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Chia seed protein as a promising source for plant-based foods: Functional properties, processing methods and potential food applications

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ABSTRACT

Plant-based foods have prevailed around the world, and various high-quality plant proteins have been explored and studied in recent years. Chia seeds have received extensive attention for their rich nutrients, with up to 20 % protein content. Protein in chia seed contains 18 essential and non-essential amino acids, which can be considered as an alternative plant protein source for individuals who are vegans and allergic to soy or gluten. This review provides an overview of the functional properties of chia seed protein and its fractions, focusing on solubility, water and oil absorption capacity, water and oil holding capacity, emulsifying, foaming as well as gelling properties. The chemical methods of chia seed protein processing using acidic or alkaline solutions, including purification and fractionation, are also discussed. The few literature studies on the application of chia protein, chia seeds or chia seed flour used in food production were exclusively investigated. Furthermore, the current challenges and future opportunities related to the economy, environment, and ethics render it the potential to become a main ingredient for plant-based foods are also thoroughly analysed.

1. Introduction

With the gradual growth of the global population and economy, there is an increasing trend in meat consumption worldwide, such as beef, pork, chicken, lamb, etc. However, rearing too many livestock can cause adverse effects on the environment, such as excessive use of water resources, loss of vegetation, elevated emission of greenhouse gases, and the risk of spreading germs, which may break the ecological sustainability (Singh et al., 2021). Besides, there are also some ethical issues concerning animal welfare and animal rights among people because of the cruel slaughter related to meat production (McClements & Grossmann, 2021a, 2021b). On the other hand, excessive meat consumption is usually associated with the potential risk of cardiovascular diseases. Considering a plant-based diet can also meet the needs of daily nutrition requirement, hence it is commonly perceived to be healthier than an animal-based diet from consumers' perspective (McClements & Grossmann, 2021a).

Plant-based food can be produced by a blend of plant-derived ingredients with different functions, including proteins, carbohydrates, lipids, and other additives. Proteins, the most important components in plant-based foods, are mainly derived from soybeans, peas, wheat, potatoes, rice and other plant sources. Generally, these proteins can be classified into globular, fibrous, and flexible types with respect to their molecular structure. It is hard to find flexible proteins from plant-based protein sources because they do not have flexible random-coil structures or micellar structures (Sim et al., 2021). Most plant proteins are globular proteins that can be functioning as emulsifying, foaming as well as gelling agents (McClements & Grossmann, 2021a, 2021b; Sim et al., 2021). For fibrous proteins, only glutenin in wheat and a few numbers of mycoproteins have the characteristics of cohesiveness and viscoelasticity (McClements & Grossmann, 2021a; Sim et al., 2021). Carbohydrates include monosaccharides, disaccharides, oligosaccharides, and polysaccharides, of which polysaccharides play a vital role in the creation of meat analogues due to their multiple structural functions. Starches and flours, such as from potato, rice, and wheat, are able to improve the texture and consistency of the meat analogue products. Fibres from bamboo, oats, and some fruits as well as gums, including xanthan gum, gum Arabic, and carrageenan can help to thicken and stabilize the products (Bohrer, 2019; Boukid, 2021b). High levels of unsaturated fatty acids are found in plant-based lipids, such as canola oil and olive oil, whereas only very few of them with the predominant components of saturated fatty acids (e.g., coconut oil). Plant-based fat can contribute to the texture and mouthfeel of the food matrix, and act as a carrier of lipophilic flavour compounds and fat-soluble vitamins

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(Kołodziejczak et al., 2022). Minor ingredients usually employed in plant-based foods are the pigments and flavouring agents from natural sources. For instance, betalains from beet extract, carotenoids from carrots, anthocyanins from various berries and some other natural pigments can act as colouring agents. On the other hand, it is common to use the extract from yeast as well as some plants, such as pepper and rosemary as flavourings (Kołodziejczak et al., 2022; McClements & Grossmann, 2021b).

Even though many proteins are promising for manufacturing meat analogues, their molecular assembly are substantially different from meat proteins. Unlike animal-based proteins, plant-based proteins are primarily made up of globular proteins, which makes them difficult to form the fibrous texture (Sha & Xiong, 2020). Besides, plant proteins lack some of the essential amino acids, such as valine and lysine, while animal proteins contain a complete source of indispensable amino acids (Bohrer, 2019; Ewy et al., 2022). Furthermore, animal proteins are more digestible for people than plant proteins because they show differences in the types and numbers of amino acids and absorption rates (Ewy et al., 2022).

Nowadays, as plant-based diets become increasingly popular, a broad spectrum of plant proteins from various plant sources have been explored, as shown in Table 1 with the type, source, function, and application of each listed plant-based protein. Pea, chickpea, lentil and lupine belong to legumes which have a high protein content and the protein profile mainly consists of legumin and vicilin. Among legume proteins, pea protein is the most promising material to create meat analogues for its fibrous whole-muscle-like characteristic after high-moisture extrusion, which provides more options for consumers (Kyriakopoulou et al., 2019). Oil plants include soybean, rapeseed, flaxseed, sunflower seed and so forth, whose proteins can be employed in the baking industry and meat analogue production, especially the soy proteins, due to their various functional properties, such as solubility (in

Table 1
Overview of selected plant-based proteins, sources, functionality, and current food application status.

Type of proteins	Sources	Main proteins	Functionality	Applications	References
Legume protein	Pea	Legumin and vicilin	Solubility, foaming capacity, emulsion ability, gelation, and film forming capacity	Bakery products; pasta; meat products; beverages	(Boukid et al., 2021; Kumari & Deka, 2021)
	Chickpea	Legumin and vicilin	Solubility, water- and oil- holding capacity, emulsifying capacity, foaming capacity, and gelation	Bakery products; meat products; plant-based beverages; weaning foods; components of microencapsulates	(Boukid, 2021a; Kaur & Prasad, 2021)
	Lentil	Legumin and vicilin	Solubility, water and oil absorption capacity, emulsifying properties, foaming capacity, and gelation	Bakery products; meat products; milk substitutes; extruded products	(Jarpa-Parra, 2018; Shrestha et al., 2023)
	Lupine	Conglutin	Solubility, emulsifying properties, foaming capacity, and gelation	Animal feeds; bakery products; paste; meat products; yoghurt alternative	(Boukid & Pasqualone, 2022; Chukwuejim et al., 2024; Shrestha et al., 2021)
Oilseed protein	Soybean	Glycinin and β-conglycinin	Solubility, gelation, emulsifying properties, foaming capacity, water- and oil- holding capacity	Traditional foods; soy protein powder; components of nanostructured interfaces of emulsions	(Amagliani et al., 2021; Nishinari et al., 2014; Tang, 2019)
	Rapeseed	Cruciferin and napin	Solubility, emulsifying capacity, foaming capacity, and gelation	Meat substitutes; bakery products; beverages; protein-based films; protein-derived plastics	(Chmielewska et al., 2021)
	Cottonseed	Legumin and vicilin	Solubility, water- and oil- holding capacity, emulsifying properties, and foaming properties	Meat products; bakery products; extruded products	(Kumar et al., 2021)
	Flaxseed	Linin and colinin	Solubility, water- and oil- holding capacity, emulsifying properties, and foaming properties	Animal feeds; fertilizer; bakery products	(Marambe & Wanasundara, 2017; Peng et al., 2022; Wu et al., 2019)
	Peanut	Arachin and conarachin	Solubility, water- and oil- holding capacity, emulsifying properties, foaming properties, and gelation	Bakery products; dairy products; meat products; nanoparticles; protein-based films	(Cui et al., 2023)
	Sunflower seed	Sunflower albumins and helianthinin	Solubility, water- and oil- holding capacity, emulsifying properties, foaming properties, and gelation	Animal feeds; meat/seafood/egg substitutes	(Hadidi et al., 2024; Kaur & Ghoshal, 2022)
Cereal protein	Wheat	Gliadin and glutenin	Viscoelasticity, gelation, emulsifying properties, and foaming properties	Flour-based products; meat products; meat substitutes	(Zhang et al., 2023)
	Corn	Zein	Viscoelasticity, layer-forming properties, gas and moisture barrier properties	Animal feeds; bakery products; functional foods; food additives; natural drugs; biodegradable/edible films	(Lan et al., 2023; Li et al., 2019; Zhang et al., 2022)
	Barley	Hordein and glutelin	Emulsifying properties, foaming properties, and film forming capacity	Bakery products; snacks; biodegradable films	(Jaeger et al., 2021; Lyu et al., 2022)
	Oat	Avenalin	Solubility, emulsifying capacity, foaming properties, and gelation	Oat-based foods; oat milk	(Spaen & Silva, 2021; Zhang et al., 2021)
	Rice	Glutelin	Solubility, water- and oil- holding capacity, water absorption capacity, emulsifying properties, and foaming properties	Food additives; bakery products; edible films	(Roy et al., 2023; Zheng et al., 2024)
Pseudo-cereal protein	Amaranth	Albumins (albumin 1 and albumin 2) and amarantin	Solubility, water and oil absorption capacity, emulsifying properties, foaming capacity, gelation, and film formation	Gluten-free foods; gluten-free beverages	(López et al., 2019; Martínez-Villaluenga et al., 2020; Tovar-Pérez et al., 2019)
	Buckwheat	Globulin	Solubility, emulsifying properties, foaming capacity, and gelation	Noodles; bread; fermented products; composite film	(Zhu, 2021)
	Quinoa	Chenopodin	Solubility (high at alkaline pH), water holding capacity, water and oil absorption capacity, emulsifying properties, foaming capacity, gelation, and film formation	Gluten-free products; industrial products; edible film	(Dakhili et al., 2019; López et al., 2019)

