Talwar *et al.*
Food Production, Processing and Nutrition (2025) 7:22
https://doi.org/10.1186/s43014-024-00294-w

Food Production, Processing and Nutrition

REVIEW

Open Access

Use of flaxseed cake as a source of nutrients in the food industry and possible health benefits- a review

Binanshu Talwar[1], Rajni Chopra[1*], Neetu Kumra Taneja[2], Monika Chand[1], Snigdha Homroy[1], Aishwarya Dhiman[1], Priyanka Kumari Singh[3] and Shreya Chaudhary[1]

Abstract

Oilseed cake is a potential by-product with a rich nutrient profile that can be used to develope value-added products. Flaxseed cake (FC), a by-product of flaxseed oil extraction, has gained considerable attention due to its diverse nutritional profile, bioactive constituents, and potential health benefits. It is an economical source of various bioactives, especially proteins, alpha-linolenic acid, lignan, flaxseed gum, and dietary fiber with potential health benefits. FC also contains residual fat which is a rich source of omega-3 fatty acids. Its high protein content and non-toxic nature make it a potential ingredient for use in human nutrition.

This review paper provides an overview of the nutritional profile of FC which includes macro and micronutrients as well as bioactive components such as lignans, phenolic compounds, and antioxidants along with their health-promoting properties. Due to the presence of antinutrients, processing is required for flaxseed cake which has been discussed. Furthermore, the health benefits linked to the consumption of FC are scrutinized.

Despite the positive attributes of FC, antinutrients namely cyanogenic glycosides, phytic acid, and tannins could restrict the absorption of nutrients. Several processing methods such as soaking, steaming, and fermentation have been proven to be beneficial in improving the nutritional quality of oilseed cake and the bioavailability of nutrients.

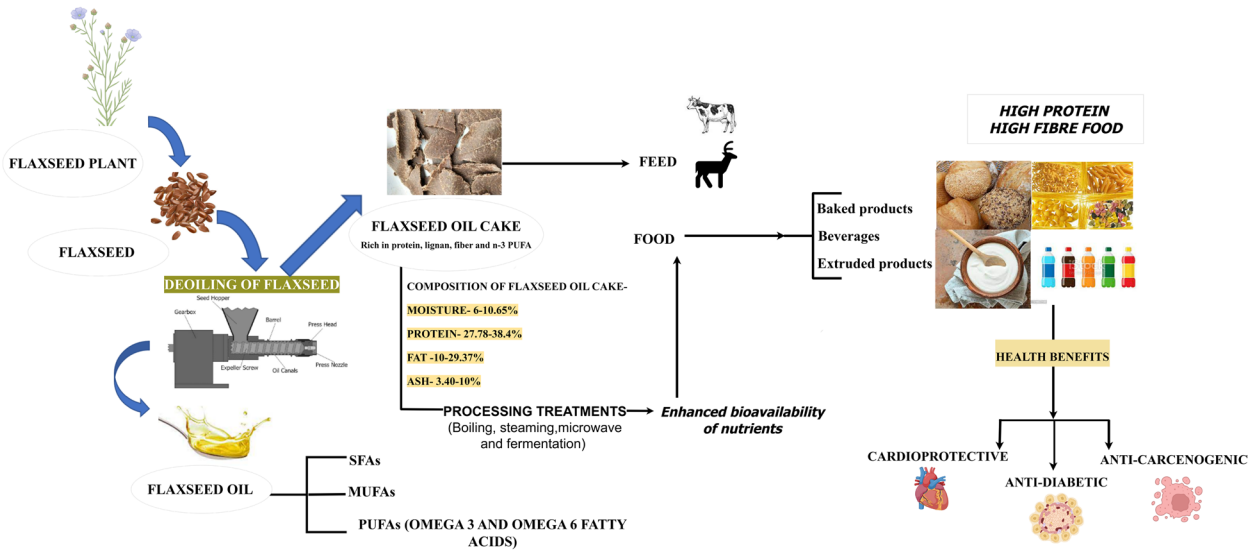
Highlights

- Flaxseed cake is a by-product of the oil industry.
- Protein, fiber, residual oil (PUFA), polyphenols, flavonoids, and antioxidants are the major components comprising the profile of flaxseed cake.
- Secoisolariciresinol diglucoside (lignans) are present in abundance in flaxseed cake.
- Processing treatments help to inactivate cyanogenic glycosides which are the major antinutrient in flaxseed cake.
- Feasibility of utilizing flaxseed meal as a potential nutrient-dense by-product in different food has been well explored.

*Correspondence:
Rajni Chopra
rajnichopra.niftem@gmail.com
Full list of author information is available at the end of the article

Keywords Flaxseed cake, Bioactive, Proteins, Functional, Antinutrients, Circular economy

Graphical Abstract



Introduction

Globally, a substantial quantity of oilseed crop was approximately 580 million tonnes in the year 2017–2018 (Singh et al., 2022). The production and processing of oilseed crops lead to the generation of agro-industrial by-products (Mannucci et al., 2019). India is one of the major oilseed crop producers that simultaneously produce oilseed cake after the oil extraction process. In the year 2016, 317 million tonnes of OSC was produced. Projections indicate that by the year 2025, it is anticipated to increase to 386 million tonnes (Kaur et al., 2021). Oilseeds, an essential crop, play a prominent role in augmenting the human diet with high-quality lipids, proteins, and fibers. A flow chart of the oil extraction process is shown in Fig. 1. Various oilseed cakes, including soybean, groundnut, rapeseed, sunflower, cottonseed, and flaxseed, possess considerable nutritional value but are predominantly utilized as animal feed (Stodolak et al., 2017). OSCs can also function as a source of antioxidants that can be consumed by humans after processing. Additionally, OSCs also serve as valuable substrates for the extraction of bioactive compounds, surfactants, enzymes, and vitamins. Despite having a rich nutritional profile, oilseed cake also contains antinutrients. Some non-edible oilseed cakes such as neem, mahua, and castor have a restricted role as agricultural manure (Gupta et al., 2019). OSC can serve as an exceptional starting point for the production of plant-based foods that are rich in protein, dietary fiber, and antioxidants (Kaur et al., 2021). OSC is an affordable by-product that is available throughout the year. Moreover, it may serve as a suitable raw material for the development of different food products with higher nutritional content along with mitigating the burden of industrial waste.

Flaxseed (*Linum usitatissimum* L.) also called linseed is an oilseed and its global production is 1.2 million tonnes (Łopusiewicz et al., 2021). As shown in Fig. 2, there has been an increase in the production of flaxseed in the past five years. There are two different varieties of flaxseed from which oil is extracted namely fiber flaxseed and oil flaxseed. Flaxseed oil which consists of polyunsaturated fatty acids, monounsaturated fatty acids, and saturated fatty acids, is obtained after seeds are pressed (Goyal et al., 2014; Sun et al., 2021). In addition, flaxseed oil contains fat-soluble vitamins: vitamin A (carotenoids, 57 ppm) and E (tocopherols, 20–70 mg/100 g) (Mohanan et al., 2018). The cold-press technique of oil extraction is one of the techniques used to expel oil. Cold-pressed flaxseed cake (FC) has relatively high levels of soluble fiber, high-quality protein, lignans, minerals, and residual oil which provides health benefits to humans if incorporated in food (Poreda et al. 2017). The abundance of important fatty acids, particularly alpha-linolenic acid

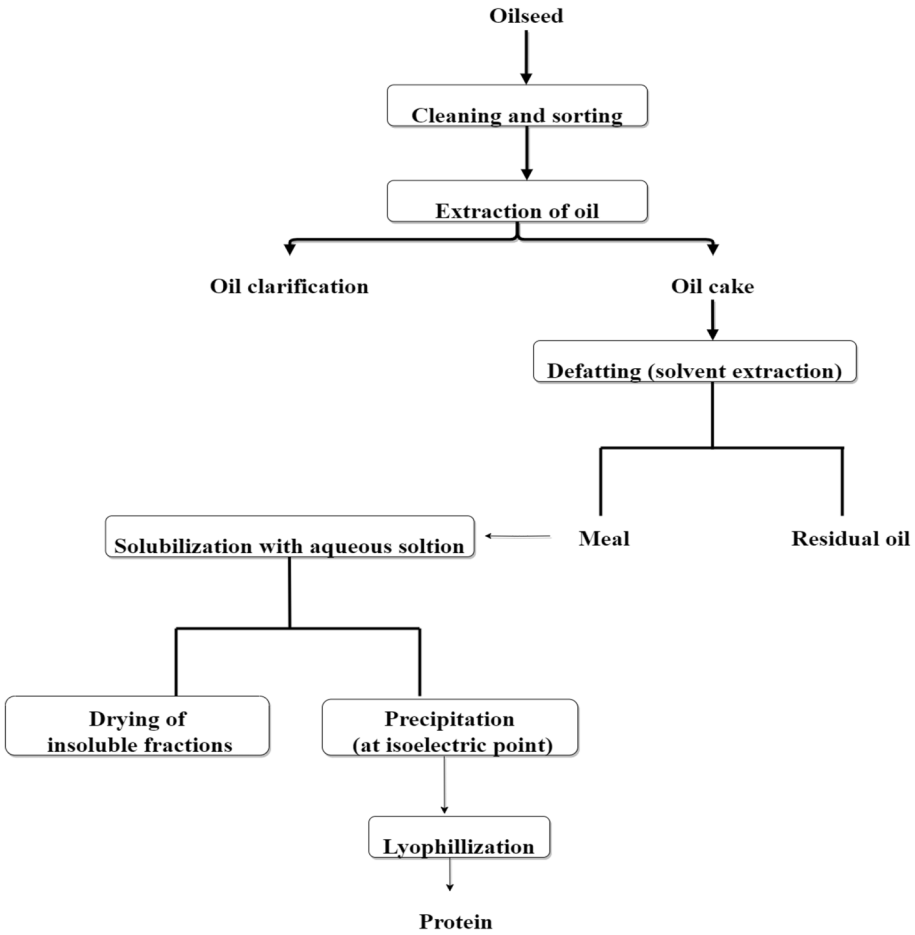


Fig. 1 Flow-chart showing the processing steps for oilseeds

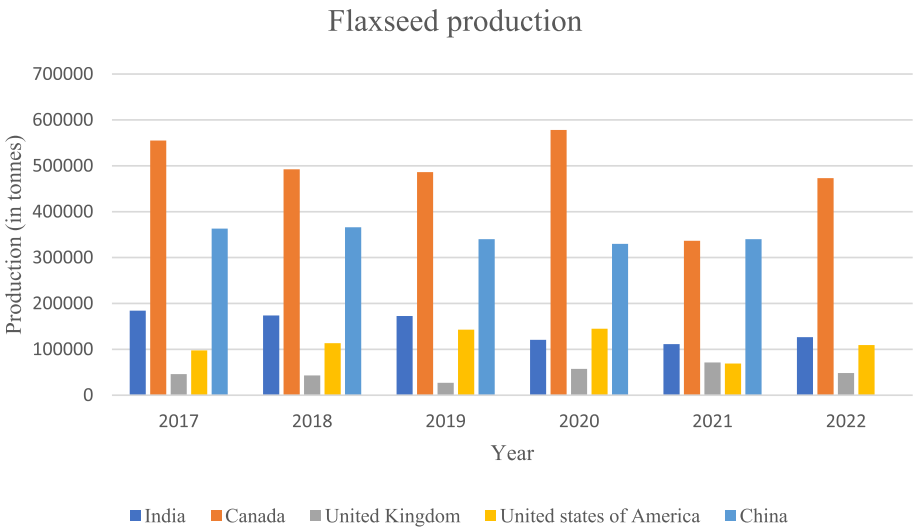


Fig. 2 Production scenario of flaxseed in past years in India, Canada, the United States of America, China, and the United Kingdom. (FAOSTAT, https://www.fao.org/faostat/en/#data/QCL/visualize)

and, linoleic acid which are present in residual oil, makes FC suitable for incorporation into a variety of food products (Teh & Birch, 2014a, 2014b). The environmental and genetic variables affect the nutritional profile of flaxseed while processing procedures have an impact on the composition of FC (Kajla et al., 2017). The milling conditions and the techniques used at the time of pressing, relative temperature, and humidity of the mill could cause fluctuations in the moisture content of the seeds which affects the oil as well cake (Ogunronbi et al., 2011). Unlike in the soybean industry where, after oil is extracted from soybean, soybean oil cake is defatted and used to develop value-added protein, in the flaxseed oil industry, defatted FC is either discarded or utilized in animal feed. Due to a lack of knowledge concerning the potential uses for the cake and the presence of antinutrients such as phytates and cyanogenic compounds, FC is overlooked. Although FC has a robust nutritional profile, it also carries several kinds of antinutritional compounds. The protein and carbohydrate fractions of FC possess various functional properties such as water binding capacity, oil holding capacity, and emulsification capacity (Bekhit et al., 2013). This review aims to provide insights regarding the nutritional composition, anti-nutritional factors, removal of anti-nutrients by different processing techniques, applications in various food products, and corresponding health benefits of these products. The network visualization of the content is shown in Fig. 3.

