional roles, chia-derived peptides also exhibit significant bioactive properties, such as antioxidants, antihypertensive, anti-inflammatory, neuroprotective, anti-diabetic, antimicrobial, anti-aging, hypolipidemic, and hypoglycaemic effects. These properties make them beneficial for improving health and wellness. Integrating DCF peptides into food products provides a natural approach to managing chronic diseases, promoting longevity, and improving overall health. To fully realize the potential of DCF peptides, future research should focus on understanding their bioactivities at the molecular level and exploring how they interact with various physiological systems. Interdisciplinary collaboration among food science, biotechnology, pharmacology, and nutrition is essential, along with careful evaluation of safety and potential risks. Regulatory frameworks will be crucial for the broader use of DCF peptides in food and nutraceuticals. Additionally, advancements in peptide production, extraction, and purification technologies will be necessary for large-scale, sustainable applications. Focusing on these areas will maximize the benefits of chia peptides for human health, nutrition, and environmental sustainability.

1. Introduction to chia seeds

Chia (*Salvia hispanica* L.) has garnered significant attention for its nutritional and health benefits, making it an important crop in modern agriculture. Chia is a summer-blooming annual plant belonging to the mint family (*Lamiaceae*), which comprises approximately 900 species worldwide (Rajput et al., 2021; Agarwal et al., 2023; Vera-Cespedes et al., 2023). *Salvia hispanica* L. is the only species currently grown domestically. Chia has been cultivated for millennia in regions spanning South Africa, Central America, and Southeast Asia among ancient civilizations for food, medicine, cosmetics, and religious rituals (Rajput et al., 2021; Masood, 2022; Lara et al., 2021; Hrncic et al., 2019). It was a staple food for the pre-Columbian societies, particularly ancient Mayans and Aztecs (Rajput et al., 2021), particularly between 1500 and 1000 before common era (BCE) (Ullah et al., 2016). However, after the Spanish conquest, many agricultural traditions and crops were lost due to conflict and religious beliefs. Consequently, chia cultivation declined and was replaced by foreign crops like wheat, barley, maize, and

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amaranth, which were introduced by the colonizers (Munoz et al., 2012; Ali et al., 2012).

In recent years, chia has gained global popularity for its nutritional and medicinal benefits (Ullah et al., 2016; Das, 2017; de Falco et al., 2017; Silva et al., 2016). It is now cultivated in countries such as Australia, Bolivia, Colombia, Guatemala, Mexico, Peru, and Argentina with Mexico being the largest producer, exporting chia seeds to Japan, the United States, and Europe (Mordor Intelligence). The global chia seed market is expected to grow from USD 1.51 billion in 2024 to USD 2.93 billion by 2029, at a compound annual growth rate (CAGR) of 14.19 % over the forecast period (2024–2029). This expansion is driven by the increased demand for superfoods and functional foods. Recognized for their numerous health benefits, chia seeds are increasingly popular and widely used in various products, including cereals, energy bars, baked goods, and beverages (Mordor Intelligence). Europe is anticipated to be the fastest-growing market, driven by consumer demand for natural ingredients and the adoption of vegetarian diets (Ferreira et al., 2023). As chia's popularity continues to grow, it has become a key crop in the food industry. Its expanding use in human nutrition has led to increased research and development by universities, research centres, and industries to explore its potential in food supplements, processed foods, and nutraceuticals.

Chia seeds are small, oval-shaped mericarps, measuring approximately 1–1.2 mm in width, 2–2.2 mm in length, and 0.8–0.88 mm thickness (Garcia-Selcado et al., 2018). These seeds are highly valued for their nutritional content, including omega-3 fatty acids, protein, fibre, antioxidants, and essential minerals. Chia seeds are found in two primary colour variants: black and white (Fig. 1). Both varieties originate from the same species and share nearly identical nutritional profiles (Hrncic et al., 2019). However, they do exhibit distinct morphological traits that may influence agricultural practices and food processing (Agarwal et al., 2023). White chia seeds exhibit a marginally larger, thicker, and have a greater surface area compared to black seeds (Hrncic et al., 2019). While black chia is more commonly grown, it is common to find a small percentage of white seeds (5–8 %) in fields of black chia (Hrncic et al., 2019; Marevci et al., 2019). Conversely, when chia is cultivated for white seeds only, the entire harvest will consist of white seeds. This pattern is thought to result from genetic factors that influence seed colour expression during cultivation, although the underlying genetic and environmental interactions remain subjects of ongoing research.

Chia seeds have been recognized as plant-based nutraceutical, gaining attention for their well-balanced composition of essential macronutrients and micronutrients (Ullah et al., 2016; Ali et al., 2012; Das, 2017; Kulczynski et al., 2019). This rich nutritional profile has led to extensive research and interest in both academic and food industries. As illustrated in Fig. 2, the nutritional profile of chia seeds according to USDA National Nutrient Database (USDA Food Data Central), highlights their abundance content in fats, protein, dietary fibre, alongside of vitamins and minerals. Chia seeds are primarily valued for their high nutritional density, comprising approximately 30–33 % fat, 26–41 % carbohydrates, 18–30 % dietary fibre, and 15–27 % protein (Din et al., 2021; Grancieri et al., 2019a). The fats in chia seeds are predominantly polyunsaturated fatty acids (PUFAs), particularly omega-3 (α-linolenic acid, ALA) and omega-6 fatty acids, which are essential for human health but cannot be synthesized by the body (Ali et al., 2012). These fatty acids are vital for cardiovascular health, reducing inflammation, and supporting cognitive function, contributing to chia seeds' status as a 'superfood' and earning them accolades such as 'The Seed of the 21st Century' and 'New Gold' (Arnold et al., 2021; Dincoglu and Yesildemir, 2019).

The increasing popularity of chia seeds as a superfood has concurrently driven significant growth in the chia oil industry, with the rising demand for chia oil attributed to its numerous health benefits, including cardioprotective effects (Mishima et al., 2021; Mohamed et al., 2021), improved insulin sensitivity (Batista et al., 2023; Dalginli et al., 2023), reduced fat mass accumulation (Dalginli et al., 2023; Syeda et al., 2021), lowered cholesterol levels (Han et al., 2020; Alarcon et al., 2022), anti-inflammatory effects (Syeda et al., 2021; Khalifa et al., 2023), and antioxidant properties (Batista et al., 2023; Khalifa et al., 2023). The production of DCF generated through various methods like cold

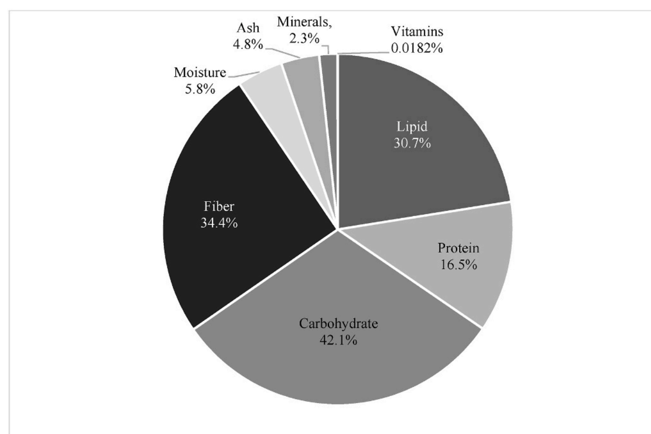

Fig. 2. Nutritional compositions of dry chia seeds.

Fig. 1. Types of chia seeds. (Left) Black chia seeds; (Right) White chia seeds.

pressing, solvent extraction, and supercritical fluid extraction (SFE) (Rajput et al., 2021; Fernandez-Lopez et al., 2019; Olivos-Lugo et al., 2010; Segura-Campos et al., 2014; Katunzi-Kilewela et al., 2022), all of which result in a dietary fibre and protein-rich by-product (Aranibar et al., 2019; Mas et al., 2020). Cold pressing, also known as mechanical or expeller pressing, is the most commonly used method, which involves crushing the seed to release the oil without applying heat, thereby preserving the oil's natural properties and bioactivities (Ferreira et al., 2024; Durazzo et al., 2022). The rising demand for chia oil has had a profound impact on the chia industry, leading to a notable increase in the production of defatted chia flour (DCF), a waste, or by-product of the oil extraction process. Despite the removal of oil, DCF retains a protein-rich composition, including essential amino acids, making it an underutilized yet highly valuable resource. This paper aims to explore nutritional profiles, techno- and bio-functional properties, and future direction of chia peptides, shedding light on their potential applications in food technology and health-enhancing products.