dilute solutions of neutral salt), emulsifying and foaming capacity, etc. Besides, the addition of other food ingredients is useful for the functional properties of oilseed proteins to become more desirable, for example, adding sugars can help to improve their whipping properties (Kurek et al., 2022). Amongst the cereal proteins (e.g. wheat, corn, barley, oat and rice proteins), wheat protein is the most common because of its viscoelasticity. Cereal plants have relatively high carbohydrate content and low protein content, however, the viscoelastic properties of their proteins can help to provide consistency and fibrous characteristics in meat analogue manufacture (Bohrer, 2019; Kurek et al., 2022). Pseudocereals primarily refer to quinoa, amaranth, buckwheat, and chia seed, which are gluten-free crops that can be applied to individuals with celiac disease (Constantino & Garcia-Rojas, 2022). Compared with cereals, they are richer in proteins and can be utilized as alternative proteins to produce meat analogues (Kurek et al., 2022).

Fig. 1 presents an overview of the nutritional composition, functionalities, and applications of chia seeds. Chia seeds contain nearly 20 % of protein, which is greater than that of all other cereals and pseudocereals. Different functional properties are demonstrated in chia seeds and their proteins, including their solubility, water and oil absorption capacity, foam forming capacity and stability, emulsifying property and stability, colour properties, and the capability of forming gels (López et al., 2019). On the other hand, previous literature has shown tremendous potential health benefits of chia seed consumption, such as the anti-inflammatory property, the control and prevention of cardiovascular diseases, diabetes, hypertension and so on (Ullah et al., 2016; Wang et al., 2024). In addition, what makes chia seeds special and precious to patients who suffer from celiac disease is the absence of gluten protein Knez Hrnčič et al. (2020). Chia seeds have broad applications in diverse fields, from food substitution and fortification to pharmaceutical and cosmetic use (Fig. 1) (Chiang et al., 2021; Knez Hrnčič et al., 2020; Motyka et al., 2023). For the application of chia seed proteins, they are suitable to act as supplements and be added into bakery products, or potentially use as alternative proteins in the meat analogue industry (Fernández-López et al., 2021; López et al., 2019).

In this review article, various functional properties, processing methods, potential applications in the food industry as well as future trends and challenges of chia seed protein are discussed. Through the elaboration of the versatile functions of chia seed proteins, it is expected to expand its applications in food formulations and the development of functional foods etc.

2. Processing methods for chia seed protein

The main processing methods for plant-based proteins involve physical, chemical, and enzymatic methods, where the chemical method is commonly used for processing chia seed protein. In order to obtain the protein extract with high protein content, the purification process is necessary, while the fractionation step is to generate the chia seed protein fractions which are albumins, globulins, prolamins, and glutelins (Senna et al., 2024; Wang et al., 2023).

2.1. Extraction of chia seed protein

The extraction of protein from chia seeds is an essential and prospective process since the protein extracts can be potentially used in the food and pharmaceutical industry, in the form of functional ingredients, supplements, or carriers for small molecules etc. Up to date, all the protein extraction methods of chia seeds presented in the current literature generally follow a similar chemical process as shown in Fig. 2A.

The protein extraction process starts with the selection of chia seeds that damaged seeds are discarded and sound seeds are mixed with distilled water. Based on literature protocols, the seed-to-water ratio may be controlled at 1:10 to 1:40 (w/v), with constant stirring for 1–2 h until the seeds became swollen (Salazar Vega et al., 2020; Sandoval-Oliveros & Paredes-López, 2013; Segura-Campos, 2020; Timilsena, Adhikari et al., 2016). The mucilage is from the testa epidermal cell of mature chia seeds, and it will immediately expand and rupture thus surrounding the seed when hydrated (Muñoz et al., 2012). It can be removed mechanically from the seeds through freeze-drying or centrifugation for 15 min at 10,000 g (López et al., 2018; Timilsena, Adhikari et al., 2016). The seeds could be milled into coarse flours before being defatted and the oil can be extracted in different protocols, such as the Soxhlet extraction method by using hexane as a solvent at 65–70 °C for 4 to 6 h, or in a Friedrich system by using four refluxes of 80 min each (Grancieri et al., 2022; Julio et al., 2019; Salazar Vega et al., 2020; Segura-Campos, 2020; Timilsena, Adhikari et al., 2016). The sequence of the mucilage separation step and the oil extraction step could be

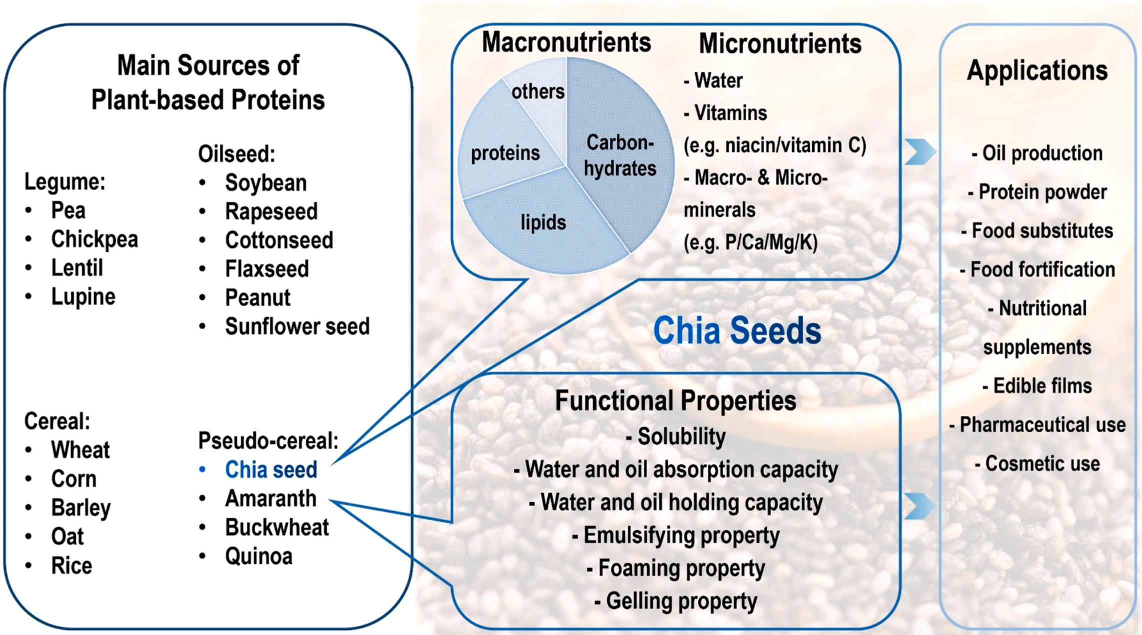

Fig. 1. Conceptual chart of main sources of plant-based proteins, and chia seed's composition, properties, and potential applications.