FC- a by-product and waste management through circular economy

The current economic model is based upon an unsustainable approach of the grow-use-dispose principle. An increase in human activities causes post-industrial global issues that negatively affect the ecosystem. These problems include mismanagement as well as overexploitation of natural resources and unsustainable consumption patterns (Ancuța & Sonia et al. 2020). To resolve the issues regarding waste management, the application of a circular economy-based model is necessary which can be accomplished by using the resources wisely and eliminating the concept of waste along with the supply chain. Any substance disposed of by any industry is known as waste. A potential approach for the efficient utilization of waste involves maximizing the concentration of valuable products during extraction (Ancuța & Sonia et al. 2020; Borrello et al., 2017; Esposito et al., 2020). An inclination towards plant-based foods which have potential health

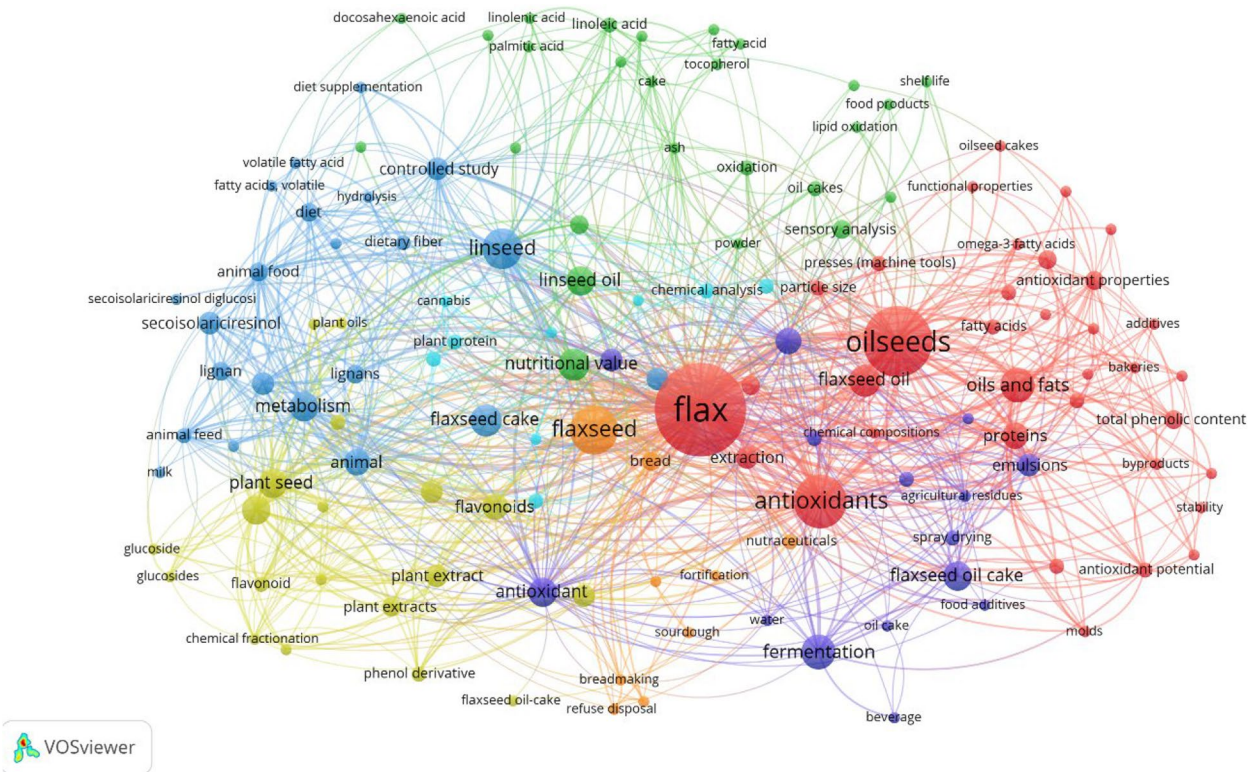


Fig. 3 Network visualization of bibliographic coupling

benefits as well as no harmful effect on the environment has been observed. These include plant-based sources of protein which may come from food waste. For example: banana peels, pineapple peels, spent grains, and many more can be used as novel raw materials for the production of various metabolites using different technologies (Tachie et al., 2023). As the world's population grows it is expected that both the production of food and the associated waste will increase. An increase in waste production might have negative effects on the environment and economy. Managing food waste in the 21st century has become one of the major concerns. According to the FAO, one-third of the food produced is wasted. The primary issue, however, is that the extent of food waste and its effects have not been thoroughly researched and quantified. After a complete understanding of food waste is reached, informed policies and strategies are aimed at reducing food waste can be developed (Tamasiga et al., 2022). Food waste is estimated to be responsible for 8% of the world's greenhouse gas emissions, which in turn contributes to the increase in global temperature (Vilariño et al., 2017). Although consumption is one of the most crucial components of every economy, particularly those that are developing, it is becoming increasingly prevalent in today's society and frequently leads to food waste. Food waste is a multifaceted problem which is a current intense issue, especially for society, the economy, and the environment. The notion of a circular economy is noteworthy because when properly used, it may minimize the problem of food waste, which can be viewed from an economic, social, or environmental point of view (Dudziak et al., 2022). By strategically utilizing FC in the framework of a cirlar economy, a holistic approach can be followed. This may involve the application of various techniques and repurposing the oil cake into food products, which would not only minimize the waste but also enhance the efficiency of resource utilization. The flaxseed oil industry's use of circular economy concepts exemplifies the harmonious fusion of environmental management, economic viability, and innovation, highlighting the possibilities for sustainable development and minimal ecological effects.

Nutritional composition of FC

Flaxseed is known to be a 'superfood' and is recognized as GRAS. Flaxseed, an oilseed is recognized as a functional food by virtue of its nutritional profile and various health benefits (Frag et al. 2020). The proximate composition of oil cake depends upon the geographical location of the crop grown as well as seed processing. In addition to possessing a high protein content, FC also contains water-soluble fiber components, which contribute to its nutritional value (Russo & Reggiani, 2016; Mueller et al., 2010). Food products incorporated with FC may exhibit improved nutritional properties and better functional properties (Bekhit et al., 2013). The industrially cold pressed cake contains high residual oil, moderate protein levels, and low moisture levels (Oomah, 2020). FC consists of 36% protein (from which 85% is digestible) and 7–10% residual oil. Table 1 shows the complete composition of FC and its comparison to soybean oil cake. The above-mentioned properties make FC a significant by-product of the oil industry that could be employed as an ingredient in different food products (Singh et al., 2022).

Macronutrients

Protein

The major protein fraction of flaxseed proteins is called linin which is made up of five polypeptide subunits. The minor protein fraction is called conlinin which has a single polypeptide chain. Major proteins compromise 66% and minor proteins compromise 20–42% of the seed proteins. In addition, these various structurally small proteins (low molecular weight) are also found in flaxseed (Waszkowiak & Mikołajczak, 2020). Flaxseed consists of two storage proteins, which are salt soluble (high molecular weight) and others are water-soluble (low molecular weight) (Mueller et al., 2010). Both salt and water-soluble proteins are present in approximately equal concentrations (Wanasundara et al., 1999). Flaxseed globulin is composed of at least five subunits with molecular masses ranging from 11 to 61 kDa connected by disulfide linkages and has an overall molecular mass of approximately 320 kDa and an isoelectric point of approximately 4.75 (Łopusiewicz et al., 2020). Flaxseed proteins are rich in amino acids such as arginine, aspartic acid, and glutamic acid. Additionally, amino acids including lysine, leucine, and valine are present in FC. In addition to protein nitrogen, FC contains non-protein nitrogen in the form of vitamins, sinapine, choline, and cyanogenic glycosides (Bekhit et al., 2013). The protein content increases after the defatting of the cake (Rani & Badwaik, 2021). The extraction of protein from flaxseed is challenging due to the presence of mucilage which is a highly viscous anionic polysaccharide accounting for 8% of total dry mass. To enhance the effectiveness of protein extraction FC can be soaked in warm water or treated with enzymes for removal of mucilage thereby optimizing the protein extraction process (Sun et al., 2021).

Lipids

Flaxseed characterized by an oil content ranging from 20 to 40% has received substantial attention due to its superior nutritional profile. Approximately 58.03% linolenic acid is present in flaxseed oil (Zhang et al., 2011a, 2011b). Flaxseed oil is a conglomerate of

Table 1 Comparison between the composition of flaxseed and soybean oil cake

Component	Concentration (%)		References
	Flaxseed	Soybean	
Carbohydrate	34–40	14.98–30.75	Singh et al. (2011); Stodolak et al. (2013); Zamindar et al. (2017)
Moisture	6–10.65	8.4–11.3	Gutiérrez et al. (2010); Ogunronbi et al. (2011); Tirgar et al. (2017); Hady & Elsorady (2020); Zamindar et al. (2017)
Protein	27.78–38.4	39.8–47.42	Gutiérrez et al. (2010); Ogunronbi et al. (2011); Oomah (2020); (Tirgar et al., 2017; Hady & Elsorady (2020); Zdunczyk et al. (1999); Tamasgen et al. (2021)
Amino acids			Mohamed et al. (2020); Ibáñez et al. (2020)
Arginine	13.97	6.92–7.69	
Cysteine	0.17	1.26–1.65	
Histidine	6.96	2.54–3.11	
Isoleucine	6.26	3.92–5.73	
Leucine	4.92	7.21–7.98	
Lysine	2.70	5.51–6.60	
Methionine	2.88	1.26–1.52	
Phenylalanine	4.29	4.86–5.41	
Threonine	6.94	3.31–4.09	
Valine	3.96	4.23–5.22	
Fat	10–29.37	0.55–1.53	(Ogunronbi et al., 2011)
Total Dietary fiber	7.20–54.45	4.4–12.4	Gutiérrez et al. (2010); Ogunronbi et al. (2011); Tirgar et al. (2017); Hady & Elsorady (2020)
Soluble dietary fiber	7.81–10.15	-	Gutiérrez et al. (2010); Ogunronbi et al. (2011); Oomah (2020); Ganorkar et al. (2016)
Insoluble dietary fiber	18.20-22.85	-	Khare et al. (2021); Zdunczyk et al. (1999); Tamasgen et al. (2021)
Ash	3.40–10	6.1–7.8	Gutiérrez et al. (2010); Ogunronbi et al. (2011); Oomah (2020); Tirgar et al. (2017) Zdunczyk et al. (1999); Tamasgen et al. (2021)
Mineral element Macro minerals	Concentration (g/kg)		Ogunronbi et al. (2011); Batal et al. (2010); Kolláthová et al. (2019)
Na	0.34	0.23	
Ca	3.61	3.49	
Mg	4.41	2.09	
P	9.52	6.08	
K	12.41	20.47	
Micro minerals	Concentration (mg/kg)		
Mn	13.73	25.62	
Zn	48.60	44.77	
Cu	17.75	14.68	

saturated fatty acids (9%), monounsaturated fatty acids (18%) and polyunsaturated fatty acids (73%) which are present at low, moderate and high concentrations respectively (Gutte et al., 2015). Flaxseed oil is considered a rich source of omega-3 fatty acid (Zhang et al., 2011a, 2011b). Apart from their use in cooking and other culinary purposes, various oils are used in the raw form as salad dressing. Currently flaxseed oil is utilized in various food products because of its distinctive flavor (Sun et al., 2021). FC has high levels of ALA (alpha-linolenic acid), which is an essential fatty acid (Zhang et al., 2011a, 2011b). ALA plays an important role in human development. It also has various biological effects such as preventing coronary heart disease, diabetes, some autoimmune diseases and some type of cancer (Gallardo et al., 2014). ALA has also been proven to be a powerful anti-inflammatory agent that can lower serum cholesterol levels (Zhai et al., 2019).

Dietary fiber

Dietary fiber is present in soluble and insoluble forms in FC. Insoluble dietary fibers found in FC include lignan, cellulose, and hemicellulose. It contains approximately 30% of dietary fibers which are mostly water

extractable one-third of which are viscous. The dietary fibers present in FC are made up of heterogeneous polysaccharides. These polysaccharides are composed up of a mixture of neutral arabinoxylans and acidic rhamnose (Basiri et al., 2018). These dietary fibers induce satiety, postprandially as they suppress the ghrelin hormone (Ibrügger et al., 2012). The abundant mucilage in flaxseed cake can be freeze-dried or vacuum-dried and then stored to create a stable powder that can be utilized as an emulsifier and thickener in the food industry. The main constituents of the soluble fiber fraction are mucilage gums, while the insoluble fiber fraction mostly consists of cellulose and lignin (Bongartz et al., 2022). Monosaccharides from FC are composed of a mixture of polymers namely; arabinoxylans, galactose and fructose. The dietary fiber present in flaxseed and its cake is in the form of mucilage which helps to ensure a well-functioning gut by functioning as a prebiotic (Kristensen et al., 2012).

Minerals

Minerals are micronutrients that are consumed through the diet. Minerals play a vital role in the metabolism of some major biological processes and, minerals also play a vital role in osmotic pressure and acid-base regulation in the human body. Both macro and micro minerals are present in flaxseed. In macro minerals, magnesium is present in the highest concentration followed by potassium and sodium, whereas for micro minerals zinc is present in the highest concentration followed by manganese, copper, and iron (Kaur et al., 2017). Compared with oil cakes such as soybean, nigella, groundnut, and mustard seed FC is high in minerals such as phosphorous (9.52 g/kg), potassium (12.41 g/kg), manganese (13.73 mg/kg), copper (17.75 mg/kg) (Kolláthová et al., 2019).

Bioactives from flaxseed cake

The utilization of oil cake obtained after extraction depends upon the origin and constituents present in the oilseed. FC is a rich source of valuable components such as leftover proteins, fibers, and lipids. Residue of extraction process, contains secondary metabolites, especially phenolic acids and flavonoids. During the oil extraction process components such as tocopherols and phospholipids (partially) are removed whereas during the extraction process, the phenolic content does not decrease because there is a high content of phenolic compounds in the oil cake (Marczak, 2014). The concentration of phenolic acids and lignans in the defatted flaxseed increases when the oil is removed before extraction. Most phenolic compounds and antioxidants are bound to the cell so they remain insoluble in lipids and do not migrate to oil during the pressing of oilseeds (Singh et al., 2022). In some of the studies, it is observed that owing to the presence of a bioactive component, FC has a powerful antioxidant effect. The bioactive components of FC must be utilized and its overall utilization value must be increased (Sanmartin et al. 2020).