2. Defatted chia flour: by-product with potential

2.1. Sustainable by-products derived from the chia oil industry

The growing global demand for chia oil has significantly increased the production of DCF, a byproduct of the oil extraction process. This surge in chia oil consumption has consequently created new opportunities for utilizing DCF, which, despite being traditionally seen as waste, is emerging as a nutrient-dense resource offers an opportunity to unlock the full potential of chia seeds while addressing sustainability concerns within the agri-food sector. DCF is rich in proteins, essential amino acids, dietary fibre, and bioactive compounds, making it a valuable ingredient with potential applications in both the food and nutraceutical industries. The composition and quality of DCF are influenced by the source of the chia seeds, extraction method, and processing conditions (Ziemichod et al., 2019; Kibui et al., 2018). Factors such as geographical origin, cultivar, and growing conditions affect the nutritional profile and functional properties of DCF (Lara et al., 2021; Wang et al., 2023a). The choice of extraction technique impacts the residual oil content, protein content, and bioactive components in DCF (Olivos-Lugo et al., 2010; Segura-Campos et al., 2014).

The chia oil processing industry generates about 650–700 kg of DCF per ton of chia seeds (Chen et al., 2023; Ozon et al., 2022), raising concerns within the agri-food sector regarding waste management and its environmental impact. Food industry by-products often present significant challenges in waste treatment and disposal, contributing to substantial economic costs globally. Previously, DCF was discarded or conventionally used as animal feed and fertilizer (Vinayashree and Vasu, 2021). However, the growing demand for chia oil has sparked increased interest in harnessing the nutritional benefits and versatility of DCF, leading to its repurpose for higher-value applications. These innovative strategies are imperative to exploit and enhance the value of DCF, while addressing waste management and supporting economic and environmental sustainability. Effective approaches include commercial techniques such as alkaline extraction (Khushairay et al., 2023), acid precipitation (de Figueiredo et al., 2018), mechanical extraction (Tabtabaei et al., 2017), and aqueous extraction (Choudhry et al., 2023), as well as the production of protein hydrolysates using enzymatic hydrolysis methods (Ibrahim and Ghani, 2020), all of which have been employed to isolate functional proteins from DCF. The choice of extraction technique influences the final composition of DCF, including its residual oil content, protein concentration, and bioactive components in DCF (Olivos-Lugo et al., 2010; Segura-Campos et al., 2014). These factors, in turn, impact the nutritional value and functional properties of the DCF, which are crucial for further food and nutraceutical applications.

2.2. Nutritional profiles of DCF

2.2.1. Macronutrient compositions

DCF, derived from chia seeds post-oil extraction retains a rich and diverse nutritional profile. Despite the removal of oil content, DCF is rich in protein, dietary fibre, and essential minerals, offering substantial health and functional benefits. Its specific macronutrient profile, however, can vary, influenced by factors such as the chia seed variety, cultivation conditions, and extraction methods employed (Ferreira et al., 2023; Fernandez-Lopez et al., 2019; Khushairay et al., 2023). DCF is particularly rich in protein, with concentrations ranging from 26 % to 38 % (Alarcon et al., 2022; Ferreira et al., 2024; Khushairay et al., 2023). The protein composition of DCF is characterized by a predominance of glutelin (42 to 45 %), which constitutes the largest fraction of its protein content, followed by globulin and albumin (Khushairay et al., 2023; Segura-Campos, 2020). These protein fractions are integral to the structural integrity and functional properties of DCF, enhancing its nutritional value and suitability for various food applications. Glutelin, which is abundantly present in plant proteins, known for its role in nutrient storage contributes significantly to high quality protein profile of DCF. This owing to its well-balanced amino acids compositions and abundance of essential amino acids (Khushairay et al., 2023; Nassef et al., 2022). Glutamine, a key amino acid in glutelin, exemplifies the versatility of amino acids metabolism, as well as its role in cell signalling, nitrogen function, and immune response (Curi et al., 2016; Cruzat et al., 2014). However, glutelin is not water-soluble due to their high content of hydrophobic amino acids and formation of large disulphide-bonded aggregates (Kumar et al., 2019). On the other hand, prolamins represent the least abundant fraction, making up only 3.67 % of the total protein content (Khushairay et al., 2023). However, the predominance of glutelin contrasts with the findings of Sandoval-Oliveros and Paredes-Lopez (2013), who reported 17.3 % albumin, 52 % globulin, 12.7 % prolamin, and 14.5 % glutelin in chia protein. These variations highlight the variability of seed protein profiles, which can be influenced by factors such as botanical source, seed variety, preparation methods, and extraction techniques (Segura-Campos, 2020).

Table 1 presents a comparative analysis of macronutrient compositions of DCF and other defatted plant seed flour from recent studies. The data demonstrates that DCF offers a highly competitive nutritional profile, particularly in comparison to other seed sources. Its substantial protein content, along with high dietary fibre and low residual oil levels, positions DCF as an excellent plant-based alternative and valuable ingredient for diverse nutritional applications (Khushairay et al., 2023). In addition to its protein content, DCF is a significant source of carbohydrates and dietary fibre. The total carbohydrate content ranges from 5 to 21 %, with a substantial portion of these carbohydrates being dietary fibre (20 to 48 %). Chia flour is distinguished by its high fibre content, ranging from 20 to 48 g per 100 g, which is notably higher than that of other seed flours. This fibre content, particularly the presence of crude

Table 1
Macronutrient compositions of defatted chia flour and other defatted plant seed sources (per 100 g).

Macronutrient	Defatted chia flour (Ferreira et al., 2023; Alarcon et al., 2022; Khushairay et al., 2023)	Defatted flaxseed flour (Ferreira et al., 2024; Mansour et al., 2018; Selim et al., 2019)	Defatted hemp flour (Absi et al., 2023; Jurgonski et al., 2020; Tufarellili et al., 2023)	Defatted sesame flour (Melo et al., 2021; Prakash et al., 2018)
Protein	26–38	28–35	31–50	29–46
Carbohydrate	5–21	8–14	4–47	3–25
Dietary fibre	20–48	8–37	15–41	4–25
Lipid	≤15	≤10	≤13	≤32

Notes: Values are presented as grams of macronutrient per 100 g of sample.

polysaccharides reaching up to 48 g per 100 g of DCF (Ferreira et al., 2023; Xiao et al., 2023), offers several health benefits. The fibre is expected to support digestive health by promoting gut microbiota, aiding digestion, and enhancing satiety (Ionita-Mindrican et al., 2022; Ehret et al., 2023). Additionally, soluble fibre content plays a key role in regulating blood sugar levels, making DCF a valuable ingredient for overall gastrointestinal and metabolic health (Giuntini et al., 2022; Mao et al., 2021; Kabisch et al., 2021). Despite undergoing oil extraction, a significant amount of residual oil remains within the flour matrix, classifying the DCF as partially defatted. This residual oil is attributed to the efficiency of the oil extraction process, which can vary depending on the method and conditions employed (Aranibar et al., 2021). While DCF retains a moderate fat content, the majority of these fats (over 80 %) are healthy polyunsaturated fats, predominantly C18:3n3c (omega-3) and C18:2n6c (omega 6) fatty acids (Garcia-Selcado et al., 2018). This profile makes DCF comparable to other seed sources, not only due to its healthy fats but also for its exceptional and competitive overall nutritional compositions. Its high-quality protein, fibre, and beneficial fats render it a valuable and essential ingredient for a wide range of dietary applications.