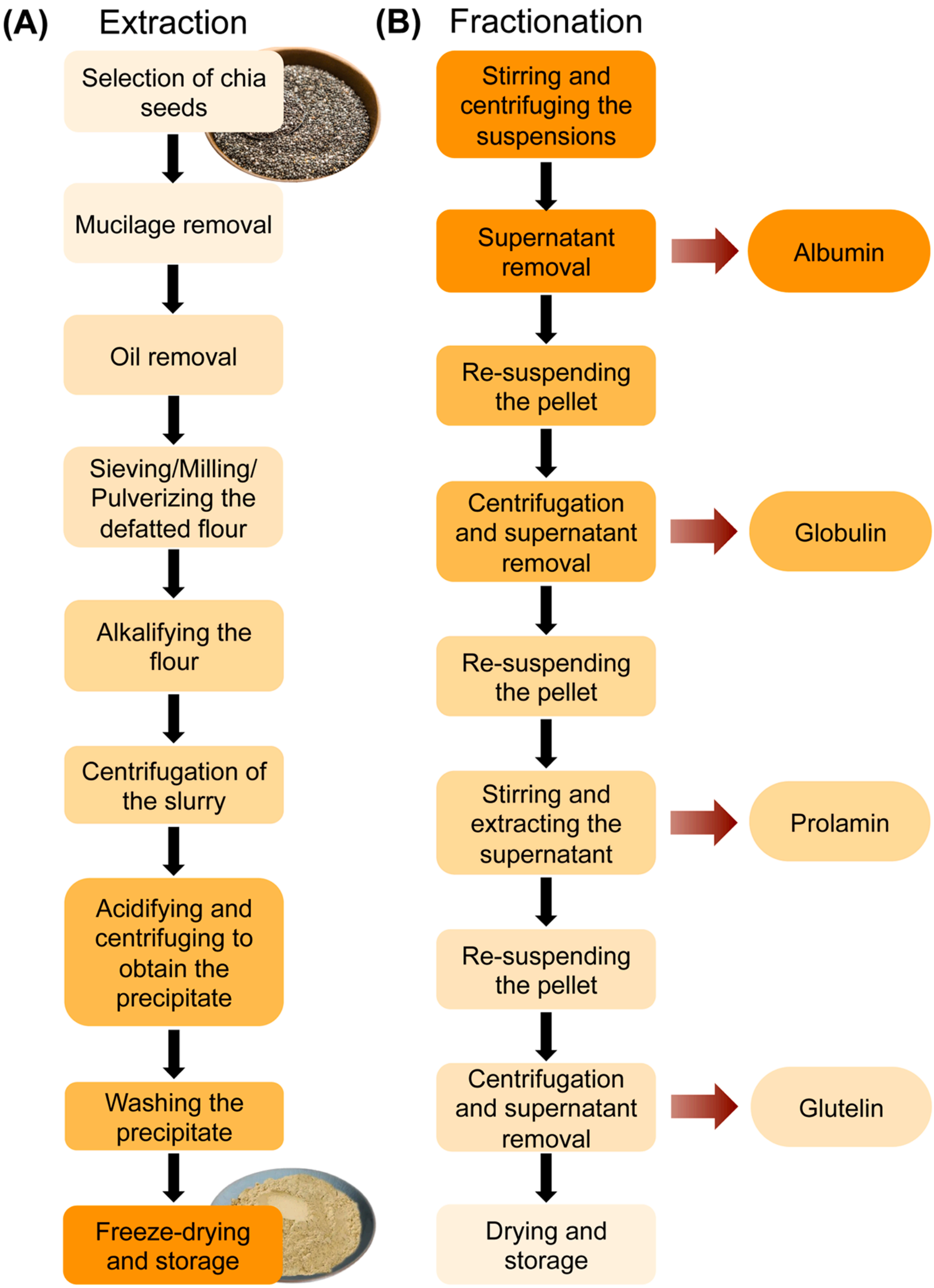

Fig. 2. Flow chart of the (**A**) extraction process and (**B**) fractionation steps of chia seed protein from whole chia seeds.

switched. The obtained defatted flours can be further pulverized and sieved to pass through 140 μm (100 mesh) to 125 μm (120 mesh) screen. The next step is to adjust the pH of chia seed flour/meal to alkaline according to specific experimental requirements. Specifically, this could be achieved by dispersing flours in distilled water with different alkaline solutions, such as NaOH, Na_2SO_3, or $NaHCO_3$ solution that contained 0.02% w/v of sodium azide (López et al., 2018; Salazar Vega et al., 2020; Timilsena, Adhikari et al. 2016; Villanueva-Lazo et al., 2022). The basic slurry then can be stirred at ambient temperature followed by a centrifugation step for 15–60 min. Citric acid or HCl solution could be used to acidify the recovered supernatant for protein precipitation. Finally, samples are subject to drying and storage at 4 °C after centrifuging and washing the precipitate (Grancieri et al., 2022; López et al., 2018; Salazar Vega et al., 2020; Timilsena, Adhikari et al., 2016; Villanueva-Lazo et al., 2022). Three methods could be chosen to dry the chia seed protein solution, which are spray, freeze, and vacuum drying according to Timilsena, Adhikari et al. (2016). Spray drying process uses a spray dryer to maintain the inlet temperature of 180 °C, and outlet temperature of 80 °C, and adjusts the feed flow rate for preventing thermal stress on protein Haque et al. (2015). In another study, a freeze dryer was used to dry the protein samples twice under 0 °C and 20 °C respectively after pre-freezing at −20 °C. The drying chamber should be maintained at about −83 °C with a vacuum of 16 Pa until the protein temperature reached the shelf temperature (Joshi et al., 2011). Vacuum drying can be carried out in a vacuum oven to dry the protein samples at 60 °C under the pressure of 60 kPa for 24 h (Joshi et al., 2011).

The yields of spray-dried chia protein isolate (SDCPI), freeze-dried chia protein isolate (FDCPI), and vacuum-dried chia protein isolate (VDCPI) were 16.17 %, 18.70 % and 17.40 %, of dry seed weight, respectively, and the protein isolate contained 90.5 to 91.2 % protein with traces of lipids (1.9–2.3 %), crude fibres (2.2–2.5 %) and minerals (2.2–2.4 %) reported by Timilsena, Adhikari et al. (2016). Among these protein isolates obtained from the three drying methods, it was found that VDCPI had the highest bulk density but the darkest colour, FDCPI had the lowest bulk density, and the colour of SDCPI was the lightest. López et al. (2018) found that the yields of chia protein could vary with different extraction pH and precipitation pH. When the pH of extraction and precipitation were 12 and 4.5, the highest yield of 17 % would be achieved, while only 1 % of chia protein would be yielded when being extracted at pH 8 and being precipitated at pH 3. As the pH increases, the protein contains a higher random coil, the tertiary structure becomes unfolded, and the thermal stability will be affected, resulting in protein denaturation, which can be extracted more easily (Chen et al., 2013). Chia seed protein has an isoelectric point at pH 3 where its solubility is the lowest so that it can precipitate (Ivanova et al., 2013; Olivos-Lugo et al., 2010), because the intermolecular interaction between chia seed protein and water is the weakest at this pH (Ivanova et al., 2013). According to Villanueva-Lazo et al. (2022), the chia protein isolate was composed of 82.85 % protein, 11.01 % dietary fibres, 4.80 % moisture as well as 0.13 % ash. The extraction yield of chia protein concentration obtained by Salazar Vega et al. (2020) was up to 40.5 %, which was low in nitrogen-free extract (6.1 %) that showed the presence of complex carbohydrates (starch), soluble fibre, gums and others, ash (2.1 %), and crude fibres (1.3 %), whereas high in protein content (89.5 %).

2.2. *Purification of chia seed protein*

According to Timilsena, Wang et al. (2016), the crude chia seed protein extract could be further purified in the following steps. The protein isolate was re-dispersed in deionized water, neutralized, and centrifuged to recover the precipitate. The pH of the suspension needed to be adjusted to about 12, to re-solubilize protein and later was precipitated by adding cold acetone after centrifugation. The purified protein would be dried under a fume hood at ambient temperature, milled to sieve through a 125 μm screen and stored until used. The purified protein isolate had a slightly higher protein content which was 92.5 % and was low in lipids (2.1 %), ash (1.9 %), and fibres (1.6 %), which indicated that some impurities and non-protein compounds could be separated to increase the protein content.

2.3. *Fractionation for chia protein isolate*

The fractionation process is significant not only for comparison with proteins from various plants, but also for studying the functional properties of different protein fractions. Albumins, globulins, prolamins as well as glutelins are the main protein fractions in chia seed protein. According to Julio et al. (2019); Sandoval-Oliveros and Paredes-López (2013); and Segura-Campos (2020), chia protein fractionation steps shown in Fig. 2B were conducted after the oil extraction step. All the suspensions were stirred at 3.5–4.5 °C for 2–4 h, followed by centrifugation for 30–60 min at the same temperature condition. The flour-to-water ratio of the first suspension was 1:10 (w/v), and the obtained supernatant was designated as the albumin fractions. The pellet could be re-suspended in Tris–HCl buffer solution at pH 8 which contained 0.5 M NaCl or 10% w/w NaCl solution. The supernatant containing the globulin fraction was then separated after centrifugation. The pellet was re-suspended in 70 % aqueous isopropanol solution and the prolamin fraction contained-supernatant phase could be extracted under constant stirring. The pellet could be re-suspended in $Na_2B_4O_7 \cdot 10H_2O$ solution at pH 10 or NaOH solution, and subsequently, the slurry was centrifuged to separate the supernatant which was glutelin fraction. After finishing all the extractions, the residue containing the pellet would be oven-dried at around 90 °C for 6 h. Eventually, the obtained protein supernatants were freeze-dried and stored at 4 °C for further analysis. After fractionation, there were 17.3 % of crude albumins, 52 % of globulins, 12.7 % of prolamins, 14.5 % of glutelins, and about 3.4 % of insoluble proteins in chia seeds protein as reported by Sandoval-Oliveros and Paredes-López (2013). After determination by sodium dodecyl sulphate−polyacrylamide gel electrophoresis (SDS-PAGE), it was found that albumin fractions and globulin fractions presented a large number of protein bands with a wide range of molecular sizes, and globulin fractions showed seven concentrated bands with molecular sizes between 18 and 35 kDa. The fractions of glutelin showing four bands with molecular sizes around 20−30 kDa were similar to that of globulins. However, due to the low resolution of the fractions of prolamins, there were only three bands between 25 and 33 kDa which were visible. In addition, the proportion obtained by Segura-Campos (2020) was 20.81 % of albumins, 17.3 % of globulins, 5.81 % of prolamins, and 42.94 % of glutelins which was the most abundant among these four protein fractions. Julio et al. (2019) found that globulin fractions were the highest (64.86 %) containing eight protein bands, prolamins were the lowest (4.04 %) containing four bands, glutelins were 20.21 % with seven bands, and albumins were 10.89 % with five bands. Eight polypeptides were mainly in chia protein-rich fractions (CPRF) between the molecular weights 8 and 60 kDa. The fractions of globulins and glutelins had a similar pattern to that of CPRF, while bands of 37, 50 and 60 kDa were not observed in the albumin fractions. For prolamin fractions, only four bands were visible around 8–14 kDa.