Table 2 Phenolic compounds of flaxseed cake

Phenolic acids	Concentration (mg/100 g)	References
Caffeic acid	49.53	Farag et al. (2012) Özkaynak (2017)
Chlorogenic acid	77.12	
Myricetin	28.94	
Querecetin	18.45	
Kaempferol	13.27	
Free phenolics (mg ferulic acid /100 g defatted cake)	784.78	
Esterified phenolics (mg ferulic acid /100 g defatted cake)	1522.69	

Polyphenols

Polyphenols are insoluble and are present in vacuoles, lipoprotein bilayers, lignin, hulls, and cell walls (Gutiérrez et al., 2010). Phenolic acids occur as esters, glycosides, and other bound complexes in plants. However, heating processes such as roasting weaken the covalent bond that binds the phenolic compounds to cell walls which in turn increases the extractable phenolic compounds (Zhang et al., 2023a, 2023b, 2023c). Total phenols found in methanolic extracts of flaxseed cake (1.728 mg/g) is found to be higher than those found in flaxseed whole (1.538 mg/g) (Quezada & Cherian, 2012). Table 2 summarizes the phenolic compounds in flaxseed cake. With a substantial concentration of acids such as chlorogenic acid, ferulic acid, coumaric acid, and p-hydroxybenzoic makes up the majority of the phenolic acids in flaxseed. Major phenolic acids present in FC are chlorogenic acid, ferulic acid, and gallic acid. Other, less prevalent phenolic acids include p-coumaric acid glucosides, cinnamic acid, caffeic acid hydroxycinnamic acid glucosides, and 4-hydroxybenzoic acid (Ganorkar et al., 2016; Teh & Birch, 2014a, 2014b). These phenolic acids also exhibit antioxidant activity which is linked to the arrangement of hydroxyl group on ring (Barthet et al., 2014). The phenolic content extracted from FC differs due to differences in the extraction process. A high total phenolic content of HPC (hot pressed cake) extract may be due to the chemical reaction of plant tissues caused by heat treatment, which alters the structure of lignocellulose and

Table 3 Antioxidant potential of flaxseed cake

Component	Antioxidant Assessment Method	Major findings	References
Defatted flaxseed extracts Non- Defatted flaxseed extracts	DPPH FRAP	-DPPH radical levels ranged from 19.7 to 76.1% and 28.7–76.3% for defatted and non-defatted flaxseed extracts respectively. -Non-defatted extracts had higher scavenging activity The DPPH scavenging activity increased with extract concentration. -The FRAP values for defatted and non-defatted flaxseed extracts were found to be 0.058 and 0.062 mmol TE/g, respectively. Non-defatted extracts showed lower ferric reducing capacity The antioxidants in flaxseed oil lowers DPPH capacity of defatted flaxseed	Brodowska et al. (2014)
Flaxseed cake extract	β- carotene coupled oxidation DPPH Reducing antioxidant BHT was used as a control.	-The β-carotene coupled oxidation value (73.52%), DPPH value (55.28%), and reducing antioxidant value (4240 µg/g) of flaxseed cake extract strongly suggest its antioxidant power. -For β-carotene coupled oxidation and DPPH when compared to BHT (82.91% and 61.72%), the value of the extract is slightly lower. For reducing antioxidants, the value for flaxseed extract was found to be significantly lower.	Akl et al. (2020)
Flaxseed extracts (from different varieties)	DPPH(g/L) ABTS (mmol Trolox/g) FRAP (mmol $FeSO_4$ /g) Chelating activity (g/L)	-The ethanolic extracts contained 6–11 times higher phenolics when compared to the aqueous extracts. The ethanolic extraction is more selective than aqueous extraction for phenolic compounds. A similar trend was found in the case of DPPH and ABTS assays as ethanolic extracts were 5-8.5 and 7.5-9 times higher than the aqueous extracts, respectively. -The difference in the values of different extracts is due to the contents of phenolics.	Waszkowiak et al. (2015)
Flaxseed cake extracts from- Hot-pressed cake (HPC) Cold-pressed cake (CPC) *n*-Hexane cake (HC) Supercritical CO2 cake (SCC) Subcritical *n*-butane cake (SBC)	DPPH FRAP ABTS Reducing power	-The DDPH scavenging activity of HPC was found to be highest followed by CPC, SCC, SBC, and HC. Bound phenolics are generally released upon heating which justifies the highest value of HPC. Also, the DPPH scavenging activity of pressed cake extract was twice as compared to solvent-extracted cakes. -The FRAP values were in a sequence of highest to lowest as-HPC followed by SCC, SBC, CPC, and HC. The higher the FRAP value, the higher the antioxidant capacity. FRAP values of press cakes were higher than solvent-extracted cakes. -HPC showed the highest values for scavenging ABTS free radicals. -HPC extract showed the highest total reducing power. The extracts of pressed cakes possess reducing agents when compared to solvent-extracted cakes.	Zhang et al. (2023a, 2023b, 2023c)

Table 3 (continued)

Component	Antioxidant Assessment Method	Major findings	References
Flaxseed cake(FSM) extract Flaxseed cake extract	DPPH (mmol TE/g) ABTS (mmol TE/g) FRAP (mmol TE/g) DPPH	-Methanol (high polarity) and ethyl acetate (low polarity) were used as solvent for extraction. The value of DPPH for methanolic extracts of FSM is three-fold higher than the ethyl acetate extracts. ABTS values of methanolic extracts of FSM were twice as compared to flaxseed. -For flaxseed cake, the FRAP value of methanolic extracts was eight times higher than that of ethyl acetate extracts. -Extracts made with 60% and 80% ethanol showed 21.22% and 72.95% scavenging activity whereas a 100% ethanolic extract showed ineffective results. Also, hydrolyzed extracts showed double values of scavenging activity due to the breakage of linkages and deglycosylation of phenolic compounds. Natural antioxidants and flaxseed cake extract showed comparable values for radical scavenging activities.	Quezada and Cherian (2012) Pag et al. (2014)

BHT(butylated hydroxytoluene)

increases the availability of phenolic chemicals in plant extracts. Phenolic extracts of supercritical extracted cake were found to be more than hot pressed as in supercritical fluid extraction diffusion coefficient as well solubility of phenolics increased (Sanmartin et al. 2020). Flaxseed cake (FC) exhibits antioxidant activity due to the substantial amount of phenolics present in it (Hao et al., 2020). The antioxidant potential of FC can be assessed through various methods such as DPPH (1,1-Diphenyl 2-picrylhydrazyl), FRAP (Ferric reducing ability power), and ABTS (2.2´-azino-bis(3-ethylbenzothioazoline-6-sulphonic acid) (Table 3). DPPH act as a scavenger of the free radical (Terpinc et al., 2012), FRAP assay is based on the reduction ability to convert Fe(III) to Fe(II) at pH 3.6 (Teh et al., 2014a, 2014b) and ABTS assay is based on radical decolorization (Marczak, 2014).

Flavonoids

Flavonoids are a group of secondary plant metabolites with potential antioxidant activity that prevent the oxidative deterioration of food. The accumulation of flavonoids in plants depends upon various factors such as the presence of enzymes required in the flavonoid pathway, the supply of amino acids, and much more (Oomah et al., 1996a, 1996b). Flavonoids are a category of plant phenolics, that are composed of two aromatic rings connected by a 3-carbon bridge in a heterocyclic arrangement. The flavonoids present in FC are flavanols, flavones, and flavanones. These compounds act as strong reactive species scavengers, that act as signal molecules as protective measures against pathogens. The flavonoid content in the methanolic extract of flaxseed is found to be 1.7 mg/g whereas in flaxseed cake is 2.8 mg/g (Quezada & Cherian, 2012). The content of flavonoids is higher in the extract of pressed cake as compared to solvent-extracted cakes. Flavonoids are polar substances retained in pressed cakes during oil production. There is a weak relation between the flavonoid content and oil content in flaxseed.

Lignans

Lignans are phytoestrogens found as minor elements that are responsible for the development of plant cells. Lignans are made up of two units of phenylpropane. Lignans are phytochemical compounds that have anticarcinogenic and antioxidant properties. SDG scavenges free radical activity which leads to the antioxidant potential of flaxseed cake. SDGs can make complex divalent transition metal cations that are responsible for the health-promoting effects (Prasad, 1997). Lignans are the major polyphenols present in the extract of defatted FC (Teh & Birch, 2014a, 2014b). When SDG is ingested, it is not present in circulation rather it is metabolized into its metabolites enterodiol and enterolactone. Due to ester linkages with 3-hydroxy-3-methyl glutaric acid (HMGA) and glycosidic linkages with phenolic substances, such as hydroxycinnamic acid derivatives and herbacetin diglucoside, lignans found in FC are oligomers. Lignan is composed of monomeric units of SDG which has high biological activity as it has antioxidant and anti-inflammatory properties that prevent cardiovascular diseases and other metabolic syndromes (Tavarini et al., 2021). Flaxseed and FC are considered the richest plant sources of the lignan precursor,

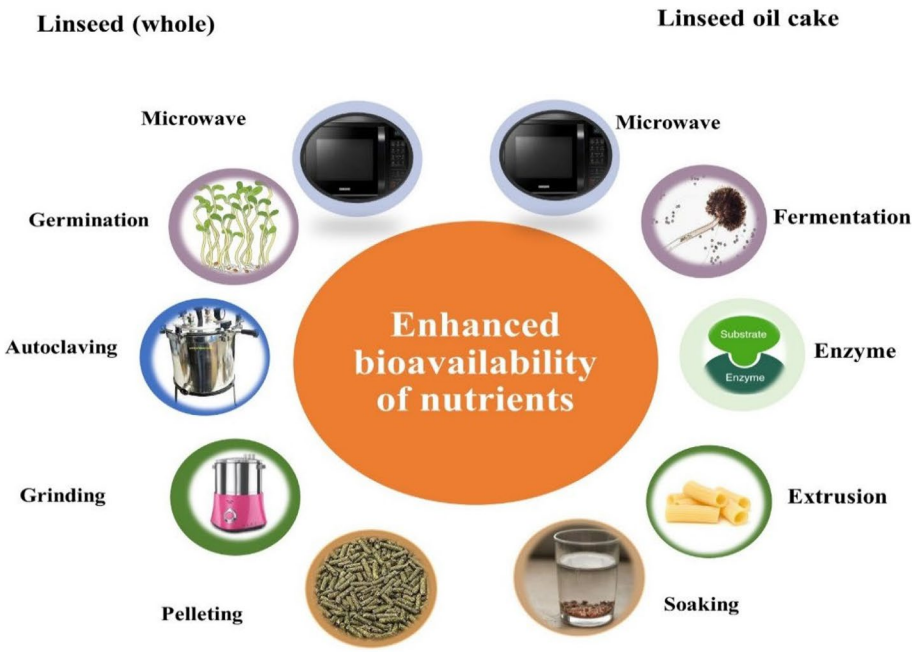


Fig. 4 Different processing methods for removing antinutrients from flaxseed (whole) and flaxseed cake

secoisolariciresinol diglucoside (SDG) (Rudra et al., 2021). Lignans present at minor levels include matairesinol and pinoresinol (Williams et al., 2007). Lignans are known to exhibit antioxidant potential due to their properties to scavenge free radicals such as hydroxyl ions. Flaxseed lignans have a higher antioxidant potential as compared to vitamin E (Khattab et al. 2012).

Amino acids and bioactive peptides

The majority of studies highlight the benefits of flaxseed for human health such as ALA-rich flaxseed oil, flaxseed lignans, and soluble polysaccharides whereas the protein component remains underutilized. Dietary nitrogen which is assimilated in humans in the form of small peptides has various physiological activities. Food proteins can generate bioactive peptides that are known to have a positive influence on the human body. Currently, there is much research and understanding of how dietary proteins might produce bioactive peptides. Bioactive peptides are unique protein fragments that have a positive impact on the overall health (Wanasundara, 2008).

Anti-nutritional factors in FC and their mitigation strategies

FC contains several antinutrients that can be minimized by various processing methods, such as boiling, fermentation, and pelleting (Ogunronbi et al., 2011). After the extraction of flaxseed oil, protein and fiber fractions of flaxseed are concentrated (Drozłowska et al., 2020a, 2020b). FC is considered a source of nutritional compounds such as proteins, lignans, and fibers. In addition, various anti-nutrients such as linustatin, neolinustatin, linamarin, and lotaustralin are also present in FC and are known to be cyanogenic glycoside compounds (Russo & Reggiani, 2016). These antinutrients increase as the oil is extracted which can act as a potential health risk factor if consumed directly. The primary anti-nutrient present in flaxseed is cyanogenic glycoside (Sun et al., 2021). Another anti-nutrient present in FC is phytic acid. Both flaxseed (whole) and FC have cyanogenic compounds. The cyanogenic compounds release cyanide in the human gut by acid-catalyzed hydrolysis or hydrolysis by endogenous seed enzymes (Bacala & Barthet, 2007). Various processing methods have been proven to be effective in removing anti-nutrients of FC and depicted in Fig. 4.