2.2.2. Amino acids compositions

Amino acids are the fundamental units of proteins, are crucial in numerous biological functions, from cellular metabolism to muscle physiology. The amino acid profile is a key component that contributes to its value as a protein source. DCF exhibits a highly favourable amino acid profile, making it a potent source of both essential and non-essential amino acids, which are vital for numerous physiological functions. The amino acid profile of DCF shows a well-balanced distribution of essential (EAA) and non-essential (NEAA) amino acids (Khushairay et al., 2023). EAA are indispensable for growth and maintenance, as they cannot be synthesized de novo by the human body and other mammalian cells, or the synthesis rate is insufficient to meet the body's requirement (Church et al., 2020). Consequently, these nine EAA must be acquire through dietary protein sources. They are integral to the stimulation of muscle protein synthesis and the regulation of whole-body protein metabolism, playing a crucial role in tissue repair, muscle development, and overall metabolic homeostasis (Church et al., 2020; Li et al., 2024; Negro et al., 2024). DCF is notable for its significant content of several EAA. Table 2 provides the amino acids' compositions of chia seeds and DCF from recent studies. The data is presented for both essential (EAA) and non-essential amino acids (NEAA) in chia seeds (from the USDA database) and three different recent sources of DCF. In DCF, EAA make up approximately 37 % of the total amino acid content (de Figueiredo et al., 2018), with lysine (Lys), leucine (Leu), valine (Val) and phenylalanine (Phe) being the most abundant (Ferreira et al., 2023; Khushairay et al., 2023; Nassef et al., 2022). Notably, DCF is particularly rich in Lys, an EAA that plays a pivotal role in protein synthesis, collagen formation, and the maintenance of healthy connective tissues. Lys also supports immune function and facilitating absorption of key minerals, such as calcium (Gunarathne et al., 2024; Matthews, 2020; Hall and da Costa, 2018). The relatively high Lys content in DCF is especially advantageous, as Lys is often the limiting amino acid in many plant-based diets (Kumar et al., 2022; Yang et al., 2021; Leinonen et al., 2019). As such, DCF offers a valuable source of Lys especially for vegans and vegetarians, helping them meet their nutritional needs and ensuring a more balanced amino acid profile.

Leu and Val are essential hydrophobic branched chain amino acids with an aliphatic side chain, offering several important benefits to physiological functions, particularly in supporting muscle health and regulating overall metabolic function. Unlike other EAAs, Leu and Val are initially transaminated in extrahepatic tissues and require inter-organ or inter-tissue shuttling for complete catabolism (Sperringer et al., 2017). Due to the similarity in the structure of their side chains, both Leu and Val share a common transport system for amino acid absorption, facilitating their uptake into cells (Wang et al., 2023b; Neinast et al., 2019). Leu plays a central role in stimulating muscle protein synthesis by initiating intracellular signalling cascades and promoting cellular proliferation through the mammalian target of rapamycin (mTOR) kinase pathway (Rehman et al., 2023; Zhao et al., 2021). Val contributes to muscle metabolism by working synergistically with leucine and isoleucine to support the overall muscle-building process (Wang et al., 2023b; Reifenberg and Zimmer, 2024). The significantly higher Val content in DCF, which complements Leu's anabolic effects, helps maintain a positive nitrogen balance and may enhance its potential to support muscle recovery, making it a valuable component in post-workout diets. Additionally, Leu contributes to glucose homeostasis with its capacity to influence insulin secretion and improve insulin sensitivity (Pathak et al., 2023; Miao et al., 2021), highlighting its potential as a dietary supplement for managing obesity and diabetes mellitus. Moreover, Leu promotes fatty acid oxidation and supports mitochondrial function in both skeletal muscle and adipose tissue (Duan et al., 2016). Besides, Val is essential for supporting mental focus and cognitive function, as it is involved in the synthesis of neurotransmitters. A deficiency of Val in the human brain has been linked to neurological defects and mental retardation (Sperringer et al., 2017). Beyond its role on cognitive health, appropriate Val supplementation has been shown to enhances growth and reproductive performances, while also modulating gut microbiota and immune functions (Wang et al., 2023b).

Moreover, DCF is also rich in Phe, an essential aromatic amino acid that serves as a precursor to Tyr via phenylalanine hydroxylase. Tyr is then further metabolized into important catecholamine, including dopamine, noradrenaline (norepinephrine), and adrenaline (epinephrine), through the intermediate L-3,4-dihydroxyphenylalanine (DOPA) (Buchmueller et al., 2024; Olguin et al., 2016). Each of these catecholamines has distinct functions: dopamine is essential for regulating mood, motivation, and motor control; noradrenaline governs the body's stress response; and adrenaline prepares the body for rapid action, particularly in response to stress or danger (Ranjbar-Slamloo and Fazlali, 2020; Ambade et al., 2009). Together, these catecholamines acts as immunomodulators, helping manage the body's stress response, regulate mood and cognitive function, and contribute to maintaining overall

Table 2
The amino acids composition of chia seeds and defatted chia flour from recent studies.

Amino acids	Chia seeds (USDA Food Data Central)	Defatted chia flour		
		Khushairay et al. (2023)	Ferreira et al. (2023)	Nassef et al. (2022)
Essential amino acids				
Lys	0.97	4.64	1.73	6.30
Ile	0.80	1.69	0.96	4.55
Leu	1.37	4.01	1.82	6.30
Phe	1.02	5.94	1.41	5.90
His	0.53	3.52	1.07	4.70
Val	0.95	4.00	1.18	5.34
Thr	0.71	5.43	1.00	4.10
Met	0.59	4.48	0.34	3.20
Trp	0.44	1.05	0.13	1.37
Non-essential amino acids				
Tyr	0.56	3.46	0.59	2.70
Glu	3.5	18.46	0.46	18.00
Pro	0.78	3.72	0.95	0.75
Ala	1.04	3.33	1.38	6.30
Arg	2.14	12.69	3.38	8.49
Ser	1.05	7.40	1.61	6.30
Gly	0.94	5.58	1.43	4.90
Asp	1.69	9.72	4.89	NR
Cys	0.41	0.88	NR	NR

Notes: Values are presented as grams of amino acid per 100 g of sample. NR indicates data not reported. Lys: lysine; Ile: isoleucine; Leu: leucine; Phe: phenylalanine; His: histidine; Val: valine; Thr: threonine; Met: methionine; Trp: tryptophan; Tyr: tyrosine; Glu: glutamine, Pro: proline; Ala: alanine; Arg: arginine; Ser: serine; Gly: glycine; Asp: aspartic acid; Cys: cysteine.

physiological balance. Since Phe is fundamental for maintaining healthy levels of these neurotransmitters, adequate dietary intake of Phe is essential for proper central nervous system function. This is particularly important in managing conditions such as chronic pain, depression, and other disorders linked to nervous system dysfunction (Akram et al., 2020). Additionally, Tyr, derived from Phe, plays a significant role in mitigating oxidative stress by reacting with free radicals such as peroxynitrite. This reaction facilitates detoxification and leads to the formation of nitrotyrosine, a by-product that serves as a marker for oxidative stress (Bartesaghi and Radi, 2018; Bandookwala and Sengupta, 2020). As a nootropic, the elevated Phe content in DCF may enhance motivation, concentration and focus, while also reducing anxiety and improving mood. Furthermore, catecholamines derived from Phe are pivotal in regulating the cardiovascular, metabolic, and immune systems (Buchmueller et al., 2024), reinforcing the wide-ranging benefits of incorporating DCF into the diet.

NEAA are those that the body can synthesize independently, as cells are capable of generating their carbon skeletons (Litwack, 2018). Although not strictly essential from the diet, NEAAs are still vital for overall health, supporting variety of physiological functions and maintaining metabolic balance. The variability in the NEAA profile of DCF across different studies can be attributed to several factors, including differences in source, processing methods, and sampling variability. These factors, such as geographical origin, cultivation conditions, and the specific techniques used for both defatting and analysis, can all contribute to variations in the reported NEAA composition. Glu consistently reported as one of the most abundant amino acids in chia seeds, consistent with general pattern observed in many plant-based proteins, such as those from seeds, beans, lentils, soy and certain grains (Kumar et al., 2022). Glu, as an amino acid with an amine group in its side chain, serves as a primary amino donor in transamination reactions, playing a critical role in nitrogen metabolism (Liao et al., 2022; Kim et al., 2019). This process is crucial for maintaining balanced amino acids profile and regulating nitrogen metabolism, thereby preventing the toxic accumulation of ammonia, a by-product of protein metabolism (Liao et al., 2022; Ling et al., 2023). Additionally, Glu, in its ionized form as glutamate, is known for its umami flavour, making it a common ingredient to enhance the taste of plant-based dishes (Yamamoto and Inui-Yamamoto, 2023), while also contributing to reduced salt intake and promoting healthier dietary practices (Tanaka et al., 2023; Morita et al., 2023). As previously discussed, Tyr plays an important role in supporting cognitive function and mood regulation. Furthermore, the increased level of proline (Pro), alanine (Ala), Arginine (Arg), serine (Ser), glycine (Gly), and aspartic acid (Asp) in DCF suggest improved protein quality and highlight its potential functional benefits, further supporting its nutritional value in plant-based diets.