3. Structural and functional properties

3.1. *Structural properties*

Chia seed proteins possess a balance of essential and nonessential amino acids as shown in Table 2, which contain 10 essential amino acids (arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine) and 8 nonessential amino acids (cysteine, tyrosine, alanine, aspartic acid, glutamic acid, glycine, proline, serine) (Kulczyński et al., 2019). Studies confirmed that chia seed

Table 2
Amino acid profile of chia seed protein in different samples from literature.

Amino acid	Amino acid content (%)		
	Chia protein-rich fraction	Chia protein concentrate	Chia protein isolate
Arginine	0.106	0.109–0.113	0.12–0.13
Histidine	0.027–0.033	0.027–0.034	0.034–0.039
Leucine	0.07–0.08	0.072–0.075	0.044–0.065
Isoleucine	0.032–0.039	0.031–0.035	0.035–0.039
Lysine	0.05	0.055–0.064	0.041–0.049
Threonine	0.038–0.039	0.035–0.037	0.028–0.031
Valine	0.046–0.048	0.041–0.046	0.05
Alanine	0.05	0.03–0.05	0.046–0.047
Glycine	0.04–0.05	0.042–0.044	0.041–0.045
Serine	0.051–0.063	0.054	0.05
Proline	0.041–0.048	0.047–0.051	0.044–0.046
Tryptophan	0–0.008	ND	ND
Aspartic acid	0.094–0.106	0.082–0.098	0.077–0.081
Glutamic acid	0.169–0.192	0.182–0.187	0.118–0.144
Methionine + Cysteine	0.033–0.055	0.04–0.05	0.018–0.019
Phenylalanine + Tyrosine	0.112–0.113	0.099–0.106	0.068–0.074
References	(Coelho & Salas-Mellado, 2018; Julio et al., 2019)	(Coelho & Salas-Mellado, 2018)	(Malik & Riar, 2022)

*ND: not determined.

protein had a relatively high content of arginine, glutamic acid, and aspartic acid (Table 2), while the genotype and protein extraction method can be the factors for different content of amino acids (Coelho & Salas-Mellado, 2018; Malik & Riar, 2022; Wang et al., 2023).

Globulin is the most dominant protein fraction of chia seeds in the form of 11S and 7S proteins and the molecular size ranges from 15 to 50 kDa (Mensah et al., 2024; Ullah et al., 2016). The elements of the secondary structure of chia seed protein are able to be determined by Fourier-transform infrared (FTIR) spectroscopy and far UV circular dichroism spectroscopy, where the content of each element (α-helix, β-sheet, β-turn, and random coil) is 19.8–53 %, 5.85–48.7 %, 16.3–24.2 %, and 14.7–23.6 %, respectively (López et al., 2018; Segura-Campos, 2020; Timilsena, Adhikari et al., 2016). The secondary structure composition can be affected by different isolation methods, extraction pH as well as drying methods according to Coelho and Salas-Mellado (2018), and Timilsena, Adhikari et al. (2016).

3.2. *Functional properties*

Functional properties of chia protein refer to how the protein behaves during food preparation, processing, and storage, which depends on the protein's size, shape, amino acid composition, charge distribution, structure and so on (Małecki et al., 2021; Zayas, 1997). They play an important role in the quality of food products while being sensitive to certain external factors, such as pH, temperature, salt addition, extraction method, and hydrolysis conditions. The primary functional properties discussed here are solubility, water and oil absorption capacity, water and oil holding capacity, emulsifying property, foaming capacity and foam stability as well as gelling property, along with the associated factors enhancing or suppressing such characteristics in practice (Fig. 3).

3.2.1. *Solubility*

Solubility is a complex function of protein, which is of importance because it can have influences on other functional properties, including emulsifying activity, foaming capacity, gelling property and so forth (Julio et al., 2019; Timilsena, Adhikari et al., 2016). Chia protein solubility can be altered by not only pH and temperature, but also by salt addition, different drying methods as well as hydrolysis.

Chia protein isolates studied by Timilsena, Adhikari et al. (2016) were nearly fully soluble when the pH value was close to 12, whereas the highest solubility of protein isolates from black and white chia seeds could be obtained at pH 10, which was 77.75 % and 76.07 %, respectively (Malik & Riar, 2022). This is because the electrostatic repulsion between negative-charged proteins will become stronger under a relatively high pH, preventing them from aggregating (Grossmann & McClements, 2023). Also, aspartic acid and glutamic acid are the main negatively charged amino acids in chia seed protein whose content is about 3.50 and 1.69 g/ 100 g (Kulczyński et al., 2019). According to Kramer et al. (2012), negatively-charged amino acids are able to bind water more tightly. When pH is lowered to 3, the minimum solubility could be observed because it is near the isoelectric point of chia seed protein Coelho and Salas-Mellado, (2018); Timilsena, Adhikari et al. (2016). For the temperature factor, the increase in solubility occurs as the temperature increases and would reach a plateau once reaching 50 °C, which is because of the enhanced protein-water interactions, mainly the hydrogen bonding, while the protein will not denature under this temperature condition (Timilsena, Adhikari et al., 2016). According to Guo et al. (2021) and Renoldi et al. (2023), high-pressure homogenization treatment could slightly decrease the protein solubility (from 27.4 % to less than 20 %) due to the conformational changes in protein tertiary structure where the hydrophobic portion of the protein was exposed on the surface. The solubility of chia protein achieved the highest when adding 1 M of NaCl due to the fact that globulins are easily soluble in salt solution, while it decreased with the high levels of NaCl, which results from the salting out effect (Timilsena, Adhikari et al., 2016). Water molecules tend to bind to salt instead of protein at higher salt concentrations, which leads to the protein-water interactions becoming weaker than the protein-protein interactions, and can further reduce the solubility of protein in water (Lorenzo, 2009; Timilsena, Adhikari et al., 2016). In addition, Timilsena, Adhikari et al. (2016) also reported that chia protein isolates obtained by spray drying had a higher solubility than those dried by freeze or vacuum drying methods since the outlet spray drying temperature (80 °C) is lower than chia protein denaturation temperature, which is close to 100 °C of chia protein Timilsena, Adhikari et al. (2016). Protein hydrolyzed by Alcalase and Flavourzyme was studied by Urbizo-Reyes et al. (2019), suggesting that

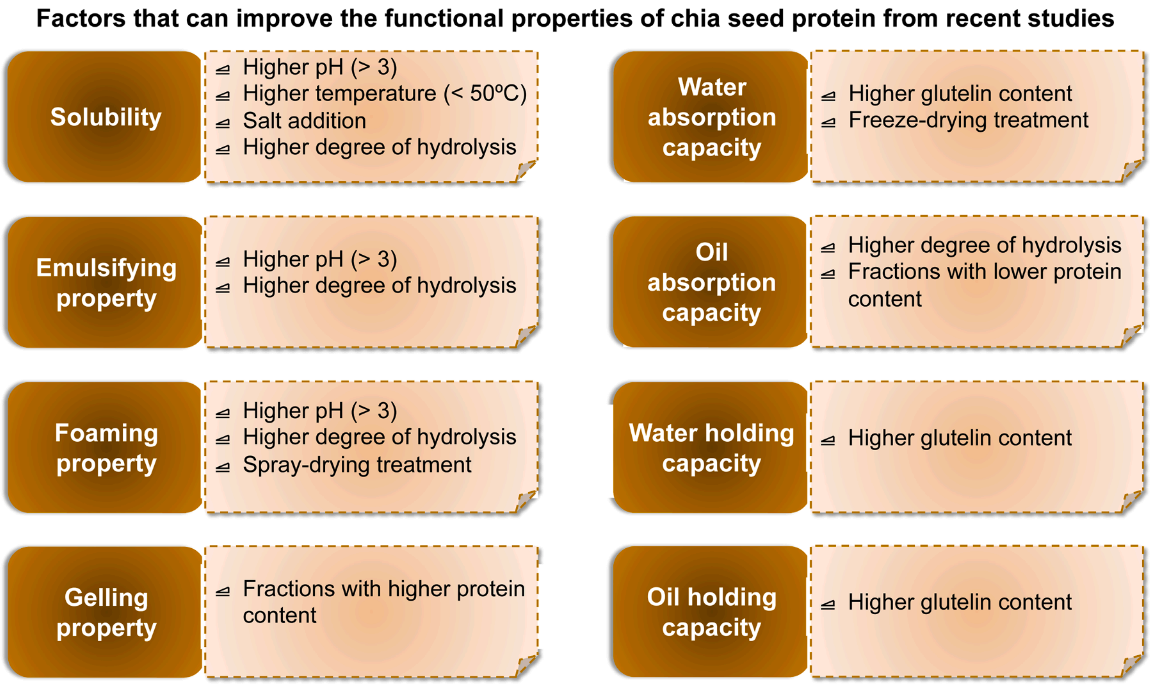

Fig. 3. List of the main functional properties of chia seed protein and the associated enhancing factors from recent literature.

enzymatic hydrolysis enhanced the solubility of chia protein in the tested pH range (pH 3–9). In a similar study, Villanueva-Lazo et al. (2021) found that the solubility of protein hydrolyzed by Alcalase at pH 8 and 50 °C significantly increased in the first 15 min and remained constant, while the solubility would continually increase within 120 min if protein treated with Flavourzyme at pH 7 and 50 °C.