Cyanogenic glycosides (CGs)

Cyanogenic glycosides are the main antinutritional factors present in flaxseed that are concentrated in the cake. When cyanogenic glycosides are digested, hydrogen cyanide is formed which can cause acute toxicity in adults. Cyanogenic compounds are nitrogenous secondary plant metabolites derived from valine and isoleucine which can cause chronic effects if ingested in high quantities (Russo & Reggiani, 2016), synthesized through tonoplast glycosyltransferase that accumulates in vacuoles. After the cell structure is ruptured cyanogenic glycosides decompose to hydrogen cyanide which is catalyzed by β-glucosidase

and α-hydroxy nitrile lyase (Russo & Reggiani, 2014). Due to the intestinal β-glucosidase activity, cyanogenic glycosides liberate toxic HCN which is known to have a toxic effect on the respiratory, nervous, and endocrine systems (Zhai et al., 2019). Cyanogenic glycosides are known to be composed of α-hydroxy nitrile-type aglycon and a sugar part (glucose or gentobiose) (Russo & Reggiani, 2016). Additionally, cyanogenic glucosides are unstable at low temperatures (Mannucci et al., 2019). Cyanide decreases the bioavailability of iron, manganese, or copper ions because it can bind minerals. Flaxseed contains cyanogenic compounds in the range of 264–354 mg per 100 g of seeds. Due to damage to plant tissue and the presence of the enzyme, linase, cyanogenic compounds can produce 100–300 mg/kg hydrocyanic acid (HCN) (Imran et al., 2013). According to previous studies 100 mg of CG, if consumed might be toxic to human health (Russo & Reggiani, 2016). These compounds can be removed partially by microwave treatment, autoclaving, and boiling of seeds (Russo & Reggiani, 2016). Cyanogenic glycosides are further fractioned into linustatin and neolinustatin. Linatine, another anti-nutrient binds to vitamin B6 and reduces its absorption which in turn causes its deficiency in humans (Teh & Birch, 2014a, 2014b). If consumed, these compounds form a complex with ferric ions of mitochondrial cytochrome oxidase and cause acute or chronic intoxication which leads to abnormal respiration and nervousness. FC contains relatively high concentrations of hydrogen cyanide (HCN) which has been proven to be a potent respiratory inhibitor (Feng et al., 2003). Vomiting, nausea, dizziness, arrhythmias, headache, and difficulty in vision are some of the symptoms caused by acute intoxication caused by cyanogenic glucoside. CG is found not only in flaxseeds but also in cassava (linustatin, limarin), passiflora (neolinustatin), wheat, and oat (linamarin) (Russo & Reggiani, 2014).

Phytic acid

Phytates are the primary phosphorus storage form in plants. Mineral absorption is hampered by phytic acid. Minerals and proteins are electrostatically bound in complexes by a highly charged phytic acid molecule, reducing their bioavailability (Poreda, 2017). Phytic acid is the primary form of stored phosphate and is a naturally occurring plant inositol hexaphosphate that is frequently detected in seeds. The phytic acid content in flaxseed depends upon the season and geography (Zhang et al., 2023a, 2023b, 2023c). Phytic acid forms insoluble complexes with metals such as calcium, magnesium, zinc, copper, iron and molybdenum which hinders their absorption by the gastrointestinal tract. In addition, various mineral and protein complexes with phytic acid are formed which then decreases their bioavailability. Phytic acid strongly affects the bioavailability of various minerals. In defatted and dehulled oilseed cakes made from oilseeds including soy, peanut, and sesame, phytic acid accounts for approximately 1.5%. In flaxseed, the concentration of phytic acid ranged from 23 g/kg to 33 g/kg. Phytin extracted from flaxseed flour accounts for 13% of organic phosphorus. Approximately 70% of the total phosphorus is present in the form of phytic acid (Oomah et al., 1996a, 1996b). Proteins and starch may also directly interact with phytic acid, reducing its solubility and digestibility (Farag et al. 2012; Oomah et al., 1996a, 1996b).

Tannins

Tannins are categorized as phenolic compounds with molecular weights of 500–3000 Da. Tannins are water-soluble compounds that are found in vacuoles and can bind with protein and form soluble or insoluble tannin-protein complexes. Based on their structure and molecular weight, tannins can be divided into two categories, namely condensed and hydrolyzable tannins. The commercial use of flaxseed is limited due to the presence of various toxic compounds, including tannins, which not only decrease micronutrient bioavailability but also hinder the protein digestibility. Additionally, tannins are compounds that impart an astringent taste to the oil cakes (Imran et al., 2014).

Effect of processing methods on flaxseed (whole) and FC

It has been scientifically proven that proper processing operations are required to remove the antinutrients present in FC to make it suitable for human consumption (Bekhit et al., 2018). Some methods of removing antinutrients are enzymatic hydrolysis, fermentation, roasting, microwave, and extrusion. Heating processes such as steaming and boiling can reduce the antinutrient factors (Xu et al., 2022). High temperature and short time combinations used in extrusion technology are employed to reduce the concentrations of anti-nutrients in soybean, canola and cottonseed (Imran et al., 2013). The extraction process is not sufficient to remove cyanogenic compounds completely, apart from the fact that some beneficial compounds are also removed during the extraction process (Zhai et al., 2019; Yamashita et al., 2007). The process of heating decreases the nutritional value and it is difficult to remove residual solvent through the solvent extraction process. Fermentation is known to be the ideal treatment for the removal of antinutrients. The fermentation process has been known to decrease the HCN content (Zhai et al., 2019). Fermentation is also known to increase phenolic content, radicle scavenging

activity and bioavailability (Stodolak et al., 2017), (Zhai et al., 2019). When *Aspergillus niger* and *Candida utilis* were used in combination, HCN levels decreased and nutritional content was more bioavailable because of the utilization of cyanide compounds by these microorganisms (Zhai et al., 2019). Other physical methods are also employed to remove the antinutrient factors to acceptable levels. The effects of different processing methods on antinutrient factors of FC and flaxseed (whole) are presented in Table 4.

Functional properties

Research on the nutritional qualities and potential applications of protein from affordable, underutilized high-protein oilseeds and legumes has become important due to the rising costs and insufficient availability of animal proteins. To facilitate their incorporation into food formulations, protein flours from unique sources must exhibit the required interaction characteristics with other food components (Khattab & Arntfield, 2009). The nitrogen solubility of different protein-rich products is regarded as a reliable indicator of functional properties. Different solvents are used to extract them which significantly affects the functional properties as hexane-extracted cakes showed 9.7 times higher adsorption of water than their weight. It was also observed that hexane-extracted cake adsorbed 2.6 times more soybean oil than their original weight whereas cakes extracted with methanol-ammonia-water increased fat adsorption capacity by 3.2 times (Wanasundara & Shahidi, 1994). To develop processed foods such as baked goods, sauces, soups, and similar food products with improved quality and yield, several functional qualities are crucial. Compared with mustard and soybean oil cake, FC has the highest oil absorption capacity (OAC). The OAC depends upon the hydrophilicity of the protein and its retention for binding to lipids. Bulk density depends on the intermolecular forces, which are essential for wet processing and development of new products. FC and the defatted cake had moderate bulk densities. Foaming capacity is always related to the content of soluble protein as well as polar and non-polar lipids in any matrix, FC accounts for a moderate amount of foaming capacity when compared to the soybean and mustard oilseed cake as well as defatted cake. Emulsification is also a property that directly depends upon protein content, as flaxseed has a moderate protein content compared to soybean and mustard, and the emulsification property of flaxseed is also moderate, whereas emulsion capacity was found to be highest in FC (Bárta et al., 2021). A previous study reported that the water holding capacity (WHC) changes with changes in plant variety, geography, cultivation temperature, and extraction method (Bekhit et al., 2013). Alkali-treated oilseed cakes such as hemp and canola had the highest water-holding capacity followed by acid-treated oilseed cakes due to changes in the protein structures of hemp and canola as a result of alkali and acid extractions, exposing more hydrophilic binding sites that allowed the proteins to bind more water whereas a study done showed that FC has highest water absorption capacity (WAC) compared to canola and soybean oil cake because of the presence of mucilage polysaccharides which have a high tendency for absorption and swelling (Khattab & Arntfield, 2009). The emulsifying activity was found to be different reason being the physicochemical characteristics such as protein and ionic strength (Mueller et al., 2010). Different processing methods such as microwave processing, autoclaving, boiling, soaking, and solvent extraction lead to alterations in the functional properties of defatted flaxseed flour. Defatting leads to an increase in the water-holding and oil-holding capacity of the flour. This may be due to the increased availability of hydrophilic components such as mucilage or carbohydrates and the increased ability to hold oil by the capillary attraction process. The swelling indices of other functional groups increase due to the elimination of non-polar groups which act as interfering components in the interaction between flour and water. The foaming capacity depends upon the pH and protein structure, and defatted flaxseed flour shows better foaming properties at pH 2 because protein denaturation occurs at a particular pH. Denaturation of proteins is caused by whipping and aggregation formation in liquid-air interphase formation. A higher protein content is associated with better emulsion capacity and emulsion stability. The defatting of flaxseed flour leads to an increase in protein concentration content which positively impacts the emulsion properties as it forms a protective layer around the oil droplets and minimizes the interfacial tension (Safdar et al., 2020).

Application of FC in the food industry

Currently, increased awareness of health issues among consumers is observed which has led to a spike in the demand for new products. Additionally, as a result of the expanding population, there is an increased need for plant proteins to meet dietary needs. It is perceived that plant-based food products are a blend of antioxidants, vitamins, dietary fiber, and minerals (Łopusiewicz et al., 2020). Oilseed cake is an exceptional raw material that can be incorporated into food products because it contains high levels of antioxidants, vitamins, proteins, minerals, and dietary fiber. FC can serve as a possible delivery system for bioactive substances, opening the door for the production of premium goods with improved nutritional profiles and desired health benefits. FCis a source of numerous compounds such as antioxidants, omega-3

Table 4 Various processing methods for removing antinutrients from flaxseed cake and flaxseed (whole)

Method	Sample	Treatment	Conclusion	References
Physical	Flaxseed Cake	Heated at 90 °C for 1 h which was stirred continuously.	94.3% reduction due to either heat. Deactivation of glycoside or evaporation of HCN (which is formed after hydrolysis) or both takes place.	Safdar et al. (2020)
		Boiling for 15–30 min at intervals of 5 min.	94.3% removal of HCN	
		Soaking for 12–48 h at intervals of 12 h.	48.2% removal of HCN	
		Autoclaving at 120 °C for 5–20 min at interval of 5 min.	62.6% reduction of HCN	
	Flaxseed (whole)	Pelleting under high pressure and temperature	Repeated pelleting (with or without other ingredients decreased HCN content.	Feng et al. (2003)
		Autoclaving to sterilize at 16.5 kg cm^{-2} at 120 °C for 15 min	High temperature inactivates glycosidase, decreased HCN to negligible levels.	
		Steaming-	Reduction in tannins by2.86%2.39%2.06%	Damayanti and Sjofjan (2022)
		Treatment time for tannin-10 min20 min30 min	Reduction in phytic acid by38.39%33.88%29.73%	
		Treatment time for phytic acid-10 min20 min30 min	Removal of HCN upto detectable limit	
		Microwave-400 W power for 4 min 50 s	80.72% and 50.87% reduction of cyanogenic glycosides and phytic acid respectively.	Dusica et al. (2012)
		Germination-Incubation at 42 °C	70% reduction in cyanogenic glycosides.	Kajla et al. (2017)
		Sprouting in dark for 4 days at 20 ± 2 °C	70% reduction in cyanogenic glycoside content.	Hady & Elsorady (2020)
		Soaking done for 12 h followed by germination	39.72% reduction in trypsin inhibitor activity	Khare et al. (2021)
Fermentation	Flaxseed cake	*Aspergillus niger* and *Candida utilis* (1:1 ml inoculum incubated at 30 °C for 72 h)	The lowest HCN was observed after 60 h fermentation.	Zhai et al. (2019)
	Flaxseed (whole)	Fermentation using consortium of Lactobacilli (incubated at 30 °C for 72 h)	Reduced the cyanogenic glycosides to undetectable limits.	Huang et al. (2023)
Enzymatic treatment	Flaxseed cake	Incubation with 0.1 M sodium citrate buffer at 30 °C for 18 h.	100% removal of cyanogenic compounds	Yamashita et al. (2007)
	Flaxseed (whole)	12.5% beta-glucosidase and 8.9% cyanide hydratase (no use of steam to evaporate HCN which prevents environmental pollution and low energy consumption) followed by fermentation	Up to 99.3% reduction in cyanogenic glycosides after 48 h of fermentation.	Wu et al. (2012)
Extrusion	Flaxseed cake	Extrusion conditions-screw speed- 96.8 rpm, barrel temperature-80 °C 40% moisture level	Reduction of tannin by 61.27%	Mukhopadhyay et al. (2007)
Multi-stage solvent treatment	Flaxseed cake	Increasing the volume of solvent and duration of extraction. Multistage extraction using methanol-ammonia-water or hexane as solvents	80% removal of linustatin and neolinustatin. Up to 90% removal of cyanogenic glycosides. Among the solvents used, methanol was found to be the most efficient solvent for removal of CGs.	Wanasundara et al. (1993)