3. Chia protein: innovative extraction and processing techniques

Chia seeds have gradually gained attention for their exceptional nutritional profile, including high levels of omega-3 fatty acids and dietary fibre. Beyond these well-established benefits, chia protein is emerging as a promising alternative to animal-based proteins due to their lower environmental impact and easier production (Timilsena et al., 2016a, 2016b). The food industry is increasingly focused on producing plant protein concentrates and isolates, not only for their functional properties in food products, but also for their ability to enhance qualities such as texture, flavour, consistency, and overall nutrition (Wang et al., 2023a). With the growing shift towards plant-based diets, chia protein seen as a viable alternative offers a balanced amino acid profile, excellent digestibility, and is well-suited for vegan and vegetarian diets. As demand for sustainable protein sources increases, chia seeds are emerging as an important crop, supporting food security sustainable agriculture. However, extracting protein for use in food and other applications depends heavily on the efficiency of the extraction method, which influences the protein's yield, quality, functional properties, and bioavailability (Mondor et al., 2022). Protein extraction is challenging due to their sensitivity to the environment, which can alter their structural properties (Gadalkar and Rathod, 2020). The main goal of extraction is to maximize the yield of protein, while minimizing damage to its properties and avoiding the extraction of unwanted compounds (Pojic et al., 2018). Table 3 provides an overview of these eco-innovative plant protein extraction approaches, highlighting their respective advantages and limitations.

Traditional protein extraction techniques, such as aqueous extraction or acid-alkaline processes, are widely employed in the food and agricultural industries, but often present several challenges that hinder the optimal recovery of high-quality proteins. These methods typically result in lower yields due to protein degradation caused by extreme pH, temperature, solvent conditions, and prolong extraction times. The most common method for extracting chia proteins is alkaline extraction coupled to isoelectric precipitation (Wang et al., 2023a; Khushairay et al., 2023; Mondor et al., 2022; Lopez et al., 2018; Coelho and Salas-Mellado, 2018). However, this method has some drawbacks as the alkaline and acid treatments may influence the functional properties and nutritional quality of the protein, therefore, optimizing the extraction conditions is crucial to minimize undesirable changes (Khushairay et al., 2023; Lopez et al., 2018; Coelho and Salas-Mellado, 2018). Additionally, the residual lipid content in DCF may interfere with the extraction process, as the presence of sodium hydroxide in alkaline extraction can induce saponification reactions (Khushairay et al., 2023; Coelho and Salas-Mellado, 2018). As the demand for high-quality sustainable plant proteins escalate, the need for innovative extraction methods to overcome these challenges becomes more critical. There is a growing focus on eco-innovative green technologies to improve extraction efficiency while preserving the bio- and techno-functional properties of proteins. Techniques such as subcritical water extraction, aqueous two-phase system, enzyme-assisted extraction, and cell disruption are emerging as efficient and environmentally friendly alternative to traditional methods (Gadalkar and Rathod, 2020; Franca-Oliveira et al., 2021). These techniques not only increase the recovery of proteins but also improve their nutritional and techno-functional characteristics, and are considered affordable, safe, effective, and ecologically sustainable, supporting clean-label status (Pojic et al., 2018; Tiwari, 2015).

4. Chia protein: techno- and bio-functionality properties

4.1. Techno-functional attributes

Beyond the nutritional content, recent studies have emphasized the techno-functional properties of chia protein, revealing its potential for diverse applications in food processing, formulation, and nutraceuticals. These functional properties, which refer to the protein's behaviour during food preparation, processing, and storage, are influenced by factors such as protein size, shape, amino acid composition, charge distribution, and structural conformation (Malecki et al., 2021). Such properties are integral to the quality and performance of food products, yet they remain highly sensitive to external conditions, including pH, temperature, salt content, extraction methods, and hydrolysis processes. Chia proteins possess valuable functional attributes, including solubility, emulsifying capacity, foaming ability, water and oil absorption, water and oil holding capacity, and gelling properties. These characteristics significantly impact the texture, consistency, and overall quality of food products, making chia proteins highly beneficial for food formulation. Table 4 provides a comprehensive overview of the key functional properties of chia protein, along with the factors that enhance each property based on recent studies.

4.2. Bio-functional attributes

DCF is renowned not only for its high-quality protein content but also

Table 3
Potential eco-innovative approaches for plant protein extraction.

Extraction Techniques	Descriptions	Advantages	Disadvantages	Recent Publications
Chemical Extraction Techniques	Rely on various solvents, such as water, alkalis, organic solvents, and acids, to extract proteins. Examples of these methods include aqueous extraction, alkali/acid extraction, and organic solvent extraction, all of which use solvents to solubilize proteins.	Cost-effective, simple, and suitable for large-scale operations.	Potential for protein denaturation, requires pH adjustments, lipid interference in alkaline extraction due to sodium hydroxide causing saponification.	(Khushairay et al., 2023; Lopez et al., 2018; Coelho and Salas-Mellado, 2018)
Subcritical Water Extraction (SWE)	Uses hot water under pressure below its supercritical point (normally between 100 and 374 °C) to extract protein. The heat helps to dissolve proteins and break down plant cells, making the extraction easier.	Eco-friendly, no organic solvents, and efficient for polar compounds.	Requires precise control of temperature and pressure, limited to polar compounds.	(Nathia-Neves and Alonso, 2023; Ardali et al., 2023; Powell et al., 2016, 2017)
Aqueous Two-Phase System (ATPS)	Used for efficient protein extraction due to their unique properties, such as phase hydrophobicity and protein bioaffinity. This method separates, concentrates, and purifies proteins by mixing two different components that form two distinct layers.	Rapid, flexible, cost effective, biocompatible and safe for biological material, higher selectivity and purity, and do not denature proteins.	Limited solubility, require complex optimization, scale up challenges due to phase stability and reproducibility, limited to certain proteins especially those with very high or very low molecular weight.	(Kumar et al., 2021; Varadavenkatesan et al., 2021; Menegotto et al., 2021)
Enzyme-Assisted Extraction (EAE)	Utilizes specific enzymes to break down cell wall components like cellulose and pectin, disrupting the wall and releasing protein. Proteases then break down large protein into smaller peptides.	Higher protein yield, produces specific peptides with desired bioactivities, product with higher purity and suitability for human consumption	High cost of enzymes, potential for incomplete hydrolysis, elevated energy consumption, and irreversible carbohydrate-protein matrix disruption.	(Khushairay et al., 2023; Pojic et al., 2018; Kumar et al., 2021; Ochoa-Rivas et al., 2017)
Ultrasound-Assisted Extraction (UAE)	Uses ultrasonic waves to enhance extraction efficiency by disrupting cell walls, leading to higher yields and lower solvent usage.	Higher yield, lower solvent consumption, and shorter extraction time.	High initial investment in equipment, potential for thermal degradation.	(Sengar et al., 2020; Ashfaq and Younis, 2021; Fatima et al., 2023; Yeasmen and Orsat, 2024; Sert et al., 2022; Kadam et al., 2015)
Microwave-Assisted Extraction (MAE)	Uses microwaves to heat the solvent and sample, speeding up extraction time and often improving yield and purity.	Rapid, efficient, and can improve the quality of extracts.	May require specialized equipment and optimization for each sample type.	(Penas et al., 2023; Gorguc et al., 2019; Tungchaisin et al., 2022; Bedin et al., 2019; Prandi et al., 2022; Varghese and Pare, 2019)
High Hydrostatic Pressure-assisted Extraction (HHP)	Applies pressure of 100–1000 MPa through water, causing cell membranes and proteins to break down, allows solvents to enter cells and release their contents. Known as cold pasteurization.	Reversible denaturation, enhance digestibility, enzyme activity control.	Potential of protein aggregation and can modify protein-protein and protein-solvent interaction, leading to undesired changes in protein functionality	(Sezer et al., 2019; Gharibzahedi and Smith, 2021; Ahmed et al., 2019; Marciniak et al., 2018; Ulug et al., 2021)