3.2.2. *Water and oil absorption capacity*

Water absorption capacity refers to the amount of water that is absorbed by a material when in contact with or being immersed in water, while the ability of a material to entrap oil is referred to as oil absorption capacity (Villanueva-Lazo et al., 2021). The common measurement method for both of them is the determination of the mass of the water/oil absorbed in the total mass of water/oil used (Timilsena, Adhikari et al., 2016). The lowest water absorption capacity for chia protein could be obtained at pH 3, the isoelectric point where the protein has fewer intermolecular interactions with water (Coelho & Salas-Mellado, 2018). Based on the results of Timilsena, Adhikari et al. (2016), protein isolates extracted through freeze drying had a slightly higher water absorption capacity value (2.9 g/g) than that through spray and vacuum drying methods, whereas the isolates dried by vacuum obtained the highest oil absorption capacity (3.6 g/g) among all three methods as more hydrophobic sites would appear (Timilsena, Adhikari et al., 2016). As for the protein fractions of chia, glutelins showed the highest water absorption value which was 4.17 g/g, followed by albumins (2.04 g/g), while almost no water absorption was observed in globulins and prolamins (Segura-Campos, 2020). Also, Segura-Campos et al. (2014) found that protein in chia gum was able to help to interact with water because of the hydrophilic residues on it. Besides, the results in another study presented that the chia protein-rich fractions had a lower oil absorption capacity due to the hydrophilicity of the surface of the isolated protein, which was because the heat treatment of extraction could partially denature the protein, leading to the exposure of lipophilic sites of the protein Coelho and Salas-Mellado, (2018). The oil absorption capacity of chia protein hydrolyzed by Alcalase for 15 min was about 200 times higher than that of protein isolates (Villanueva-Lazo et al., 2021).

3.2.3. *Water and oil holding capacity*

When an external force is applied to a protein, such as centrifugation, the ability of the protein to entrap and retain water or oil is regarded as its water or oil holding capacity (Aryee et al., 2018; Moure et al., 2006). It is helpful for proteins with water and oil holding capacity to support the structure and provide a viscosity of food, including sausage, doughs and so forth, maintaining the product quality (Ge et al., 2020; Shanthakumar et al., 2022). The study by Malik and Riar (2022) reported the water and oil holding capacity of protein isolates were respectively 3.10 and 2.30 g/g in black chia seeds, and 3.00 g/g and 2.20 g/g in white chia seeds. The water holding capacity value of chia protein fractions lowered with the high-pressure homogenization as the treatment modified the structure of chia protein by exposing its hydrophobic amino acid residues; however, the oil holding capacity decreased by the same treatment method (Renoldi et al., 2023). Among four chia protein-rich fractions, glutelins had the highest water holding capacity at 3.67 g/g due to the higher number of polar residues but there was no value could be detected for prolamins from lack of ability to entrap water. The highest oil holding capacity was witnessed in globulins (6.34 g/g) whereas albumins were the weakest in holding oil with the value of 2.66 g/g (Segura-Campos, 2020). In addition, the study by Segura-Campos et al. (2014) have demonstrated that proteins contained in chia gums enabled the improvement of water or oil retention.

3.2.4. *Emulsifying property*

The emulsifying property is a crucial protein functionality in producing ice cream, margarine, dressings and other foods, which requires protein to act as an emulsifier to blend two immiscible liquids thoroughly. Generally, the emulsifying property can be measured by physical characterization, using emulsifying activity, emulsifying capacity, and emulsion stability as expression: Emulsifying activity can be determined by the total interfacial area and the protein mass; emulsifying capacity is calculated by the ratio of the height of the emulsified layer to the height of total content in the tube; emulsion stability is measured in a similar way that is the percentage of the volume of oil in the volume of protein but after being treated (heating, centrifugation, etc.) in several specified time intervals (Mir et al., 2019; Zhang et al., 2023). To measure the emulsifying properties of chia seed protein or protein hydrolysate, chia oil (Julio et al., 2016), corn oil (Segura-Campos, 2020; Vázquez-Ovando et al., 2013; Villanueva-Lazo et al., 2021), refined sunflower oil (Julio et al., 2019), soybean oil (Coelho & Salas-Mellado, 2018), and canola oil (Urbizo-Reyes et al., 2019) have been used. The emulsifying capacity and emulsion stability of chia seed protein can be greatly affected by the various treatment methods, such as pH adjustment, fractionation, and enzymatic hydrolysis.

According to Coelho and Salas-Mellado (2018), chia seed protein-rich fraction showed similar results on emulsifying capacity and emulsion stability, approximately 80 % between pH 2 and 11. In comparison, chia protein concentrate had a much lower emulsifying capacity and stability for an average of 10 % and almost zero at pH 7 because of protein structural changes during its extraction. However, the emulsifying activity of protein-rich fraction studied by Vázquez-Ovando et al. (2013) was about 50 % on average, lower than the one in research by Coelho and Salas-Mellado (2018) from pH 2 to 10, while the stability was relatively high, especially at the alkaline condition which was higher than 95 %, except for the one at pH 6 (63.5 %). Segura-Campos (2020) reported that after chia seed protein fractionation, the highest average emulsifying capacity could be observed in prolamin and glutelin which were approximately 61 % and 60 %, respectively, suggesting the potential of using chia seed protein as a food emulsifier. Emulsions stabilized with globulins and glutelins presented better stability under the alkaline condition, especially at pH levels of 7 and 9, which could be related to the higher solubility (Julio et al., 2019). Protein hydrolyzed by Alcalase had an emulsifying activity value 50 times higher than the intact protein and the hydrolysis achieved by microwave exhibited slightly higher emulsifying activity than using water bath heating (Urbizo-Reyes et al., 2019; Villanueva-Lazo et al., 2021). For the emulsion stability of hydrolyzed protein, treatment with Alcalase and microwave is the most stable in emulsion at 30 and 60 min, while Alcalase-microwave as well as Alcalase and Flavourzyme enzyme-water bath heating treated protein showed a higher stability than protein with other treatments at 90 min, according to the research outputs from Urbizo-Reyes et al. (2019).

3.2.5. *Foaming capacity and foam stability*

Foaming properties are vital in the food manufacturing industry, such as in beer brewing, whipping cream production, and so forth. The formation of foam is referred to as the process of air bubbles dispersing into a continuous liquid or solid phase, which generates a flexible interfacial film (Moure et al., 2006). Foaming capacity indicates the ability of the protein to produce foams, which can be reflected by the increase in foam volume or the percentage of increased foam volume, and foam stability reveals the capability of the formed foam to persist over a certain period of time (Mauer, 2003; Segura-Campos, 2020; Vázquez-Ovando et al., 2013).

There are several factors that have an impact on proteins' foaming capacity and stability, involving pH, hydrolysis treatments, protein concentration, and extraction methods. The lowest foaming capacity value was reported at pH 3, which is near the isoelectric point of chia seed protein Coelho and Salas-Mellado, (2018); Timilsena, Adhikari et al. (2016). Chia protein isolates extracted by spray drying (Timilsena, Adhikari et al., 2016) exhibited a higher foaming capacity and stability than those extracted by vacuum or freeze drying. Besides, the values of foaming capacity and stability increased as the protein concentration increased when it was lower than or equal to 10 %; however, it would decrease after the concentration grew over 10 %. This is because when the protein concentration becomes higher, the protein-protein interactions become stronger, restricting the formation of the flexible air-water interfacial film that can help to entrap air bubbles (Aluko et al., 2009; Timilsena, Adhikari et al., 2016). The results collected by Urbizo-Reyes et al. (2019) indicated that the highest foaming capacity of protein hydrolysate could be generated through Alcalase and microwave heat treatment (about 75 %), and protein hydrolyzed by Alcalase and heated with a water bath showed the best foaming stability whose values were more than 45 %, compared to microwave treatments, since the smaller peptides formed when using microwave gradually became unstable over time. In addition, globulins within the alkalic pH range, especially at pH 8, had a higher foaming stability than other chia seed protein fractions (albumins, prolamins and glutelins), with volume decline from nearly 20 mL after 5 min to 15 mL after 20 min Segura-Campos, (2020). The authors suggested that a higher pH value could increase the charge density, helping to prevent the air bubbles from coalescing quickly, which would further stabilize the foams. The colour of chia seed coats, which is because of different genotypes, had almost no effect on foaming properties since the foaming capacity was found to be 77.66 % for black chia seed protein isolates and 76 % for the white ones, without significant volume decrease after 15 and 30 min Malik and Riar, (2022).