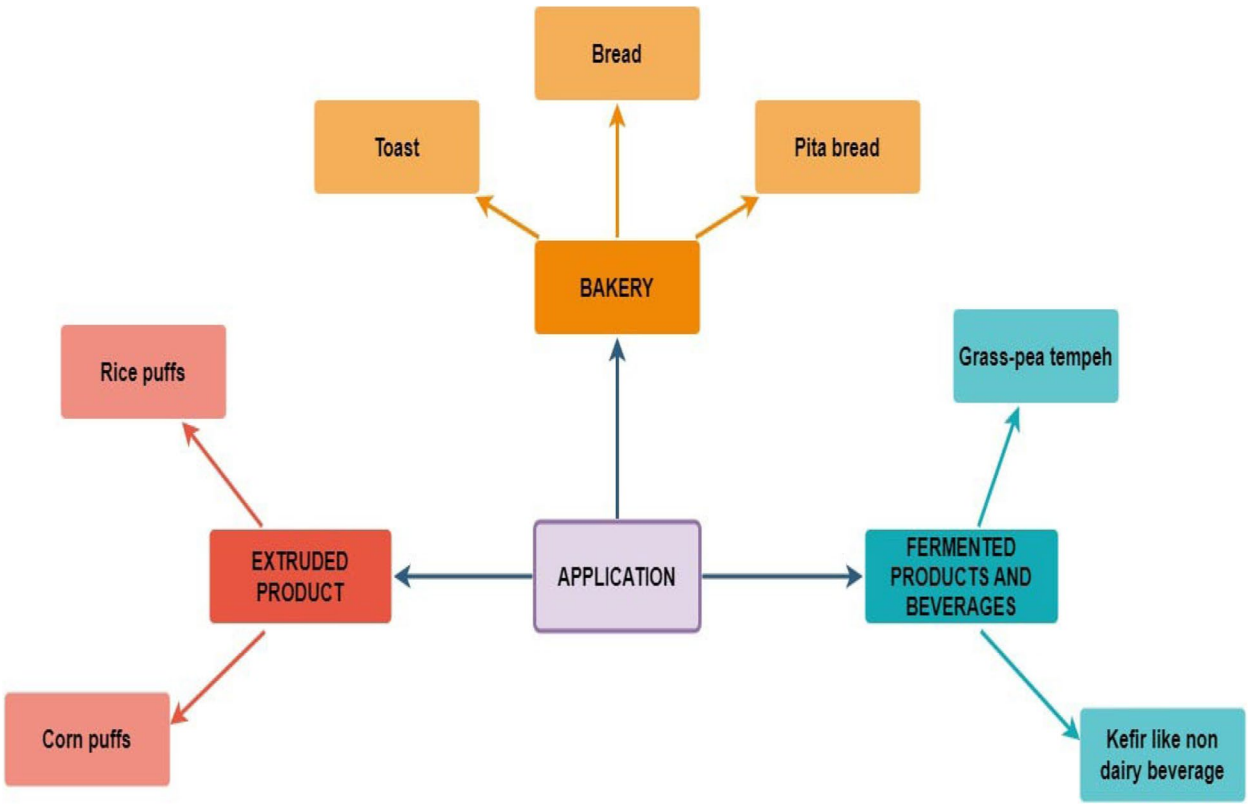


Fig. 5 Potential applications of flaxseed cake in the food industry

fatty acids, bioactive proteins, soluble and insoluble fibers, lignans, and minerals such as Mg, K, Na, and Zn) (Łopusiewicz et al., 2020). Over the past few decades an increase in the value of flaxseed, an essential oilseed crop, has been observed due to its distinctive nutrient profile. The potential application of FC as an additive to enhance the nutritional profile of food products is shown in Fig. 5. The presence of antinutrients (cyanogenic glucosides and phytic acid) should be considered, but these compounds can be removed by various methods. Researchers are more interested in utilizing oilseed cake to develop new functional food products. FC has been used to develope various functional foods including beverages, bakery, extruded and fermented products. Potential food applications of FC are listed in Table 5.

Health benefits

Various health benefits are associated with plant-based diets (Lea et al., 2006). Various components of FC such as lignans, proteins, and dietary fiber are beneficial for treating cardiovascular diseases, cancer, and diabetes (Kumar et al., 2019). Various studies have reported a positive influence of flaxseed consumption on human health (Drozłowska et al., 2020a, 2020b). An equal quantity of FC and oil significantly improved the body weight and feed efficiency in broiler chickens (Lee et al., 1991). Flaxseed is known to have polysaccharides that have mucoadherent properties and therapeutic benefits (Łopusiewicz et al., 2021). Polysaccharides from FC are known to have anti-tumor effects due to their antioxidant properties (Gutiérrez et al., 2010). FC also possesses anti-microbial properties due to the presence of chitooligosaccharides against pathogens such as *Candida albicans*, *Penicillium chrysogenum*, *Fusarium graminearum*, and *Aspergillus flavus* (Pag et al., 2014). Polyphenols present in flaxseed exhibit various therapeutic effects. In addition, FC has been known to have anti-microbial, anti-inflammatory, anti-thrombotic, anti-allergenic, and antioxidant properties (Akl et al., 2020). FC also has tocopherols and these are known to show beneficial effects on human health which include anti-inflammatory qualities, neoplastic transformation prevention, artery wall protection, and LDL oxidation prevention (Mannucci et al., 2019). Lignans and phenols have outstanding biological properties as antioxidants, anti-bacterial agents, and anti-carcinogenic substances (Kajla et al., 2015; De Silva & Alcorn, 2019). This valuable laxative property is due to the high fiber content of flaxseed and its defatted cake has been known to reduce the symptoms of irritable bowel syndrome as it stimulates fecal output during constipation

Table 5 Applications of flaxseed cake in different food

Food Product	Level of incorporation of flaxseed cake (%)	Pre-treatment of flaxseed/oil extraction methods	Major findings	References
Bakery products				
Bread	0–10%	Cold-pressed oil extraction	1.A significant increase in α- linolenic acid was observed. 2. A significant increase in free fatty acid, total phenols, total flavonoids, antioxidant power and n-3 alpha-linolenic acid was observed as the content of flaxseed cake flour increased whereas an inverse relationship was observed between the n-6/n-3 ratio and percentage fortification of flaxseed cake flour.	Taglieri et al. (2020)
Gluten free bread with flaxseed cake extract (FCE)	-	-	1. A significant increase in SDG was observed in gluten-free bread from undetectable to as high as 526 µg/100 g dry matter in 100% replacement of water by FCE. 2. The texture profile analysis of bread indicated that substituting water with FCE up to 100% resulted in reduced softness and deterioration of texture due to the presence of mucilage and gums whereas 50% replacement bread was comparable to the control.	Łopusiewicz et al. (2023)
Pita bread	5–20%	-	1. Protein (40%), fibers (6%) and ash (8.63%), increased on increasing the concentration of flaxseed cake. 2. Baking process led to 100% removal of major antinutrient, namely cyanogenic glycosides. 3. More than 2-fold increase in calcium was noted. A 21%, 48% and 29% increase in phosphorus, magnesium and potassium were noted.	Khattab et al. (2012)
Toast	5–15%	Cold-pressed oil extraction	Mineral such as potassium, magnesium, phosphorus, and calcium increased by 30%, 27%, 14%, and 21% respectively in toast with 5% substitution of flaxseed cake.	Hamid Selim et al. (2019)
Extruded products				
Extruded product	7–20%	Roasted flaxseed in a microwave oven. Hand-operated oil expeller for oil extraction for cake extraction	1. Flaxseed cake incorporation from 7.5–20% increased the breaking strength. 2. Fiber in defatted flaxseed cake provides structural integrity due to protein-fiber interaction which increases breaking strength. 3. The expansion ratio and overall acceptability decreased due accumulation of protein molecules as the % defatted flaxseed cake increased.	Ganorkar et al. (2016)

Table 5 (continued)

Food Product	Level of incorporation of flaxseed cake (%)	Pre-treatment of flaxseed/oil extraction methods	Major findings	References
Flaxseed-corn puffs	0–15%	-	1. High lignan content in the final product, whereas 25–52% lignan decreased due to extrusion. 2. Higher flaxseed cake levels up to 15%, gave browner products with a hard texture.	Puff et al. (2006)
Fermented beverages				
Grass pea tempeh	5–35%	Cold-pressed oil extraction	1.The fat content was observed to be three times with 35% of flaxseed cake substitution. 2. Reduction in the percentage of saturated fatty acids mainly palmitic and stearic acid.	Stodolak et al. (2013)
Yogurt like plant milk	-	Cold pressed oil extraction	1.The increase in total phenolics and flavonoids is directly proportional to increased concentration of flaxseed cake. 2.High antioxidant property (67%) of the final product substituted with flaxseed cake.	Łopusiewicz et al. (2020)
Kefir like non-dairy beverage	-	Cold pressed oil extraction	1. Proliferation of microorganisms helped in protein synthesis. 2. Enhanced antioxidant activity of fermented beverages may be attributed to the development of phenolic compounds and bioactive peptides from the protein present in flaxseed cake.	Łopusiewicz (2019)

(Xu et al., 2012). SDG is also known to have antimicrobial effects on bacteria and fungi. In a study performed on Fischer 344 male rats, a 15% decrease in tumor formation and size was observed when FC was substituted for corn cake and flaxseed oil was substituted for corn oil by 15% each respectively (Bommareddy et al., 2009). Flaxseed is recognized for its significant positive impact on digestive health. ALA plays a positive role in decreasing gastrointestinal tract inflammation (Plissonneau et al., 2022). Omega-3 fatty acids play an important role in human growth and development because it reduces blood pressure and other inflammatory diseases (Coorey et al., 2015). The results of different studies related to the health benefits associated with the consumption of FC are summarized in Table 6.

Cardioprotective

Cardiovascular heart disease (CHD), also known as ischemic heart disease, stroke, and peripheral vascular disease, is the leading cause of death in industrialized nations (Prasad et al., 1994). Flaxseed is the richest source of lignans (secoisolariciresinol diglucoside, SDG) and has high antioxidant activity. In addition, it also helps in preventing hypercholesterolemic atherosclerosis (Prasad, 2000). In a study of 73 people suffering from type-2 diabetes type were subjected to lignan supplements for 12 weeks and the other 36 subjects started placebo. After 12 weeks a significant reduction in HbA_{1c} was observed (Pan et al., 2007). Omega-3 fatty acids show cardioprotective effects, and in addition, they protect against lipid abnormalities and atherosclerosis (Austria et al., 2008). Lignans from FC prevent complications such as atherosclerosis, hyperlipidemia, ischemia, hypertension, and cardiotoxicity (Zanwar et al., 2014). When oil is extracted from flaxseed, lignan secoisolariciresinol remains which is known to have the ability to suppress atherosclerosis. This suppression is due to antioxidant activity resulting from a decrease in the serum lipid concentration. In a study of a rabbit model, the reduction in the development of hypercholesterolemic atherosclerosis was 73% due to flaxseed lignan complex and 34% due to SDG (Prasad, 2009).

Anti-carcinogenic

Lignans are the major component contributing to the anti-carcinogenic properties of these plants. In a study, lignan showed dose and time-dependent anti-proliferative effects on acute myeloid leukemia cells (Tannous

Table 6 Animal studies showing health benefits of flaxseed oil cake

Study design	Dosage	Experimental model	Inference	Reference
Administration of equimolar amounts of SDG (secoisolariciresinol diglucoside) and SECO (secoisolariciresinol) (aglycon metabolite)	0, 3, or 6 mg SDG/kg/ d 0, 1.6, or 3.5 mg SECO/kg/d	Rat	The lignan component of flaxseed (SDG and SECO) contributes to hypocholesterolemic effects which reduced the hepatic cholesterol.	Felmlee et al. (2009)
A normal diet incorporated with SDG to compare the development of atherosclerosis on a regular diet as well as on a high-cholesterol diet	SDG20 mg/kg (0.04% SDG) for 4 months	Rabbit	Serum cholesterol-lowering or antioxidant activity of SDG or both decreased serum malondialdehyde (MDA) and serum cholesterol which is responsible to reduce oxidative stress. No progression in atherosclerosis which is directly proportional to the time for which rabbits were fed with SDG.	Prasad (2008)
Supplementation of flaxseed- derived lignan on glycemic control, lipid profiles, and insulin sensitivity in type 2 diabetic patients	360 mg/day for 12 weeks	Human	Flaxseed lignan may be responsible for decrease in glycemic index. Fiber, alpha-linolenic acid and SDG may be responsible Cholesterol-lowering property	Pan et al. (2007)
Role of flaxseed cake in the diet as a source of omega-3 fatty acid	100 g/kg for 3 weeks	Broiler chicken	Significant improvement in fatty acid profile, lipid metabolism, and health indices of meat. A decrease in the percentages of myristic acid, palmitic acid, stearic acid, and SFA. Quicker gastrointestinal absorption due to higher PUFA in flaxseed.	Kumar et al. (2019)
Administrationof soaked flaxseed cake	0,6 and 12% for 10 weeks	Hens	Enhanced immune function Increase in n-3 sources in diet estradiol circulation gets affected which reduces the digestibility of fat due to which vLDL (very low-density lipids) decreased.	Attia et al. (2022)
Five graded levels of flaxseed cake were incorporated into the diets of chicken. Carcass characteristics and pectoral muscle fillets were evaluated from 21 to 39 days.	0–80 g/kg	Broiler chicken	Significant positive correlations in pectoral muscle major (PMJ) fillet of male birds between dietary flaxseed cake and CWLP (cooking water loss percentage) were observed. Growth performance was negatively affected by the increased concentration of flaxseed cake. Reduced digestibility of feed and protein decreased the growth performance. .	Shafey et al. (2014)

et al., 2020). The early stages of carcinogenesis are inhibited by flaxseed, which is a rich source of the mammalian lignan precursors secoisolariciresinol-diglucoside (SDG) and alpha-linolenic acid (ALA). The initiation (before carcinogen), promotion (after carcinogen), and progression (visible tumors) stages of carcinogenesis have all been the subject of animal model research using dimethylbenzanthracene (DMBA) and a rat mammary cancer model. DMBA was used as the carcinogen, and it was discovered that 1.5 mg of SDG supplied daily at the beginning stage (1 week after DMBA for 20 weeks) caused 46% fewer tumors per group and 37% fewer tumor multiplicities (Thompson et al., 1996). Secoisolariciresinol diglucoside (SDG), which is present at the highest concentration in flaxseed, and its cake has been known to have various health benefits. The various properties of SDG are anticancer, including reducing the growth and proliferation of cancerous cells (Wang et al., 2005).