for its rich composition of bioactive peptides. These peptides, like those derived from other sources, are initially inactive within their complex protein structure since most bioactive peptides are buried or encrypted in the structure of mature proteins, but become active through various extraction and hydrolysis processes, offering a range of potential pharmacological benefits to human health (Peighambardoust et al., 2021). To be considered bioactive, peptides must exhibit significant biological activity without inducing toxicity or allergenicity (Mensah et al., 2024). Bioactive peptides derived from chia typically consist of 3–20 amino acids, with molecular weights of less than 3 kDa (Jones et al., 2019). Recent studies have utilized advanced techniques to isolate and identify bioactive peptides from natural food sources. Enzymatic hydrolysis, which involves the use of proteases such as pepsin, alcalase, flavourzyme, bromelain and papain, as well as digestive enzymes like pepsin, trypsin, chymotrypsin (Rader et al., 2018) is a widely employed method for generating bioactive peptides. These enzymes cleave protein molecules into smaller peptides, often enhancing their wide range bioactivity, including biogenic, opioid, immunomodulatory, salt/metal-binding, antihypertensive, and antimicrobial peptides by releasing biologically active fragments (Barati et al., 2020). Surface-coated enzymes, or immobilized enzymes, are preferred over conventional soluble enzymes in large-scale industrial processes, such as those in food, pharmaceuticals, and textiles, due to their enhanced stability under harsh conditions like high temperatures and extreme pH levels (Maghraby et al., 2023). Immobilization also facilitates easy enzyme recovery, reducing the production of secondary metabolites from autolysis and improving both efficiency and cost-effectiveness (Akbarian et al., 2022). Another widely adopted method is continuous hydrolysis, an efficient and cost-effective technique that uses reactors with ultrafiltration membranes, often integrated with additional purification methods (Musa et al., 2020). This process fully converts food proteins into hydrolysis products with improved nutritional and functional properties, further enhancing the value of the final products. Fig. 3 provides a visual representation of the key techniques utilized in the production of chia peptides.

The health benefits of chia peptides at the molecular level have been widely documented in literature. These peptides exhibit a broad spectrum of bioactivities, including antioxidant, anti-inflammatory, antihypertensive, and antidiabetic effects, as well as neuroprotective and antimicrobial properties. The molecular mechanisms through which these peptides exert their beneficial effects are varied and complex, often involving interactions with key cellular pathways, enzymes, and receptors. Table 5 provides a summary of the bioactive properties of chia peptides from recent studies and outlines the mechanisms underlying their actions. The diverse range of activities attributed to these peptides highlights their potential as functional ingredients in health-promoting foods and as therapeutic agents for managing various health conditions.

5. Food product development and nutraceutical applications

5.1. Fortification of chia seeds-derived ingredients in food product development

Bioactive peptides derived from DCF have shown considerable promise for enhancing the nutritional value and health benefits of functional food products. However, there is currently still limited

Table 4
The techno-functionalities of chia protein from recent studies.

Techno-functional properties	Descriptions	Enhancing factors	References
Solubility	A key factor in protein's ability to interact with other food components, influencing its emulsifying, foaming, and gelling properties, while also enhancing dispersion and consistency in aqueous food systems.	• pH: Highest solubility at pH 10 (76 to 78 %). • Temperature: Solubility increases with temperature up to 50 °C. • Salt: Highest at 1 M NaCl. • Drying: Spray drying improves solubility. • Hydrolysis: improves solubility in a range of pH 3 to 9.	(Khushairay et al., 2023; Coelho and Salas-Mellado, 2018; Malik and Riar, 2022; Guo et al., 2021)
Water and oil absorption capacity	Refers to protein's ability to absorb and retain water or oil. It is essential for food texture, viscosity, and emulsification. It improves moisture and fat retention, enhancing the texture, richness, and structure of products like batters, sausages, and doughs.	• pH: Lowest absorption at isoelectric point (pH 3–4). • Drying method: Freeze drying increases water absorption (2.9 gg^{-1}). • Hydrolysis: Protein hydrolysis increases oil absorption.	(Khushairay et al., 2023; Segura-Campos, 2020; Coelho and Salas-Mellado, 2018; Villanueva-Lazo et al., 2021; Timilsena et al., 2016c)
Water and oil holding capacity	Refers to protein's ability to retain water or oil under external forces. It is crucial for maintaining texture, stability, and consistency in foods like mayonnaise and sausages, while preventing separation during storage and processing.	• High-pressure homogenization decreases water and oil holding capacity. • Protein fractions: Glutelin has the highest water-holding capacity, while globulin has the highest oil-holding capacity.	(Segura-Campos, 2020; Malik and Riar, 2022; Renoldi et al., 2023; Aryee et al., 2018)
Emulsifying capacity and stability	Refers to the protein's ability to stabilize oil and water into uniform mixture. It is essential for improving texture, stability and preventing separation in products like margarine, dressings, mayonnaise, sauces and ice cream.	• pH: Emulsifying capacity stable across pH 2–11 for protein-rich fractions. • Hydrolysis: Alcalase protein hydrolysates shows 50 times higher emulsifying activity. • Protein fraction: Glutelin and prolamins have better emulsifying capacity.	(Khushairay et al., 2023; Segura-Campos, 2020; Coelho and Salas-Mellado, 2018; Urbizo-Reyes et al., 2019)
Foaming capacity and stability	Refers to the protein's ability to form and stabilize foams by trapping air bubbles within a liquid or solid. It enhances the texture and appearance of food by increasing foam volume, stability, and lightness in products like meringues, whipped cream, cakes, beer, and mousse.	• pH: Foaming capacity is lowest at isoelectric point (pH 3–4). • Drying method: Spray drying improves foaming capacity. • Hydrolysis: Alcalase proteolysis and microwave treatments enhance foaming capacity.	(Khushairay et al., 2023; Segura-Campos, 2020; Coelho and Salas-Mellado, 2018; Timilsena et al., 2016c; Urbizo-Reyes et al., 2019)
Gelling properties	Gelling properties refer to a protein's ability to form a gel under certain conditions, like heat or cooling. It influences texture, firmness, and water retention, contributing to the overall stability of products like jams, jellies, gummies, gels, puddings, and plant-based alternatives.	• Protein fraction: Glutelin has the best gelling property. • Denaturation: Protein denaturation enhances gel formation when combined with carbohydrates.	(Khushairay et al., 2023; Coelho and Salas-Mellado, 2018; Ramos et al., 2017)

literature on the direct use of chia protein or its fractions, such as isolates, concentrates, and hydrolysates, in food production, highlighting a significant opportunity for further exploration and innovation in this area. Chia seeds derivatives can serve as a valuable health-boosting ingredient in a variety of foods. The primary aim of fortifying food products with bioactive peptides is to provide a natural alternative to synthetic additives, adding value to the product while potentially enhancing consumer trust and acceptance of these functional foods (Jia et al., 2021). In general, the application of chia-derived ingredients has been explored across four main food categories: bakery products, meat products, staple foods, and dairy products (Chen and Luo, 2024) as illustrated in Fig. 4. Chia seeds, being a naturally gluten-free pseudo-cereal (Borges et al., 2021), offer a safe alternative for individuals with celiac disease and other gluten-related disorder. Incorporating chia seed-derived ingredients into breads or pastries products will enhance both nutritional profile and texture of these products (Borges et al., 2021; Fernandes et al., 2021), offering a healthier and more versatile option for those with dietary restrictions. Chia peptides have been used to fortify bakery items (Ozon et al., 2022), dairy products, and meat analogues (Senna et al., 2024; Kothury et al., 2024), providing a source of high-quality protein and beneficial bioactivities. Ozon et al. (2022) reported that adding chia hydrolysates from DCF at concentration of 1–10 mg to fortify wheat flour in bread formulations resulted in a lighter crust, due to reduced Maillard reaction. Additionally, the substitution of 5 and 10 mg of chia hydrolysates improved the bread's textural properties, increasing its specific volume, reducing hardness, and enhancing alveoli formulation. Similarly, Coronel et al. (2021) found that fortifying premixes and bread with chia flour resulted in higher protein content and improved emulsifying activity and stability compared to the control group. Besides, fortifying biscuit formulations with 15 % chia flour enhanced water retention ability (Brandao et al., 2019), which potentially improved the texture, mouthfeel, and shelf life of the biscuits.