3.2.6. *Gelling property*

Gelation is a phenomenon or process to form three-dimensional molecular gels via the weak cross-linking of long polymer chains, which includes the modification of protein structure and aggregation (Lewis, 1996; Sasidharan & Ramakrishnan, 2022; Ziegler & Foegeding, 1990). In order to determine the ability of gel formation of chia seed proteins, the least gelation concentration (LGC) is used as an index to indicate the minimum protein concentration that is required for gels to remain immovable when flipping the gel-containing apparatus (Moure et al., 2006).

To detect the gelation capacity, protein solutions or suspensions were heated and stirred in boiling water and later soaked in ice immediately to cool down, followed by visual observation (Coelho & Salas-Mellado, 2018; Olivos-Lugo et al., 2010). The stable gels could be generated when the LGC of chia protein isolate and glutelins was 20 % and 25% w/w, respectively, as presented by the results (Olivos-Lugo et al., 2010). As for the chia seed protein-rich fractions, Coelho and Salas-Mellado (2018) have found that it had a better gelling property than chia protein concentrate, whose LGC was about 4% w/w. Besides, Ramos et al. (2017) suggested that denatured chia seed protein was able to assist in the gel formation by carbohydrates, resulting from the interactions between protein and polysaccharides.

Overall, if chia protein or its fractions are being used as raw ingredients for food applications, the change or manipulation of the above-mentioned properties are essential in altering the physical, chemical, and nutritional quality of the formulated food product. Specifically, the deliberate modification of the environmental factors such as pH and temperature can have direct impact on water retention for liquid or semi-solid foods, thereby changing the overall available water in food matrix. The increasing solubility of chia seed protein may enhance the bioavailability of the essential and non-essential amino acids that chia possesses. The emulsifying property induced by chia protein may be beneficial in stabilizing the oil-in-water emulsion system during food formulation, such as porridge, soup, or sauces, hence increasing the storage stability and shelf-life. The gelation capacity of chia seed protein indicates its potential as a gelling agent, for instance, in the formulation of jellies and jams. On the other hand, the relatively weak film-forming property of chia protein limits its direct application in developing edible films, but it can be used as an additive to modify the physical characteristics of the films made by other plant-based proteins or carbohydrates.

4. Food applications

As an emerging food material, there is not much literature that has directly used the protein or protein fractions of chia (including protein isolates, concentrates, and hydrolysates) for food production. However, in studies on food applications of chia seeds or chia seed flours, it can be found that chia proteins are promising ingredients for improving the functional and sensory properties of food due to their high content in chia seeds. As depicted in Fig. 4, the applications of four main food groups, namely bakery products, meat products, staple foods as well as dairy products, demonstrate the versatility of chia protein in food formulations and their respective functions in enhancing or maintaining the physical, chemical, or nutritional quality.

4.1. *Bakery products*

Bread, cakes, muffins, and biscuits, which belong to the most popular baked products, are in high demand all over the world. These flour-based foods are often made of wheat which contains gluten, a protein that can cause non-celiac gluten sensitivity, wheat allergy, dermatitis herpetiformis, or even celiac disease in certain individuals (Gujral et al., 2012). Thus, chia seeds and chia flours used for baking help to develop gluten-free foods and meanwhile enhance the protein content and diversity.

In a study by Ozón et al. (2023), protein concentrate hydrolysates derived from the chia expeller were added for 1, 3, 5, and 10 mg per 1 g of wheat flour, respectively, to fortify wheat bread. The bread supplemented with protein concentrate hydrolysates was found to have less dark-coloured crust, compared with the crust of bread solely produced with wheat flour, which can be attributed to a low level of lysine content in chia protein, reducing the occurrence of Maillard reaction (Desai et al., 2018; Kulczyński et al., 2019). The study also showed that substituting wheat flour with 5 and 10 mg of protein hydrolysates rendered better textural properties for the bread with higher specific volume, lower hardness, and more alveoli, indicating the capacity of air absorption of the fortified dough (Fig. 5A). Another research on chia protein hydrolysates was conducted by Segura-Campos et al. (2013) to hydrolyze protein-rich fractions that were extracted from chia flour for making white bread. The authors witnessed that the angiotensin-I-converting enzyme (ACE)-inhibitory activity of bread supplemented with protein hydrolysates increased significantly by comparison to the one without hydrolysate addition. The ACE-inhibitory effect, one of the in vitro biological activities, is conducive to suppressing high blood pressure and preventing cardiovascular diseases for human beings (Paiva et al., 2017). Moreover, chia flour mixed with light buckwheat flour or whole buckwheat flour at the ratio of 1:9 (w/w), with or without adding xanthan gum for premixes and bread production was studied by Coronel et al. (2021). Results of the selective premix and bread with the addition of chia flour presented a higher protein content as well as higher values in emulsifying activity and stability than the control group due to the protein in chia flour.

To study muffins fortified with chia seeds, the researchers employed 5, 10, 15, and 20 % (w/w) of chia seed powders into white flour, sugar, milk and other ingredients to bake muffins (Rabail et al., 2022). It was observed that as the supplementation level increased, the brown colour of the fortified muffin crust and crumb became deeper, because of the increasing protein content which enabled the Maillard reaction to take place (Desai et al., 2018). What's more, proteins contained in the chia seed powders helped to increase the water absorption and water holding capacity of the dough, making it develop completely, which further prolonged the dough's stability over time.

Besides, biscuits with the fortification of 20 % chia flour, 20 % chia seeds, 10 % chia flour and 10 % chia seeds, 30 % chia flour, 30 % chia seeds as well as 15 % chia flour and 15 % chia seeds, respectively, were evaluated in a study by Alcântara Brandão et al. (2019). Among all the samples, biscuits that contained 15 % chia flour and seeds possessed the

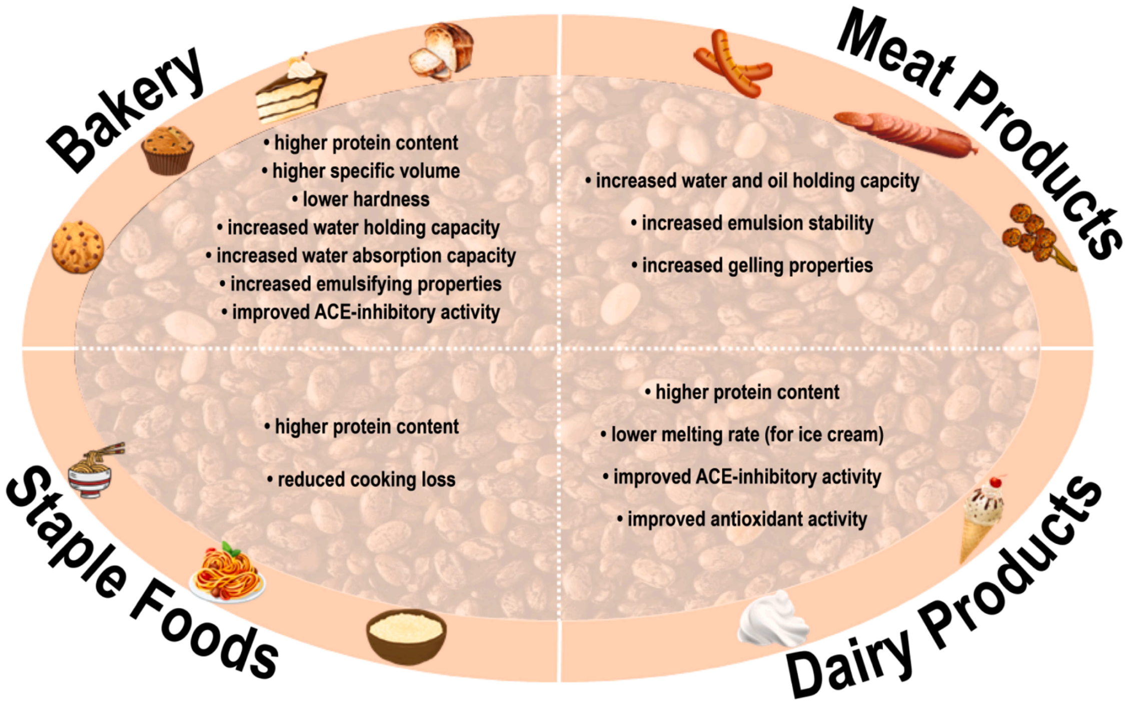

Fig. 4. Chia seed/chia seed flour in food application and the functional and sensory properties improved by the proteins or protein fractions.