Anti-diabetic

Diabetes mellitus, commonly known as diabetes is a chronic metabolic disorder caused by increased blood sugar levels. A study conducted on diabetes-induced rats revealed a 64.62% decrease in glucose levels, 48 h after SDG intake (Moree et al., 2013). In another study where BB (BioBreeding) rats were fed SDG which reduced the development of diabetes by 71%, the onset of diabetes was moderately delayed (Prasad, 2000). In a study, 60 individuals were fed with flaxseed gum incorporated *Chapatis.* A decrease in fasting blood sugar and a decrease in cholesterol by 11.6% and 10.4%, respectively was observed. Flaxseed gum is a potential ingredient for improving the blood profile of people suffering from type 2 diabetes (Thakur et al., 2009).

Conclusion

The purpose of this review was to summarize and highlight the importance of the valorization of FC. In conclusion, oilseed cake is a valuable by-product of the oil industry and includes a variety of nutrients, making it an economically viable ingredient for use in numerous foods to improve their nutritional profile. Nutritional analysis of FC revealed that it is rich in proteins, polyphenols, lignans and antioxidants which are essential for human nutrition. In addition to having a rich nutritional profile, FC also possesses several functional properties, including the ability to bind both water and oil (water and oil holding capacity) as well to swell and emulsify (swelling capacity and emulsification). Various treatments such as fermentation can improve these characteristics. Several antinutrient factors are found therefore cake needs to undergo several pretreatments. The intake of FC can be followed by various processing techniques such as boiling, autoclaving, microwaving, fermentation and others to remove antinutrient factors such as cyanogenic glucosides, phytic acid, and tannins which hinder the absorption of essential nutrients. The applications of FC in food products are diverse and promising because it acts as a plant-based protein source. It can act as a potential functional ingredient in baked goods, cereals, snacks, and beverages enhancing its nutritional properties and providing desirable textural properties. Additionally, FC which is rich in dietary fibers helps to develop fiber-rich food. The health benefits of FC are multifaceted. Lignans and antioxidants which are found in abundancee in FC help in the management of several chronic diseases such as diabetes and cancer. By including FC in the diet, the consumption of plant-based proteins increases, which would be a positive step toward human health, the environment, and sustainability.

Further research and development in this area is required to make flaxseed oil cake more palatable. Additionally, research on treating it in such a way that cake is devoid of antinutrients and has an extended shelf life is needed.

Challenges and future trends

A by-product of the extraction of oil from flaxseed is FC. Proteins, fibers, and several other components make up its profile. Due to its composition and processing needs, FC can create some difficulties when used as a culinary ingredient. The utilization of FC presents a confluence of intricate challenges. Despite being a by-product of extraction, it is an amalgamation of residual PUFAs, proteinaceous components, fibrous matter and other bioactive substances. However, its incorporation is a challenge. Due to the presence of PUFA, their shelf life and stability are limited. Other obstacles that surround the incorporation of FC into the culinary landscape include minimizing allergenic potential, dealing with regulatory frameworks, and improving the distinctive sensory qualities that it imparts to different food products, accentuating the complexity of the process.

As the global food industry is growing, it is inclining more towards sustainable approaches to combat the requirements. Overcoming the challenges of innovation and sustainability FC has emerged as a promising raw material that may fulfill protein requirements. A spike in the demand of plant-based protein has been seen, which aligns seamlessly with FC and its ability to satisfy the nutritional profile. FC has a compelling future in the culinary world due to the convergence of health-conscious consumer preferences, sustainable food practices, and dynamic adaptability.

Abbreviations

SFAs	Saturated fatty acids
MUFAs	Monounsaturated fatty acids
PUFAs	Polyunsaturated fatty acids

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43014-024-00294-w.

Supplementary Material 1.

Supplementary Material 2.

Acknowledgements
The authors extend their appreciation to the National Institute of Food Technology Entrepreneurship and Management, located in Kundli, Sonipat, Haryana, for granting access to its infrastructure and library resources. NIFTEM communication number- NIFTEM-P-2024-38. Additionally, the authors express gratitude to the funding agency UGC for their financial support.

Authors' contributions
Conceptualization: B.T., R.C., and MC.; methodology: B.T., R.C. and N.K.T.; validation: B.T., R.C. and A.A.; data curation: B.T.; M.C.; S.H.; A.D.; P.K.S.; writing- original draft preparation: B.T.; writing- review and editing: B.T., R.C., M.C.; S.H.; A.D.; P.K.S. and S.C.; visualization: B.T., and R.C; supervision: B.T.; R.C., N.K.T.; and A.A. All authors have read and approved the final manuscript.

Funding
Not applicable.

Data availability
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Department of Food Science and Technology, National Institute of Food Technology Entrepreneurship and Management, Sonipat, Haryana 131028, India. [2]Department of Interdisciplinary Sciences, National Institute of Food Technology Entrepreneurship and Management, Sonipat, Haryana, India. [3]Department of Food and Nutrition & Food Technology, Institute of Home Economics, University of Delhi, Delhi, India.

Received: 11 March 2024 Accepted: 23 July 2024
Published online: 10 February 2025

References

Akl, E. M., Mohamed, S. S., Hashem, A. I., & Taha, F. S. (2020). Biological activities of phenolic compounds extracted from flaxseed meal. *Bulletin of the National Research Centre*, *44*(1). https://doi.org/10.1186/s42269-020-0280-x

Ancuța, P., & Sonia, A. (2020). Oil press-cakes and meals valorization through circular economy approaches: A review. *Applied Sciences (Switzerland)*, *10*(21), 1–31. https://doi.org/10.3390/app10217432

C.-F. Wu , X.-M. Xu , S.-H. Huang , M.-C. Deng , A.-J. Feng , J. Peng , J.-P. Yuan & J.-H. Wang (2012) An efficient fermentation method for the degradation of cyanogenic glycosides in flaxseed, Food Additives & Contaminants: Part A, 29:7, 1085-1091. https://doi.org/10.1080/19440049.2012.680202

Attia, Y. A., Al-harthi, M. A., Sagan, A. A. A., Abdulsalam, N. M., Hussein, E. O., & Olal, M. J. (2022). Egg Production and Quality, lipid metabolites, antioxidant status and Immune Response of Laying Hens Fed diets with various levels of soaked flax seed meal. *Agriculture*, *12*(9), 1402.

Austria, J. A., Richard, M. N., Chahine, M. N., Edel, A. L., Dupasquier, C. M. C., Pierce, G. N., & Malcolmson, L. J. (2008). Bioavailability of alpha-linolenic acid in subjects after ingestion of three different forms of Flaxseed. *Journal of the American College of Nutrition*, *27*(2), 214–221. https://doi.org/10.1080/07315724.2008.10719693

Bacala, R., & Barthet, V. (2007). Development of extraction and gas chromatography analytical methodology for cyanogenic glycosides in flaxseed (Linum usitatissimum). *Journal of AOAC International*, *90*(1), 153–161. https://doi.org/10.1093/jaoac/90.1.153

Bárta, J., Bártová, V., Jarošová, M., Švajner, J., Smetana, P., Kadlec, J., Filip, V., Kyselka, J., Berčíková, M., Zdráhal, Z., Bjelková, M., & Kozak, M. (2021). Oilseed cake flour composition, functional properties and antioxidant potential as effects of sieving and species differences. *Foods*, *10*(11), 1–17. https://doi.org/10.3390/foods10112766

Barthet, V. J., Klensporf-Pawlik, D., & Przybylski, R. (2014). Antioxidant activity of flaxseed meal components. *Canadian Journal of Plant Science*, *94*(3), 593–602. https://doi.org/10.4141/CJPS2013-018

Basiri, S., Haidary, N., Shekarforoush, S. S., & Niakousari, M. (2018). Flaxseed mucilage: A natural stabilizer in stirred yogurt. *Carbohydrate Polymers*, *187*(January), 59–65. https://doi.org/10.1016/j.carbpol.2018.01.049

Batal, A. B., Dale, N. M., & Saha, U. K. (2010). Mineral composition of corn and soybean meal. *Journal of Applied Poultry Research*, *19*(4), 361–364. https://doi.org/10.3382/japr.2010-00206

Bekhit, A. E. D., Tian, X., Carne, A., & Ha, M. (2013). Effect of Kiwifruit and flaxseed flours on the texture of salami. In Proceedings of the International Congress of Meat Science and Technology, Izmir, Turkey. Chicago, 1–4.

Bekhit, A. E. D. A., Shavandi, A., Jodjaja, T., Birch, J., Teh, S., Ahmed, M., Al-Juhaimi, I. A., Saeedi, F. Y., P., & Bekhit, A. A. (2018). Flaxseed: Composition, detoxification, utilization, and opportunities. *Biocatalysis and Agricultural Biotechnology*, *13*(December 2017), 129–152. https://doi.org/10.1016/j.bcab.2017.11.017

Bommareddy, A., Zhang, X., Schrader, D., Kaushik, R. S., Zeman, D., Matthees, D. P., & Dwivedi, C. (2009). Effects of dietary flaxseed on intestinal tumorigenesis in Apc Min mouse. *Nutrition and Cancer*, *61*(2), 276–283. https://doi.org/10.1080/01635580802419764

Bongartz, U., Hochmann, U., Grube, B., Uebelhack, R., Alt, F., Erlenbeck, C., Peng, L. V., Chong, P. W., & De Costa, P. (2022). Flaxseed Mucilage (IQP-LU-104) reduces body weight in overweight and moderately obese individuals in a 12-week, Three-Arm, Double-Blind, randomized, and placebo-controlled clinical study. *Obesity Facts*, *15*(3), 395–404. https://doi.org/10.1159/000522082

Borrello, M., Caracciolo, F., Lombardi, A., Pascucci, S., & Cembalo, L. (2017). Consumers' perspective on circular economy strategy for reducing food waste. *Sustainability (Switzerland)*, *9*(1). https://doi.org/10.3390/su9010141

Brodowska, K., Catthoor, R., Brodowska, A. J., Symonowicz, M., & Ska, E. B. L. (2014). A comparison of antioxidant properties of extracts from defatted and non-defatted flax (Linum usitatissimum) seeds. *Albanian Journal of Agricultural Science*, *13*(2), 16–23.

Chemistry, C., Andreea, L. P., Radu, D. G., Popa, I. M., & Cecilia, S. (2014). Flaxseed cake – a sustainable source of antioxidant and antibacterial extracts. *Cellulose Chemistry and Technology*, *48*(3–4), 265–273.

Coorey, R., Novinda, A., Williams, H., & Jayasena, V. (2015). Omega-3 fatty Acid Profile of Eggs from Laying Hens Fed diets supplemented with Chia, Fish Oil, and Flaxseed. *Journal of Food Science*, *80*(1), S180–S187. https://doi.org/10.1111/1750-3841.12735

Damayanti, A., & Sjofjan, O. (2022). Effect of steaming on nutrients content of. *3*(2), 95–102. https://doi.org/10.30997/ijar.v3i2.199

De Silva, S. F., & Alcorn, J. (2019). Flaxseed lignans as important dietary polyphenols for cancer prevention and treatment: Chemistry, pharmacokinetics, and molecular targets. *Pharmaceuticals*, *12*(2), 21–38. https://doi.org/10.3390/ph12020068

Drozłowska, E., Bartkowiak, A., & Łopusiewicz, Ł. (2020a). Characterization of flaxseed oil bimodal emulsions prepared with flaxseed oil cake extract applied as a natural emulsifying agent. *Polymers*, *12*(10), 1–18. https://doi.org/10.3390/polym12102207

Drozłowska, E., Łopusiewicz, Ł., Mężyńska, M., & Bartkowiak, A. (2020b). Valorization of flaxseed oil cake residual from cold-press oil production as a material for preparation of spray-dried functional powders for food applications as emulsion stabilizers. *Biomolecules*, *10*(1). https://doi.org/10.3390/biom10010153

Dudziak, A., Stoma, M., & Derkacz, A. J. (2022). Circular economy in the context of food losses and Waste. *Sustainability (Switzerland)*, *14*(16), 1–21. https://doi.org/10.3390/su141610116

Dusica, I., Bojana, K., Tea, B., Radmilo, C., Djuro, V., Jovanka, L., & Slavica, S. (2012). Effect of microwave heating on content of cyanogenic glycosides in linseed. *Ratarstvo i Povrtarstvo*, *49*(1), 63–68. https://doi.org/10.5937/ratpov49-1173

Esposito, B., Sessa, M. R., Sica, D., & Malandrino, O. (2020). Towards circular economy in the agri-food sector. A systematic literature review. *Sustainability (Switzerland)*, *12*(18). https://doi.org/10.3390/SU12187401

Farag, S. E., Salem, R., & Gamal, H. (2012). Evaluation of Chemical composition and nutrition value of two varieties of flaxseed meal and oil. J. Food Ind. Nutr. Sci, 2, 197-208.

Felmlee, M. A., Woo, G., Simko, E., Krol, E. S., Muir, A. D., & Alcorn, J. (2009). Effects of the flaxseed lignans secoisolariciresinol diglucoside and its aglycone on serum and hepatic lipids in hyperlipidaemic rats. *British Journal of Nutrition, 102*(3), 361–369. https://doi.org/10.1017/S0007114508207488

Feng, D., Shen, Y., & Chavez, E. R. (2003). Effectiveness of different processing methods in reducing hydrogen cyanide content of flaxseed. *Journal of the Science of Food and Agriculture*, *83*(8), 836–841. https://doi.org/10.1002/jsfa.1412

Gallardo, M. A., Milisich, H. J., Drago, S. R., & González, R. J. (2014). Effect of cultivars and planting date on yield, oil content, and fatty acid profile of flax varieties (Linum usitatissimum L.). *International Journal of Agronomy, 2014*(1), 150570.