Moreover, chia seeds-based products and is increasingly being used as an ingredient to develop meat analogues due to its beneficial properties. Fernandez-Lopez et al. (2019) investigated the use of chia seeds and chia flour in sausage formulations made with 70 % lean meat and

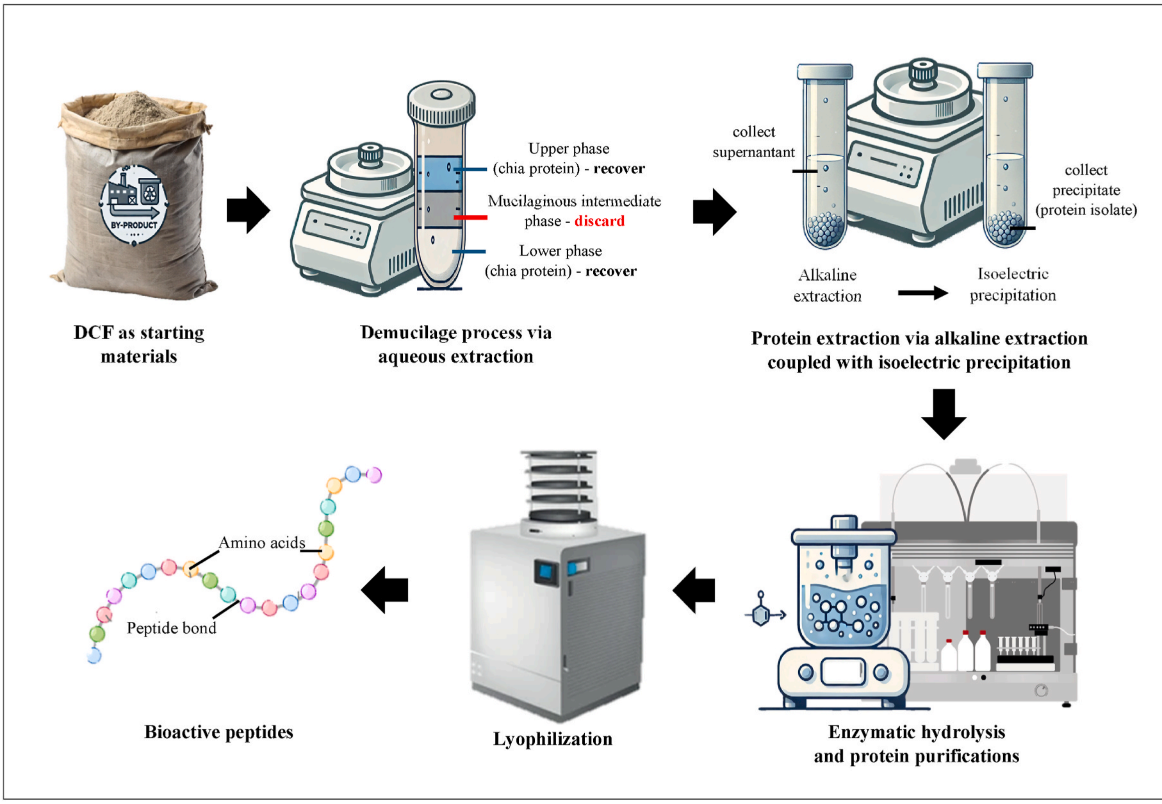

Fig. 3. Overview of the essential techniques involved in the production of chia peptides.

30 % fat. They found that emulsion stability and gelling properties were enhanced by the protein content in chia seeds and their coproducts, which are known to function as effective emulsifiers and gelling agents. Additionally, the chia-enriched sausages were less prone to oxidation, as measured by TBARs during extended storage compared to the control group. A study by Pintado et al. (2016) found that incorporating 10 % of chia flour as a fat replacer in frankfurter formulations reduced the purge value to below 2 %, demonstrating chia's strong ability to retain water, likely due to the water- and oil-holding capacity of its protein. The frankfurter also exhibited lower saturated fat, higher mono- and poly-unsaturated fats (400 % increase in omega-3), improved fat and water-binding properties, and reduced hardness compared to the control groups. In another study, Paglarini et al. (2019) found that replacing 20 % of pork fat with of DCF emulsion resulted Bologna sausages resulted in 30 % reduction in total lipid content, higher omega 3 levels, reduced hardness, and a 10 % decrease in protein content compared to the controls. The addition of DCF also impacted the microstructure, leading to a more compact protein matrix, likely due to the flour's high protein and fibre content, which enhances its ability to bind water and fat.

Chia seeds and its derivatives play a versatile role in enhancing the nutritional profile, texture, and functional properties of staple foods. They offer a range of benefits, from improving moisture retention and gelling properties to boosting omega-3 content and fibre. Staple foods are the foundation of a diet, providing essential nutrients and energy, and typically being consumed regularly and form a significant portion of daily nutrition. Khatri et al. (2023) studied the used of chia flour in gluten-free pasta formulation incorporating up to 17.5 % chia flour alongside quinoa flour and found that cooking loss decreased as the proportion of chia seed flour increased, suggesting that higher protein content in chia flour helps prevent starch granules from swelling. A similar finding was reported by Lavent (2017) in the formulation of gluten-free noodles. The study showed that as the proportion of chia flour increased, the cooking loss of the noodles decreased, likely attributed to the higher protein content in chia flour, which influences starch-protein interactions, enhancing the surface tension and rigidity of starch granules, thereby limiting their swelling. In a different study, Katunzi-Kilewela et al. (2022) found that porridge formulations combining dried mashed cassava with 5–25 % chia flour exhibited improved viscosity, taste, colour, mouthfeel, aroma, gel consistency, and oiliness, and received higher overall acceptance in sensory evaluation compared to the control group.

Chia seeds and their by-products are gaining popularity in the dairy industry due to their health benefits. Rich in omega-3 fatty acids, fibre, and antioxidants, chia seeds improve the nutritional value of dairy products like yogurt, milk, and cheese. Dairy products, particularly those made from raw milk, often require protein-enriched ingredients to preserve texture throughout processing and storage. Chia seeds, with their emulsifying and gelling properties, offer great potential stabilizing emulsions and foams, thereby enhancing mouthfeel and ensuring consistent quality of dairy products. A study by Kwon et al. (2019) demonstrated that adding 0.1 % chia seed ethanol extract to yogurt enhances its radical scavenging capacity, inhibits lipopolysaccharide-induced hydrogen peroxide production in human colon cells, and promotes the growth of LAB. Additionally, it improves the physicochemical properties and health benefits of set-type yogurt. Feizi et al. (2021) investigated the use of chia mucilage as a replacement for commercial stabilizers in ice cream, finding that a 0.2 % chia mucilage formulation resulted in high-quality ice cream with an overrun of about 103 %. The product also exhibited a destabilized fat index of 41.0 %, a fat globule size of 40.7 μm, a low meltdown rate of 0.9 g min^{-1}, and a hardness of 40.1 N. Sensory evaluations confirmed that the ice cream had the ideal hardness, smooth texture, and creamy mouthfeel, free from ice crystals and off-flavours. Madrazo et al. (2022) found that chia peptides with the sequence Lys-Leu-Lys-Lys-Asn-Leu were stable across a range of temperatures and pH levels, and effectively inhibited the growth of foodborne pathogens such as *Listeria monocytogenes*, *Staphylococcus aureus*, and *Bacillus subtilis*. They recommended their use as antimicrobial agents in dairy products. In a separate study,

Table 5
Bioactive properties of chia peptides and their mechanisms of action.