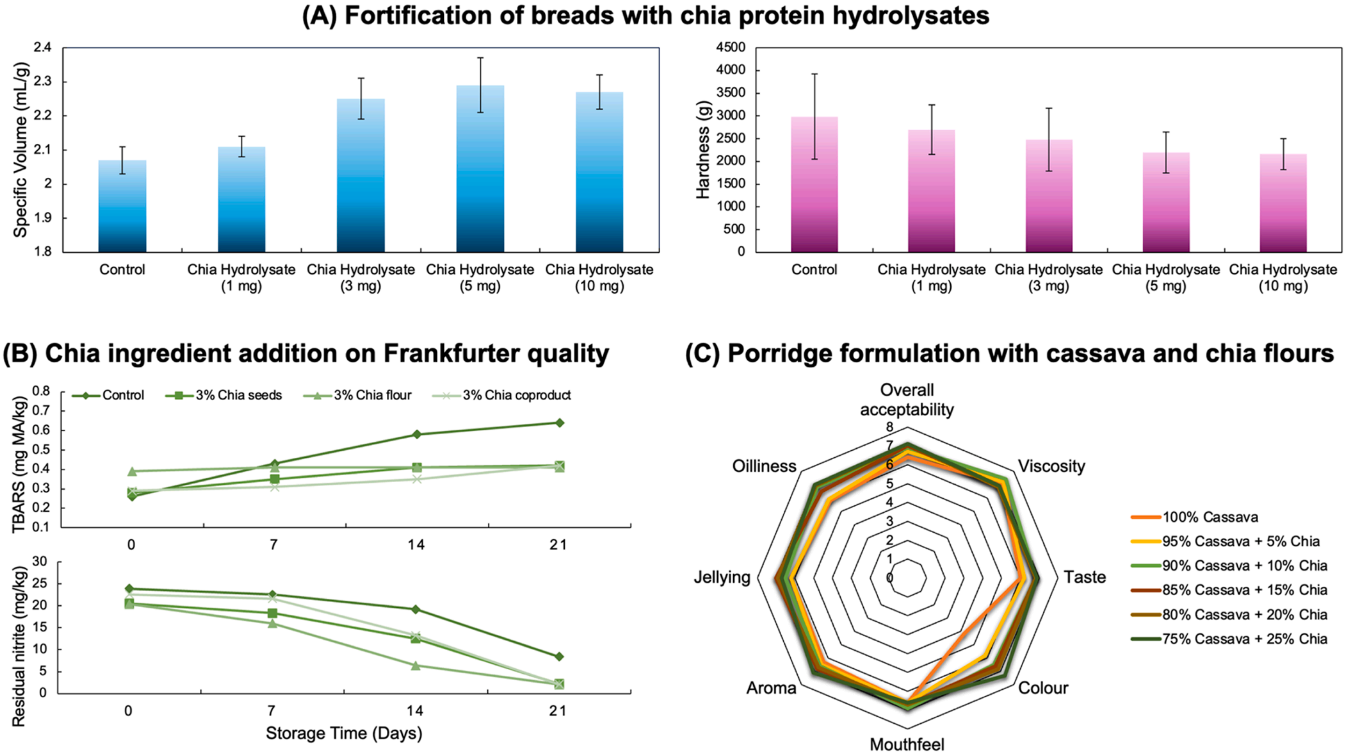

Fig. 5. Recent studies of chia application in food formulations: (A) fortification of bread with chia protein hydrolysates; (B) chia ingredient addition on Frankfurter quality; (C) porridge formulation with cassava and chia flour. [Data are reproduced from Katunzi-Kilewela et al. (2022); Osyczka et al. (2023); Ozón et al. (2023) with permissions.].

highest protein percentage of nearly 14.50. As such, it showed the strongest water retention ability as it had the highest moisture content (around 10.24 %) after storing for 40 days.

4.2. *Meat products*

Chia seeds are a health-promoting ingredient whose basic composition involves nearly 15–25 % of protein, 30–33 % of total lipids, 26–41 % of carbohydrates, 18–30 % of dietary fibre, 4–5 % of ash, and others (moisture, vitamins and minerals) (Knez Hrnčič et al., 2020). Of these, chia seed protein is composed of ten essential amino acids and eight nonessential amino acids (Kulczyński et al., 2019). Whereas, only nine amino acids exist in meat protein that are short of dietary fibre or carbohydrates in some cases (Soren & Biswas, 2020). Therefore, it is feasible to develop meat products, such as sausages, meatballs and so forth, with chia seeds or chia flour to enhance their nutritional value.

As for the research on frankfurters, Fernández-López et al. (2019) generated chia seeds and chia flour that had more than 20 % protein, and a chia coproduct via cold-press oil extraction that possessed nearly 30 % protein, while later integrated them with 70 % lean meat and 30 % back fat of pork for sausage manufacture. The texture analysis of frankfurters revealed that emulsion stability and gelling properties were promoted by supplementing chia flour and coproduct due to the presence of protein within them which have been considered a good emulsifying and gelling agent (Sandoval-Oliveros & Paredes-López, 2013; Segura-Campos, 2020). While added chia seeds were intact so that proteins and other components could not function on the texture of sausages. Based on Fig. 5B, with longer storage time, the chia-added frankfurters were less likely to be oxidized since thiobarbituric acid reactive substances (TBARS) can be used as an indicator of the degree of lipid oxidation and their nitrite content was lower, compared with the frankfurters in the control group (Osyczka et al., 2023). Similarly, frankfurters were produced with or without using 10 % chia flour as the substitution of pork back fat in another study by Pintado et al. (2016). The purge values of sausages containing chia flour were lower than 2 %, whereas the ones without chia flour were up to 2.7 %. Since the purge value belongs to one of the indicators for storage ability related to water loss during storage, chia flour-supplemented frankfurters showed a good ability to retain water, which could be attributed to the water and oil holding capacity that chia protein own (Szmańko et al., 2021). Except for the frankfurters, research on bologna-type sausages incorporated with chia flour has been conducted as well. Lean beef meat and pork back fat were blended with 10 % chia flour, oil, and other ingredients for bologna sausage formulation and analysis (Pires et al., 2020). However, the bologna protein content was found to decrease, possibly resulting from the unequal substitution of beef as the control sample contained 69 g/100 g, while the sample with replacement involved 60 g/100 g. Even though the emulsion stability of the sausage also decreased slightly to 98.12 g/100 g after adding chia flour, it was still considered stable for emulsion because good emulsion stability of bologna sausages refers to the value higher than 98 g/100 g according to Pires et al. (2017).

In addition, Elbir et al. (2023) reported that the total heterocyclic aromatic amines (HAAs) content of meatballs with chia seed powder usage ranged between 0.12 % and 0.50 %, in contrast, there were no HAAs detected in the control meatballs. Meatballs in the experiment were primarily made of beef meat and intermuscular fat, without or with the addition of 0.5 %, 1 %, or 1.5 % (w/w) of milled chia seed powders, which increased the carbohydrate and protein content. As such, it provided an opportunity for the Maillard reaction between reducing sugars (from carbohydrates) and amino acids (from proteins), which is associated with HAAs formation (Nadeem et al., 2021; Wang et al., 2023).

4.3. Staple foods

Staple foods occupy the main composition of our daily diets, playing an important role in human life by meeting the basic energy and nutrient requirements. With the improvement of people's living standards, the demand for staple foods is not limited to conventional food sources, such as rice, maize, and pulses, which drives scientists and researchers to explore and investigate alternative staple food materials that are richer in diversified nutrients, especially in plant-based proteins, for people to choose from.

The study of gluten-free noodles reported by Levent (2017) replaced the gluten-free flour made of rice flour and corn starch with varying proportions of chia seed flour (10 %, 20 %, and 30 %) to produce dough for making noodles. Results presented that as the addition of chia seed flour increased, the cooking loss of the noodles decreased. This is because a higher level of chia seed flour can lead to a high content of chia protein, which affects the starch-protein interactions, strengthening the surface tension as well as the rigidity of starch granules and further restricting the starch swelling (Klemm et al., 2018). The author also observed that higher chia seed flour usage resulted in the darker noodle colour due to the Maillard reaction as mentioned in the previous muffin research.

Additionally, Khatri et al. (2023) investigated the use of chia seed flour for 7.5 %, 10 %, 12.5 %, 15 %, and 17.5 % in gluten-free paste formulation along with quinoa flour. The cooking loss declined with the increment of chia seed flour proportion, which was similar to the gluten-free noodles studied by Levent (2017), indicating that the increased protein content would prevent the starch granules from swelling (Klemm et al., 2018).

Another research by Katunzi-Kilewela et al. (2022) was about the composite porridge manufactured by combining dried mashed cassava (1000, 950, 900, 850, 800, and 750 g) with milled chia seed flour in 0, 50, 100, 150, 200, and 250 g. The researchers suggested that the porridge viscosity would be influenced by the starch swelling because of the higher protein content as well. Through the acceptability test, the porridge containing chia flour showed more desirable viscosity, taste, colour, mouthfeel, aroma, jellying as well as oiliness and higher overall acceptance than the control group that was solely made by cassava (Fig. 5C).