Ganorkar, P. M., Patel, J. M., Shah, V., & Rangrej, V. V. (2016). Defatted flaxseed meal incorporated corn-rice flour blend based extruded product by response surface methodology. *Journal of Food Science and Technology*, *53*(April), 1867–1877. https://doi.org/10.1007/s13197-015-2134-3

Goyal, A., Sharma, V., Upadhyay, N., Gill, S., & Sihag, M. (2014). Flax and flaxseed oil: An ancient medicine & modern functional food. *Journal of Food Science and Technology*, *51*(9), 1633–1653. https://doi.org/10.1007/s13197-013-1247-9

Gupta, A., Sharma, R., Sharma, S., & Singh, B. (2018). Oilseed as potential functional food Ingredient. Trends & Prospects in Food Technology, Processing and Preservation, 1st ed.; Prodyut Kumar, P., Mahawar, MK, Abobatta, W., Panja, P., Eds, 25-58.

Gutiérrez, C., Rubilar, M., Jara, C., Verdugo, M., Sineiro, J., & Shene, C. (2010). Flaxseed and flaxseed cake as a source of compounds for food industry. *Journal of Soil Science and Plant Nutrition*, *10*(4), 454–463. https://doi.org/10.4067/S0718-95162010000200006

Gutte, K. B., Sahoo, A. K., & Ranveer, R. C. (2015). Effect of ultrasonic treatment on extraction and fatty acid profile of flaxseed oil. *OCL - Oilseeds and Fats*, *22*(6). https://doi.org/10.1051/ocl/2015038

Hady, M. A. M., A.-E.-, & Elsorady, M. E. I. (2020). Effect of sprouting on Chemical, fatty acid composition, antioxidants and antinutrients of flaxseeds. *Asian Food Science Journal*, 40–51. https://doi.org/10.9734/afsj/2020/v19i130231

Hamid Selim, K. A., Mostafa, K., Tawab Mahmoud, M., A. A.-, & Afifi Ali, R. (2019). Effect of bioactive compounds of defatted flaxseed meal on rheological and sensorial properties of toast and cake. *SDRP Journal of Food Science & Technology*, *4*(4), 707–719. https://doi.org/10.25177/jfst.4.4.ra.479

Hao, X. Y., Yu, S. C., Mu, C. T., Wu, X. D., Zhang, C. X., Zhao, J. X., & Zhang, J. X. (2020). Replacing soybean meal with flax seed meal: Effects on nutrient digestibility, rumen microbial protein synthesis and growth performance in sheep. *Animal*, *14*(9), 1841–1848. https://doi.org/10.1017/S1751731120000397

Huang, C., Tse, T. J., Purdy, S. K., Chicilo, F., Shen, J., Meda, V., & Reaney, M. J. T. (2023). Depletion of cyanogenic glycosides in whole flaxseed via Lactobacillaceae fermentation. *Food Chemistry, 403*(April 2022), 134441. https://doi.org/10.1016/j.foodchem.2022.134441

Ibáñez, M. A., de Blas, C., Cámara, L., & Mateos, G. G. (2020). Chemical composition, protein quality and nutritive value of commercial soybean meals produced from beans from different countries: A meta-analytical study. *Animal Feed Science and Technology*, *267*(April), 114531. https://doi.org/10.1016/j.anifeedsci.2020.114531

Ibrügger, S., Kristensen, M., Mikkelsen, M. S., & Astrup, A. (2012). Flaxseed dietary fiber supplements for suppression of appetite and food intake. *Appetite*, *58*(2), 490–495. https://doi.org/10.1016/j.appet.2011.12.024

Imran, M., Anjum, F. M., Butt, M. S., Siddiq, M., & Sheikh, M. A. (2013). Reduction of cyanogenic compounds in flaxseed (Linum usitatissimum L.) meal using thermal treatment. *International Journal of Food Properties*, *16*(8), 1809–1818. https://doi.org/10.1080/10942912.2011.608914

Imran, M., Anjum, F. M., Butt, M. S., & Sheikh, M. A. (2014). Influence of Extrusion Processing on Tannin reduction and oil loss in Flaxseed (Linum Usitatissimum L.) Meal. *Journal of Food Processing and Preservation*, *38*(1), 622–629. https://doi.org/10.1111/jfpp.12012

Kajla, P. S., Sharma, A., & Sood, D. R. (2017). Effect of germination on proximate principles, minerals and antinutrients of flaxseeds. *Asian Journal of Dairy and Food Research*, *36*(01). https://doi.org/10.18805/ajdfr.v36i01.7459

Kajla, P., Sharma, A., & Sood, D. R. (2015). Flaxseed—a potential functional food source. *Journal of Food Science and Technology*, *52*(4), 1857–1871. https://doi.org/10.1007/s13197-014-1293-y

Kaur, M., Kaur, R., & Gill, B. S. (2017). Mineral and amino acid contents of different flaxseed cultivars in relation to its selected functional properties. *Journal of Food Measurement and Characterization*, *11*(2), 500–511. https://doi.org/10.1007/s11694-016-9417-x

Kaur, M., Singh, B., Kaur, A., & Singh, N. (2021). Proximate, mineral, amino acid composition, phenolic profile, antioxidant and functional properties of oilseed cakes. *International Journal of Food Science and Technology*, *56*(12), 6732–6741. https://doi.org/10.1111/ijfs.15386

Khare, B., Sangwan, V., & Rani, V. (2021). Influence of sprouting on proximate composition, dietary fiber, nutrient availability, antinutrient, and antioxidant activity of flaxseed varieties. *Journal of Food Processing and Preservation*, *45*(4), 1–8. https://doi.org/10.1111/jfpp.15344

Khattab, R. Y., & Arntfield, S. D. (2009). Functional properties of raw and processed canola meal. *Lwt*, *42*(6), 1119–1124. https://doi.org/10.1016/j.lwt.2009.02.009

Khattab, R., Zeitoun, M., & Barbary, O. M. (2012). Evaluation of pita bread fortified with defatted flaxseed flour. *Current Nutrition & Food Science, 8*(2), 91–101.

Kolláthová, R., Varga, B., Ivanišová, E., Bíro, D., Rolinec, M., Juráček, M., Šimko, M., & Gálik, B. (2019). Mineral Profile Analysis of oilseeds and their By-Products as feeding sources for Animal Nutrition. *Slovak J Anim Sci*, *52*(1), 9–15.

Kristensen, M., Jensen, M. G., Aarestrup, J., Petersen, K. E. N., Søndergaard, L., Mikkelsen, M. S., & Astrup, A. (2012). Flaxseed dietary fibers lower cholesterol and increase fecal fat excretion, but magnitude of effect depend on food type. *Nutrition and Metabolism*, *9*, 1–8. https://doi.org/10.1186/1743-7075-9-8

Kumar, F., Tyagi, P. K., Akbar, N., Pramod, M., & Kapil, K. T. (2019). Role of flaxseed meal feeding for different durations in the lipid deposition and meat quality in broiler chickens. *Journal of the American Oil Chemists' Society, 96*(3), 261–271. https://doi.org/10.1002/aocs.12190

Lea, E. J., Crawford, D., & Worsley, A. (2006). Public views of the benefits and barriers to the consumption of a plant-based diet. *European Journal of Clinical Nutrition*, *60*(7), 828–837. https://doi.org/10.1038/sj.ejcn.1602387

Lee, K. H., Olomu, J. M., & Sim, J. S. (1991). Live performance, carcass yield, protein and energy retention of broiler chickens fed canola and flax full-fat seeds and the restored mixtures of meal and oil. *Canadian Journal of Animal Science*, *71*(3), 897–903. https://doi.org/10.4141/cjas91-105

Łopusiewicz, Ł, Drozłowska, E., Siedlecka, P., Bartkowiak, A., & Sienkiewicz, M. Z. (2019). Development, characterization, and bioactivity of non-dairy kefir-like fermented beverage based on flaxseed oil cake. *Foods, 8*(11), 544.

Łopusiewicz, Ł., Drozłowska, E., Siedlecka, P., Mężyńska, M., & Bartkowiak, A. (2020). Preparation and characterization of novel flaxseed oil cake yogurt-like plant milk fortified with inulin. *Journal of Food and Nutrition Research*, *59*(1), 61–70.

Łopusiewicz, Ł., Kowalczewski, P. Ł., Baranowska, H. M., Masewicz, Ł., Amarowicz, R., & Krupa-Kozak, U. (2023). Effect of Flaxseed Oil cake extract on the Microbial Quality, texture and Shelf Life of Gluten-Free Bread. *Foods*, *12*(3), 1–15. https://doi.org/10.3390/foods12030595

Łopusiewicz, Ł., Bogusławska-Wąs, E., Drozłowska, E., Trocer, P., Dłubała, A., Mazurkiewicz-Zapałowicz, K., & Bartkowiak, A. (2021). The application of spray-dried and reconstituted flaxseed oil cake extract as encapsulating

material and carrier for probiotic lacticaseibacillus rhamnosus Gg. *Materials*, *14*(18). https://doi.org/10.3390/ma14185324

Mannucci, A., Castagna, A., Santin, M., Serra, A., Mele, M., & Ranieri, A. (2019). Quality of flaxseed oil cake under different storage conditions. *Lwt*, *104*(January), 84–90. https://doi.org/10.1016/j.lwt.2019.01.035

Marczak, L. D. F. (2014). Evaluation of the Phenolic Content and Antioxidant Activity of Different Seed and Nut Cakes from the Edible Oil Industry. 1773–1782. https://doi.org/10.1007/s11746-014-2514-2

Mohamed, R. S., Fouda, K., & Akl, E. M. (2020). Hepatorenal protective effect of flaxseed protein isolate incorporated in lemon juice against lead toxicity in rats. *Toxicology Reports*, *7*(March), 30–35. https://doi.org/10.1016/j.toxrep.2019.12.001

Mohanan, A., Nickerson, M. T., & Ghosh, S. (2018). Oxidative stability of flaxseed oil: Effect of hydrophilic, hydrophobic and intermediate polarity antioxidants. *Food Chemistry*, *266*(January), 524–533. https://doi.org/10.1016/j.foodchem.2018.05.117

Moree, S. S., Kavishankar, G. B., & Rajesha, J. (2013). Antidiabetic effect of secoisolariciresinol diglucoside in streptozotocin-induced diabetic rats. *Phytomedicine*, *20*(3–4), 237–245. https://doi.org/10.1016/j.phymed.2012.11.011

Mueller, K., Eisner, P., Yoshie-stark, Y., Nakada, R., & Kirchhoff, E. (2010). Functional properties and chemical composition of fractionated brown and yellow linseed meal (Linum usitatissimum L). *Journal of Food Engineering*, *98*(4), 453–460. https://doi.org/10.1016/j.jfoodeng.2010.01.028

Mukhopadhyay, N., Sarkar, S., & Bandyopadhyay, S. (2007). Effect of extrusion cooking on anti-nutritional factor tannin in linseed (Linum usitatissimum) meal. *International Journal of Food Sciences and Nutrition*, *58*(8), 588–594. https://doi.org/10.1080/09637480701343952

Ogunronbi, O., Jooste, P. J., Abu, J. O., & Van Der Merwe, B. (2011). Chemical Composition, Storage Stability and Effect of Cold-pressed Flaxseed Oil cake inclusion on Bread Quality. *Journal of Food Processing and Preservation*, *35*(1), 64–79. https://doi.org/10.1111/j.1745-4549.2009.00452.x

Oomah, B. D., Mazza, G., & Kenaschuk, E. O. (1996a). Flavonoid content of flaxseed. *Influence of cultivar and environment. Euphytica, 90*(2), 163–167. https://doi.org/10.1007/bf00023854

Oomah, B. D., Kenaschuk, E. O., & Mazza, G. (1996b). Phytic acid content of flaxseed as influenced by cultivar, growing season, and location. *Journal of Agricultural and Food Chemistry, 44*(9), 2663–2666.

Oomah, B. D. (2020). Flaxseed By-products. *Food Wastes and By-products*, *January 2020*, 267–289. https://doi.org/10.1002/9781119534167.ch9

Özkaynak Kanmaz, E. (2017). The Effect of roasting process on fatty acid composition and phenolic content of whole flaxseed, Flaxseed Flour and Flaxseed Meal Flour. *Gida / the Journal of Food*, *42*(4), 382–391. https://doi.org/10.15237/gida.gd16081

Pag, A. I., Radu, D. G., Drăgănescu, D., Popa, M. I., & Sîrghie, C. (2014). Flaxseed cake - A sustainable source of antioxidant and antibacterial extracts. *Cellulose Chemistry and Technology*, *48*(3–4), 265–273.

Pan, A., Sun, J., Chen, Y., Ye, X., Li, H., Yu, Z., Wang, Y., Gu, W., Zhang, X., & Chen, X. (2007). Effects of a flaxseed-derived Lignan supplement in type 2 Diabetic patients: A Randomized, Double-Blind. *Cross- Over Trial*, *11*, 1–7. https://doi.org/10.1371/journal.pone.0001148

Plissonneau, C., Sivignon, A., Chassaing, B., Capel, F., Martin, V., Etienne, M., Wawrzyniak, I., Chausse, P., Dutheil, F., Mairesse, G., Chesneau, G., Boisseau, N., & Barnich, N. (2022). Beneficial effects of Linseed Supplementation on Gut Mucosa-Associated Microbiota in a physically active mouse model of Crohn's Disease. *International Journal of Molecular Sciences*, *23*(11). https://doi.org/10.3390/ijms23115891

Poreda, A. (2017). Solid-state fermentation reduces Phytic Acid Level, improves the pro fi Le of Myo- Inositol Phosphates and enhances the availability of selected minerals. *Flaxseed Oil Cake*, *55*(3), 413–419.