Bio-functional properties	References	Mechanisms/effects	Protein fractions
Antioxidant	Grancieri et al. (2019b)	Scavenge oxide, hydrogen peroxide, superoxide, and DPPH scavenging capability and inhibited 5-lipoxygenase (5-LOX), cyclooxygenase-1 and 2 (COX-1-2), and inducible nitric oxide synthase (iNOS) enzymes	Albumin, globulin, glutelin
	Orona-Tamayo et al. (2019)	Albumin strongly inhibits ABTS and DPPH radicals, while prolamin and globulin exhibit a high capacity for chelating ferrous ions.	Albumin, prolamin, globulin
Antihypertensive	Orona-Tamayo et al. (2019)	Exhibits ACE inhibitory activity	Globulin, albumin
	Pablo-Osorio et al. (2019)	Interaction of peptide sequence with 9 hydrogen and 8 hydrophobic bonds on the ACE catalytic site.	Leu-Ile-Val-Ser-Pro-Leu-Ala-Gly-Arg-Leu
Anti-inflammatory	Grancieri et al. (2019b)	Interacted with COX-2, p65-NF-kB, LOX-1, and TLR4. Reduced H_2O_2 and nitric oxide release and modulate both pro- and anti-inflammatory cytokine levels (IL-10, IL-1β, IL-6, and TNF-α).	1–3 kDa peptides fractions
	Grancieri et al. (2021)	Decreased the inflammatory mediators nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB p56) and peroxisome proliferator-activated receptor gamma (PPAR-γ) in the adipose tissue of mice.	Leu-Pro-Val-Phe-Gly-Leu-Ala-Ala-Glu-Gly-Asn-Val-Val-Thr-Tyr-Leu-His
Neuroprotective	Leo and Campos (2020)	Reduce proinflammatory mediators (TNF-α, IL-6, NO, H2O2) and reactive oxygen species in human microglial clone 3 (HMC3) cells.	<3 kDa peptides fractions
Antidiabetic	Zamudio et al. (2022)	Inhibited DPP-IV (43.60 %) and α-glucosidase (3.39 %), with IW and PW fragments showing low binding energies against these enzymes (in-silico study).	Peptides
	Crespo et al. (2021)	Reduced plasma glucose concentration 30 min after administration in 9 diabetic patients by competitively binding to the active sites of saccharase, α-amylase, and α-glucosidase, inhibiting their activities	Peptides
Antimicrobial	Coelho et al. (2018)	Inhibited *Escherichia coli* and Listeria monocytogenes by damaging their cell membranes, causing deformation and slowing bacterial growth.	<3 kDa peptides fractions
	Aguilar-Toala et al. (2020)	Inhibit E. coli O157:H7 B6-914, E. coli ATCC 25922, *Salmonella enterica* serovar Typhimurium K1028, Listeria monocytogenes 10403S, and Listeria innocua ATCC 33090.	<3 kDa peptides
	Madrazo et al. (2022)	Inhibit gram-positive bacteria *L. monocytogenes* ATCC 51,414, *Staphylococcus aureus* ATCC 25,923, and gram-negative bacteria *Bacillus subtilis* ATCC 465, *Shigella flexneri* ATCC 9748, *Salmonella typhimurium* ATCC 51,821, *Salmonella typhi* ATCC 19,430, *Salmonella Paratyphi* ATCC 9150, *Salmonella Enteritidis* ATCC 13,076, *Escherichia coli* ATCC 43,895.	Lys-Leu-Lys-Lys-Asn-Leu; Lys-Lys-Tyr-Arg-Val-Phe; Met-Leu-Lys-Ser-Lys-Arg; Met-Ser-Lys-Ala-Lys-Pro-Gly-Arg-Ser-Met; Ser-Val-Val-Ala-Lys-Ala-Pro-Val-Gly-Lys-Arg.
Antiaging	Ferreira et al. (2020)	Mimicked pathways that transduce signals to collagen and other fibrous proteins such as elastin and fibrin. BPs (i.e., palmitoyl tetrapeptide-7) downregulated IL-6, triggered the synthesis of new collagen and elastin, and delayed the formation of wrinkles.	Peptides
	Aguilar-Toala and Liceaga (2020)	Inhibited enzymes (i.e., elastase, tyrosinase, collagenase, and hyaluronidase) that responsible for skin wrinkles.	<3 kDa peptides fractions
	Montalvo et al. (2019)	Inhibited matrix metalloproteinase-1 (MMP-1), 2 (MMP-2), thus, decreased the extent of collagen damage	Peptides
Hypolipidemic and hypoglycaemic potential	Coelho et al. (2018)	Inhibited HMG-CoA reductase activity with an effect comparable to pravastatin, forming a unique class of inhibitors that block the mevalonate pathway, helping to prevent hypercholesterolemia.	<3 kDa peptides fractions

Zaky et al. (2019) investigated the potential of whole chia seeds as a stabilizer in ice milk products, finding that supplementation of 6 % chia seed powder enhanced the physical properties and melting quality of the product. Both overrun and viscosity increased with higher chia concentrations, while melting resistance improved. Additionally, chia seed powder contributed to create homogeneous structure and uniform distribution of air cells throughout the matrix, while enhancing the nutritional value of the final product.

5.2. Nutraceutical applications of chia peptides

As previously discussed, chia bioactive peptides have shown significant bioactivities, indicating their potential for incorporation into functional food products. Many scientific studies confirm the wide spectrum of health-promoting effects of chia peptides. However, the application of chia peptides in various food systems remains in its

Fig. 4. Applications of chia seeds-derived ingredients in food product development.

nascent stages, with a limited number of preclinical studies published. Villanueva-Lazo et al. (2021) reported that bioactive chia peptides exhibit immunostimulatory effects by modulating both specific and nonspecific immune responses by enhancing immunoglobulin production, boosting the phagocytic activity of immune cells, and increasing the number of cells that produce IgA antibodies. In separate studies, Rabail et al. (2021) and Grancieri et al. (2021) found that chia peptides help prevent oxidative stress associated with adipogenesis and inflammation. These peptides inhibit adipogenesis by reducing the expression of peroxisome proliferator-activated receptor γ (PPAR-γ) in mature adipocytes and also lower the activity of enzymes such as lipoprotein lipase, fatty acid synthase, and sterol regulatory element binding protein 1. A study by Coelho et al. (2018) demonstrated that chia protein can inhibit HMG-CoA reductase activity by up to 81 %, block the mevalonate metabolic pathway, and thereby help prevent hypercholesterolemia and atherosclerosis. A study by Aguilar-Toala and Liceaga (2020) found that the chia peptide fraction, with a molecular weight of less than 3 kDa (at 1 mg/ml), demonstrated a direct inhibitory effect on collagenase and tyrosinase, while exhibiting a mixed inhibition pattern against hyaluronidase and elastase, enzymes that contribute to the degradation of the skin's protein matrix. These findings suggest their potential use in the development of nutraceutical and cosmeceutical products.

6. Prospects for future research

DCF, a by-product of chia seed oil extraction, holds potential bioactivities that warrant further investigation. Despite being underutilized resource, it offers several unexplored opportunities for enhancing food products, developing nutraceuticals, and improving health outcomes. The passage delineates upcoming research paths for chia peptides, emphasizing several key areas. In pursuit of sustainability and added value, the synergistic use of various chia products represents an innovative strategy that integrates the concept of biorefinery into the chia seed processing chain.

6.1. Bioavailability and absorption mechanisms

Understanding the bioavailability of chia peptides is a critical area of research, as it determines how effectively these bioactive compounds exert their physiological effects upon consumption. Bioavailability refers to the extent and rate at which active compounds, such as peptides, are absorbed into the bloodstream and become available at target sites within the body (Khushairay et al., 2024; Stielow et al., 2023). In the case of chia peptides, the digestion, absorption, and metabolic processing of these bioactive components in the human digestive system are complex processes that require detailed investigation. Although the therapeutic potential of chia protein hydrolysates has been documented in the literature, the mechanisms underlying their absorption and bioavailability in the human digestive system remain insufficiently understood. Investigating factors such as the interactions between chia peptides and digestive enzymes, their digestive stability to resist breakdown in the digestive system, the efficiency with which these peptides enter the bloodstream, and their bioavailability (the proportion available for the body to use) is crucial for determining their potential bioactive effects in vivo. To gain a comprehensive understanding, advanced techniques such as in vitro gastrointestinal digestion simulation models can be employed to observe the breakdown of chia peptides and assess their efficiency across the intestinal barrier under various gastrointestinal conditions (Khushairay et al., 2024). However, in vitro models have limitations in mimicking the complexity of human digestion (Brodkorb et al., 2019), so human clinical trials are necessary to confirm in vitro findings and evaluate how chia peptides behave in real physiological conditions in the bloodstream.