4.4. Dairy products

In addition to bakery products, meat products, and staple foods, dairy goods are widely consumed by people all around the world, due to their rich nutritional compositions and versatility for the manufacture of various processed foods with well-controlled textures and flavours, such as ice cream, cheese, and yoghurt. The stability of such dairy products derived from raw milk commonly needs substantial protein-containing ingredients to stabilize their texture during processing and storage, via emulsifying and foaming capabilities. Thus, these appreciable functional properties of chia seeds are promising for dairy goods formulation.

Segura-Campos et al. (2013) conducted the hydrolysis of chia protein-rich fractions with Alcalase and Flavourzyme from chia flour and sequentially mixed the protein hydrolysates with carrots to generate carrot cream, which was followed by analyzing its biological potential. It was found that the ACE-inhibitory activity had a remarkable improvement when supplementing the carrot cream with protein hydrolysates, revealing the antihypertensive ability of chia protein hydrolysates to avoid cardiovascular diseases (Paiva et al., 2017). What is more, the antioxidant activity values of chia protein hydrolysates added-carrot cream were higher than that of control cream for over 8 mmol/L-mg, representing a considerable antioxidant potential of chia protein. This might be attributed to the combined effect of peptides from chia protein as well as carotenoids contained in the carrots (Tadesse & Emire, 2020).

5. Future prospects and challenges

In recent years, more and more research has been conducted either on the application of chia seeds in food or related to the functional properties of chia seed proteins and their fractions. Based on the application of chia seed protein in plant-based foods, the "SWOT" model (strengths, weaknesses, opportunities, and threats) has been used to analyse in detail (Fig. 6).

There are several advantages for why chia protein is considered a promising ingredient for plant-based food. According to the amino acids composition, chia protein isolate has a higher tryptophan, methionine and cysteine as well as phenylalanine and tyrosine content than chicken, pork, beef as well as soy protein isolate, and a higher leucine and histidine content than soy protein isolate (Day et al., 2022; Villanueva-Lazo

Fig. 6. SWOT analysis of chia seed protein application in plant-based foods.

et al., 2021). This indicates that utilizing the chia seed protein in food is more helpful with anti-ageing, cancer, arthritis and cardiovascular disease treatment, cognitive function, maintenance of glucose homeostasis and so forth. (Clemente Plaza et al., 2018; Friedman, 2018; Gao et al., 2019; Hase et al., 2015; Pedroso et al., 2015; Thalacker-Mercer & Gheller, 2020). Without glutenin and gliadin containing the high-quality protein of chia seed, plant-based foods formulated by chia seed proteins instead of wheat, barley, or rye proteins are available for patients with celiac disease. In addition, pea protein and soy protein, as raw materials for the mainstream plant-based products currently on the market, exhibit similar functional properties to meat protein. The solubility and foaming capacity of chia seed protein is similar to that of pea protein, up to nearly 80 % respectively, and chia seed protein also has high emulsifying properties, water and oil holding capacity, showing potential for the production of plant-based foods (Boukid et al., 2021).

Nevertheless, few articles have actually studied the use of chia seed protein extracts in plant-based foods, such as plant-based meat. This is due to the fact that chia seed protein itself cannot perfectly provide the same nutritional content and sensory characteristics as meat. Compared to chicken, pork, and beef, chia protein isolate contains lower lysine (46.4 mg/g) and isoleucine (35.2 mg/g) (Day et al., 2022; Villanueva-Lazo et al., 2021). Lysine plays an important role in human growth, the improvement of immunity, calcium absorption, fatty acid metabolism and the maintenance of connective tissue structure, while isoleucine is also crucial for human physiological functions, such as muscle growth, the improvement of the immune system, blood sugar balance, protein and fatty acid metabolism and so on (Choi et al., 2023; Gu et al., 2019; Palma-Granados et al., 2019; Uauy et al., 2015). The functional properties of chia seed protein largely affect the sensory characteristics of its products. Generally, animal proteins (e.g. whey protein and egg white) have a higher solubility than plant proteins, especially at neutral pH, since they are mainly made from hydrophilic types of proteins (Day et al., 2022); the water and oil absorption capacity as well as water and oil holding capacity of chia seed protein is also not as good as animal protein, which will influence the juiciness, softness and mouthfeel of plant-based foods (Day et al., 2022); chia seed protein also does not have the ability to form a gel during heating as egg white does. What's more, the colour of chia seed protein is unable to follow the colour change mechanism of animal protein (haemoglobin) during cooking. Even though it is difficult to meet the conditions for making all plant-based foods solely with chia seed protein, especially meat analogues, some ingredients can be added in manufacture to better mimic the sensory properties of meat and egg dairy products. For example, starch can be used as a binding agent for chewiness and stickiness, beet juice acts as a colouring agent, and edible gum (e.g. gelatin, agar, etc.) can be a thickener and gelling agent to improve the product structure (Langyan et al., 2022; Zhang et al., 2021).

Opportunities for the development of chia seed protein-made food products are obtained in economics, environmental, and ethical aspects. According to The Vegan Society (2022), there are about 2.6 million vegans in Europe as of 2023, accounting for about 3 % of the population. At the same time, it is estimated that the global market for plant-based foods will exceed 95 billion US dollars by 2029 (Meticulous Market Research Pvt. Ltd., 2023a), while the global market for plant-based meat will be worth 24 billion US dollars by 2030 (Meticulous Market Research Pvt. Ltd., 2023b). The economic benefits of plant-based foods are impressive, and their demand will continuously increase in the future, which provides more opportunities for emerging plant proteins to enter the market. Data from the Food and Agriculture Organization of the United Nations shows that the livestock industry uses about 30 % of the ice-free land on Earth directly or indirectly, and accounts for 80 % of total greenhouse gas emissions from the agricultural sector (Steinfeld et al., 2006). In addition to land utilization and greenhouse gas emissions, livestock also contributes to climate change, soil erosion on agricultural land, water and heavy metal pollution and so forth (Grossi et al., 2019; Li et al., 2019; Zhou et al., 2022). If human beings continue to rely on traditional meat products, these problems will become more and more serious. Owing to these enormous impacts, plant-based diets need to be vigorously developed and promoted for environmental sustainability. From the ethical perspective, as the global Muslim and Jewish population grows, so does the market for halal and kosher food, thus the demand for meat alternatives increases as well (Al-shami & Abdullah, 2023). The use of chia seed protein is able to provide a variety of options for people who cannot eat traditional meat or meat products and people who have strict restrictions on meat products due to their religious and ethical beliefs. Except that, considering the animal welfare is incorporated into the law in some regions, such as the Treaty of Lisbon of the European Union, and is receiving increasing attention from all over the world, people will be more inclined to consume plant-based foods in the future (Martinez & von Nolting, 2023).

As for the threats of chia seed protein used for plant-based food manufacture, the meat analogue market and extraction method are the major considerations. Apart from the wheat gluten, pea protein and soybean protein that are common on the market, diverse emerging plant proteins such as mung bean protein (De Angelis et al., 2023), rapeseed protein (Jia et al., 2021), rice protein (Lee et al., 2022), and even the proteins of edible insects (e.g. ants and flies) are gradually being studied and applied to meat analogue. Meanwhile, cultured meat which can be produced quickly without undergoing livestock farming and is efficient in nutrients, has also entered the market in 2020 (Lee et al., 2020). Such a wide variety of choices will intensify the competition in the meat alternative market and further affect the commercialization of chia seed protein-based foods in the future. Another challenge is that the extraction methods of chia seed protein have not been standardized. So far, researchers have not been able to determine the best extraction method to obtain the highest yield of chia seed protein, thereby cannot be used for commercial production.

6. Conclusions

In a society where individuals are becoming increasingly health-conscious, especially in dietary habits, the nutritional characteristics and functional properties of chia seed protein are not extensively studied and thoroughly reported. Based on current research outputs, this high-quality protein has been found to possess desirable water absorption capacity, water and oil holding capacity, emulsifying properties, ACE-inhibitory activity as well as antioxidant activity, which can be extracted through chemical methods. However, the current extraction methods of chia seed protein in the laboratory have a low yield and are difficult to put into large-scale production. Hence, further research should focus on how to optimize and standardize the extraction methods of chia seed protein to help find a method or technique with higher yield without affecting the nutrition and quality of the protein, so that companies can produce and use chia seed proteins on a larger scale. At the same time, after illustrating the strengths and weaknesses of the functional properties of chia seed protein, the researchers can gradually explore the potential applications of the protein in different plant-based foods, such as meat alternatives, plant-based milk and so forth, to meet the needs of the expanding plant-based product market in the future.

Ethical statement

The authors declare no ethical issues encountered in the present study, since neither human nor animal studies are involved.

CRediT authorship contribution statement

Shenying Chen: Writing – original draft, Methodology, Formal analysis, Data curation. **Xiaoyu Luo:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have no conflict of interest to be declared.

Data availability

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

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