6.2. Interdisciplinary collaborations

Beyond understanding bioavailability, the collaborative efforts of various disciplines open new approaches for the innovative application of chia peptides. As their potential applications continue to expand across various sectors, the complex nature of chia peptides requires comprehensive investigation across multiple scientific domains, including biochemistry, bioengineering, nutritional sciences, pharmacology, microbiology, and food technology, to foster their innovative development and practical application. Food technologists, microbiologists, and enzymologists are integral to understanding how chia peptides interact with food ingredients, focusing on key properties such as stability, solubility, and texture modification. In parallel, bioengineering plays a crucial role in improving the production and functionality of chia peptides by leveraging advanced synthesis methods and eco-innovative technologies to enhance yield and bioactivity. Furthermore, the development of chia peptide-enriched products requires a thorough understanding of both their physicochemical properties and the specific needs of the food industry. Thus, collaboration with food technologists enables the development of novel formulations, including micro- and nano-encapsulation, which ensure that chia peptides retain their bioactive properties and appeal in a wide range of food products. Moreover, collaboration between biochemists and nutritionists is vital to understand how chia peptides influence biological functions, their absorption, and interactions with enzymes and receptors. Investigating their therapeutic potential, particularly in modulating pathophysiological conditions, is a key area for future research. Clinical trials are essential to assess the metabolic effects, bioavailability, and impact of chia peptides on biomarkers associated with chronic diseases. Emerging also highlights the critical role of gut microbiota in the bioavailability and bioactivity of dietary peptides (Wijesekara et al., 2024), including those derived from chia seeds (Wu et al., 2022). Thus, collaboration between microbiologists, nutritionists, and immunologists is necessary to understand how chia peptides interact with gut bacteria, and how these interactions may alter their bioactive effects. Such research can provide insights into how chia peptides influence gut health, immune function, and metabolism, with potential applications in personalized nutrition and probiotics.

6.3. Safety considerations: allergenicity, synergistic interactions, and long-term high-dose risk

As chia peptides gain increasing interest for incorporation into food products and nutraceuticals, a thorough evaluation of their safety and potential toxicity is essential. While chia seeds are recognized as safe (Turck et al., 2019), the long-term effects of chia peptides in human consumption remain underexplored. Rigorous investigations into the safety profiles of chia peptides are needed, particularly concerning their potential to trigger allergic reactions (Regula et al., 2023) or synergistic interactions with other bioactive substances (Bota et al., 2024). Although chia seeds are generally regarded as low-allergenicity foods, the processing and hydrolysis may alter the peptides' structure, potentially generating new epitopes that may trigger immune responses in susceptible individuals (Zhou et al., 2024; Huang et al., 2024), especially in those with pre-existed seeds or nut allergies. While the synergistic effects of peptides with other compounds can enhance beneficial outcomes, such as improved bioactivity, better nutrient absorption, and modulation of gut microbiota to support therapeutic effects, they also raise concerns about unintended consequences. These include the risk of overstimulating biological pathways or reducing the efficacy of certain nutrients and drugs, emphasizing the need for thorough evaluation. Another critical aspect of safety that requires attention is the potential of long-term and high-dose consumption of chia peptides. While short-term studies may overlook certain risks, long-term studies are essential to identify any adverse effects that may arise with sustained use. These could include immune overstimulation, digestive disturbances such as bloating and flatulence, nutrient imbalances, or metabolic alterations (Bidram and Ganjalikhany, 2024). Additionally, the effects to chia peptides on at-risk groups, such as pregnant women, children, and individuals with chronic illnesses, should not be overlooked. Variations in metabolic rates, physiological conditions, and immune responses among these groups may heighten their sensitivity to potential adverse effects, highlighting the critical need for further research in this area. To address these concerns, a comprehensive, multi-steps approach is recommended, including animal studies, human clinical trials, and comprehensive regulatory oversight to establish clear safety guidelines for chia peptides. Such evaluations are crucial to safely integrate chia peptides into food systems and nutraceuticals, allowing their health benefits to be fully realized while minimizing any associated risks.

6.4. Sustainable production and economic viability

Leveraging underutilized grains like chia seeds presents a promising solution to address nutritional insecurity, given their exceptional nutritional profile (Prathyusha et al., 2019). The sustainability of chia peptide production is a key area for future investigation. Chia is recognized for its environmental advantages, requiring less water and thriving in arid conditions, which makes it more sustainable compared to other crops (Kirsch et al., 2024). However, the large-scale production of high-quality bioactive peptides still faces economic challenges (Franca-Oliveira et al., 2021). Future research should focus on developing cost-effective extraction methods, improving production efficiency, and minimizing waste. One significant factor in peptide production is the cost of enzymes. To address this cost barrier in chia peptide production, enzyme optimization strategies can be employed, such as using genetically engineered or recombinant enzymes with high efficiency and stability (Ndochinwa et al., 2024). Immobilized enzymes, which can be reused multiple times without significant loss of activity, and enzyme cocktails to improve bioactive peptide yields, also help reduce operational costs (Maghraby et al., 2023; Chauhan et al., 2022).

Emerging green technologies offer further cost reductions by minimizing the need for expensive solvents and lowering energy consumption. Techniques such as ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, and advanced ultrafiltration and nanofiltration systems are energy-efficient and streamline purification processes (Usman et al., 2023; Putra et al., 2023). In large-scale production, adopting continuous flow systems and process automation enhances efficiency, reduces human error, ensures consistent peptide quality, and lowers labour costs (Jungbauer et al., 2024; Schmidt et al., 2023; Boodhoo et al., 2022). Furthermore, modern tools such as artificial intelligence (AI) and computational modelling optimize processes through predictive analysis and simulation, further reducing production costs (Goles et al., 2024; Chang et al., 2024; Chen et al., 2024; Nissan et al., 2024). These innovations and advancements ensure efficiency and scalability, making chia peptides more accessible for food and nutraceutical applications in the future.

7. Conclusion

The promising potential of DCF peptides presents exciting opportunities for both the food and nutraceutical industries. These peptides, derived from chia's rich nutritional profile, offer a unique combination of functional and bioactive properties that make them ideal candidates for improving the quality and nutritional value of food products. Their diverse biological activities, from antioxidants and antihypertensive to antimicrobial and anti-aging effects, highlight their therapeutic potential in addressing chronic health issues and promoting overall well-being. Despite their significant promise, unlocking the full potential of DCF peptides requires a deeper understanding of their bioactivity at the molecular level. Further research is needed to explore their interactions within various physiological systems and the underlying mechanisms behind their health benefits. Collaborative efforts across food science, biotechnology, pharmacology, and nutrition will be essential to drive innovations and ensure the safe incorporation of these peptides into food products. Moreover, advancements in production, extraction, and purification technologies will be key to scaling up DCF peptide applications in a sustainable and economically viable manner. As the demand for functional foods and natural bioactive ingredients continues to grow, DCF peptides are positioned to play an integral role in advancing health and nutrition. With continued research and technological innovation, they hold the potential to make substantial contributions to human health, food sustainability, and environmental well-being.

CRediT authorship contribution statement

Etty Syarmila Ibrahim Khushairay: Conceptualization, Methodology, Validation, Data curation, Writing – original draft, Writing – review & editing. **Salma Mohamad Yusop:** Conceptualization, Methodology, Validation, Data curation, Writing – review & editing, Funding acquisition, Resources. **Mohamad Yusof Maskat:** Conceptualization, Validation, Data curation, Writing – review & editing, Funding acquisition, Resources. **Abdul Salam Babji:** Conceptualization, Validation, Data curation, Writing – review & editing.

Data availability statement

No data was used for the research described in the article.

Ethical statement

The authors declare no ethical issues encountered in the present study.

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Declaration of competing interest

The authors declare no conflict of interests.

Data availability

No data was used for the research described in the article.

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