Prasad, K. (1997). Hydroxyl radical-scavenging property of secoisolariciresinol diglucoside (SDG) isolated from flax-seed. *Molecular and Cellular Biochemistry*, *168*(1–2), 117–123. https://doi.org/10.1023/A:1006847310741

Prasad, K., Kalra, J., & Lee, P. (1994). Oxygen free radicals as a mechanism of hypercholesterolemic atherosclerosis: Effects of probucol. *International Journal of Angiology*, *3*(1), 100–112. https://doi.org/10.1055/s-0031-1275911

Prasad, K. (2008). *Regression of hypercholesterolemic atherosclerosis in rabbits by secoisolariciresinol diglucoside isolated from flaxseed*. *197*, 34–42. https://doi.org/10.1016/j.atherosclerosis.2007.07.043

Prasad, K. (2009). Flaxseed and cardiovascular health. *Journal of Cardiovascular Pharmacology*, *54*(5), 369–377. https://doi.org/10.1097/FJC.0b013e3181af04e5

Puff, F., Wu, W., Huff, H. E., & Hsieh, F. (2006). Processing and properties of extruded flaxseed-corn puff. *Journal of food processing and preservation, 31*(2), 211–226.

Quezada, N., & Cherian, G. (2012). Lipid characterization and antioxidant status of the seeds and meals of Camelina sativa and flax. *European Journal of Lipid Science and Technology*, *114*(8), 974–982. https://doi.org/10.1002/ejlt.201100298

Rani, R., & Badwaik, L. S. (2021). Functional Properties of Oilseed Cakes and Defatted Meals of Mustard, Soybean and Flaxseed. *Waste and Biomass Valorization*, *0123456789*. https://doi.org/10.1007/s12649-021-01407-z

Rudra, A., Arvind, I., & Mehra, R. (2021). Polyphenols: Types, sources and therapeutic applications. *International Journal of Home Science*, *7*(3), 69–75. https://doi.org/10.22271/23957476.2021.v7.i3a.1182

Russo, R., & Reggiani, R. (2014). Variation in the content of cyanogenic glycosides in Flaxseed Meal from twenty-one varieties. *Food and Nutrition Sciences*, *05*(15), 1456–1462. https://doi.org/10.4236/fns.2014.515159

Russo, R., & Reggiani, R. (2016). Evaluation of protein and antinutritional compounds content in meal from seven flax varieties. *Journal of Global Agriculture and Ecology*, *6*(3), 182–188. www.camfeed.it/en

Safdar, B., Pang, Z., Liu, X., Rashid, M. T., & Jatoi, M. A. (2020). Structural and functional properties of raw and defatted flaxseed flour and degradation of cynogenic contents using different processing methods. *Journal of Food Process Engineering*, *43*(6), 1–13. https://doi.org/10.1111/jfpe.13406

Sanmartin C, Taglieri I, Venturi F, Macaluso M, Zinnai A, Tavarini S, Botto A, Serra A, Conte G, Flamini G, Angelini LG (2020) Flaxseed cake as a tool for the improvement of nutraceutical and sensorial features of sourdough bread. Foods 9(2), 204

Shafey, T. M., Mahmoud, A. H., Hussein, E. S., & Suliman, G. (2014). The performance and characteristics of carcass and breast meat of broiler chickens fed diets containing flaxseed meal. *Italian Journal of Animal Science*, *13*(4), 752–758. https://doi.org/10.4081/ijas.2014.3514

Singh, K. K., Mridula, D., Rehal, J., & Barnwal, P. (2011). Flaxseed: A potential source of food, feed and fiber. *Critical Reviews in Food Science and Nutrition*, *51*(3), 210–222. https://doi.org/10.1080/10408390903537241

Singh, R., Langyan, S., Sangwan, S., Rohtagi, B., Khandelwal, A., & Shrivastava, M. (2022). Protein for human consumption from oilseed cakes: A review. *Frontiers in Sustainable Food Systems*, *6*(March), 1–12. https://doi.org/10.3389/fsufs.2022.856401

Stodolak, B., Starzyńska-Janiszewska, A., & Mickowska, B. (2013). Effect of flaxseed oil-cake addition on the nutritional value of grass pea tempeh. *Food Science and Technology Research*, *19*(6), 1107–1114. https://doi.org/10.3136/fstr.19.1107

Stodolak, B., Starzyńska-Janiszewska, A., Wywrocka-Gurgul, A., & Wikiera, A. (2017). Solid-state fermented flaxseed oil cake of improved antioxidant capacity as potential Food Additive. *Journal of Food Processing and Preservation*, *41*(2), 1–9. https://doi.org/10.1111/jfpp.12855

Sun, X., Wang, Y., Li, H., Zhou, J., Han, J., & Wei, C. (2021). Changes in the volatile profile, fatty acid composition and oxidative stability of flaxseed oil during heating at different temperatures. *Lwt*, *151*(April), 112137. https://doi.org/10.1016/j.lwt.2021.112137

Tachie, C., Nwachukwu, I. D., & Aryee, A. N. A. (2023). Trends and innovations in the formulation of plant-based foods. *Food Production Processing and Nutrition*, *5*(1). https://doi.org/10.1186/s43014-023-00129-0

Taglieri, I., Sanmartin, C., Venturi, F., Macaluso, M., Zinnai, A., Tavarini, S., Serra, A., Conte, G., Flamini, G., & Angelini, L. G. (2020). Effect of the leavening agent on the compositional and sensorial characteristics of bread fortified with flaxseed cake. *Applied Sciences (Switzerland)*, *10*(15). https://doi.org/10.3390/APP10155235

Tamasgen, N., Urge, M., Girma, M., & Nurfeta, A. (2021). Effect of dietary replacement of soybean meal with linseed meal on feed intake, growth performance and carcass quality of broilers. *Heliyon*, *7*(11), e08297. https://doi.org/10.1016/j.heliyon.2021.e08297

Tamasiga, P., Miri, T., Onyeaka, H., & Hart, A. (2022). Food Waste and Circular Economy: Challenges and opportunities. *Sustainability (Switzerland)*, *14*(16). https://doi.org/10.3390/su14169896

Tannous, S., Haykal, T., Dhaini, J., Hodroj, M. H., & Rizk, S. (2020). The anticancer effect of flaxseed lignan derivatives on different acute myeloid leukemia cancer cells. *Biomedicine and Pharmacotherapy*, *132*, 110884. https://doi.org/10.1016/j.biopha.2020.110884

Tavarini, S., De Leo, M., Matteo, R., Lazzeri, L., Braca, A., & Angelini, L. G. (2021). Flaxseed and camelina meals as potential sources of health-beneficial compounds. *Plants*, *10*(1), 1–17. https://doi.org/10.3390/plants10010156

Teh, S. S., & Birch, E. J. (2014a). Effect of ultrasonic treatment on the polyphenol content and antioxidant capacity of extract from defatted hemp, flax and canola seed cakes. *Ultrasonics Sonochemistry, 21*(1), 346–353. https://doi.org/10.1016/j.ultsonch.2013.08.002

Teh, S., Bekhit, A. E., & Birch, J. (2014b). *Effect of Solvents*. *li*, 67–80. https://doi.org/10.3390/antiox3010067

Terpinc, P., Čeh, B., Ulrih, N. P., & Abramovič, H. (2012). Studies of the correlation between antioxidant properties and the total phenolic content of different oil cake extracts. *Industrial Crops and Products*, *39*(1), 210–217. https://doi.org/10.1016/j.indcrop.2012.02.023

Thakur, G., Mitra, A., Pal, K., & Rousseau, D. (2009). Effect of flaxseed gum on reduction of blood glucose and cholesterol in type 2 diabetic patients. *Journal of Food Sciences and Nutrition, 60*(SUPPL. 6), 126–136. https://doi.org/10.1080/09637480903022735

Thompson, L. U., Rickard, S. E., Orcheson, L. J., & Seidl, M. M. (1996). Flaxseed and its lignan and oil components reduce mammary tumor growth at a late stage of carcinogenesis. *Carcinogenesis*, *17*(6), 1373–1376. https://doi.org/10.1093/carcin/17.6.1373

Tirgar, M., Silcock, P., Carne, A., & Birch, E. J. (2017). Effect of extraction method on functional properties of flaxseed protein concentrates. *Food Chemistry*, *215*, 417–424. https://doi.org/10.1016/j.foodchem.2016.08.002

Vilariño, M. V., Franco, C., & Quarrington, C. (2017). Food loss and waste reduction as an integral part of a circular economy. *Frontiers in Environmental Science*, *5*(MAY). https://doi.org/10.3389/fenvs.2017.00021

Wanasundara, J. P. D., & Shahidi, F. (1994). Functional properties and amino-acid composition of solvent-extracted flaxseed meals. *Food Chemistry*, *49*(1), 45–51. https://doi.org/10.1016/0308-8146(94)90231-3

Wanasundara, P. K. J. P. D., Amarowicz, R., Kara, M. T., & Shahidi, F. (1993). Removal of cyanogenic glycosides of flaxseed meal. *Food Chemistry*, *48*(3), 263–266. https://doi.org/10.1016/0308-8146(93)90138-6

Wanasundara, P. K. J. P. D., Shahidi, F., & Brosnan, M. E. (1999). Changes in flax (Linum Usitatissmum) seed nitrogenous compounds during germination. *Food Chemistry*, *65*(3), 289–295. https://doi.org/10.1016/S0308-8146(98)00176-9

Wanasundara, J. P. D. (2008). *An In-vitro investigation of selected Biological activities of Hydrolysed Flaxseed (Linum usitatissimum L.) proteins*. 1155–1164. https://doi.org/10.1007/s11746-008-1293-z

Wang, L., Chen, J., & Thompson, L. U. (2005). The inhibitory effect of flaxseed on the growth and metastasis of estrogen receptor negative human breast cancer xenografts is attributed to both its lignan and oil components. *International Journal of Cancer*, *116*(5), 793–798. https://doi.org/10.1002/ijc.21067

Waszkowiak, K., Gliszczyńska-Świgło, A., Barthet, V., & Skręty, J. (2015). Effect of extraction method on the Phenolic and Cyanogenic Glucoside Profile of Flaxseed extracts and their antioxidant capacity. *JAOCS Journal of the American Oil Chemists' Society*, *92*(11–12), 1609–1619. https://doi.org/10.1007/s11746-015-2729-x

Waszkowiak, K., & Mikołajczak, B. (2020). The effect of roasting on the protein profile and antiradical capacity of flaxseed meal. *Foods*, *9*(10). https://doi.org/10.3390/foods9101383

Williams, D., Verghese, M., Walker, L. T., Boateng, J., Shackelford, L., & Chawan, C. B. (2007). Flax seed oil and flax seed meal reduce the formation of aberrant crypt foci (ACF) in azoxymethane-induced colon cancer in Fisher 344 male rats. *Food and Chemical Toxicology*, *45*(1), 153–159. https://doi.org/10.1016/j.fct.2006.08.014

Xu, J., Zhou, X., Chen, C., Deng, Q., Huang, Q., Yang, J., Yang, N., & Huang, F. (2012). Laxative effects of partially defatted flaxseed meal on normal and experimental constipated mice. *BMC Complementary and Alternative Medicine*, *12*(1), 14. https://doi.org/10.1186/1472-6882-12-14

Xu, L., Wei, Z., Guo, B., Bai, R., Liu, J., Li, Y., Sun, W., Jiang, X., Li, X., & Pi, Y. (2022). Flaxseed Meal and its application in animal husbandry: A review. *Agriculture (Switzerland)*, *12*(12), 1–16. https://doi.org/10.3390/agriculture12122027

Yamashita, T., Sano, T., Hashimoto, T., & Kanazawa, K. (2007). Original article Development of a method to remove cyanogen glycosides from flaxseed meal. 70–75. https://doi.org/10.1111/j.1365-2621.2006.01212.x

Zhai, S. S., Zhou, T., Li, M. M., Zhu, Y. W., Li, M. C., Feng, P. S., Zhang, X. F., Ye, H., Wang, W. C., & Yang, L. (2019). Fermentation of flaxseed cake increases its nutritional value and utilization in ducklings. 5636–5647. https://doi.org/10.3382/ps/pez326

Zamindar, N., Bashash, M., Khorshidi, F., Serjouie, A., Shirvani, M. A., Abbasi, H., & Sedaghatdoost, A. (2017). Antioxidant efficacy of soybean cake extracts in soy oil protection. *Journal of Food Science and Technology*, *54*(7), 2077–2084. https://doi.org/10.1007/s13197-017-2646-0

Zanwar, A. A., Hegde, M. V., & Bodhankar, S. L. (2014). Flax Lignan in the Prevention of Atherosclerotic Cardiovascular diseases. *Polyphenols in Human Health and Disease*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-398456-2.00071-2

Zdunczyk, Z., Minakowski, D., Frejnagel, S., & Flis, M. (1999). Comparative study of the chemical composition and nutritional value of pumpkin seed cake, soybean meal and casein. *Nahrung - Food*, *43*(6), 392–395. https://doi.org/10.1002/(SICI)1521-3803(19991201)43:6<392::AID-FOOD392>3.0.CO;2-2

Zhang, Z. S., Wang, L. J., Li, D., Li, S. J., & Ozkan, N. (2011a). Characteristics of flaxseed oil from two different flax plants. *International Journal of Food Properties*, *14*(6), 1286–1296. https://doi.org/10.1080/10942911003650296

Zhang, W., Li, P., Hu, X., Zhang, F., Chen, J., & Gao, Y. (2011b). Omega-3 polyunsaturated fatty acids in the brain: Metabolism and neuroprotection. *Frontiers in Bioscience*, *16*(7), 2653–2670. https://doi.org/10.2741/3878

Zhang, T., Zhang, Z., & Wang, X. (2023a). Composition and antioxidant ability of Extract from different flaxseed cakes and its application in Flaxseed Oil. *Journal of Oleo Science*, *72*(1), 59–67. https://doi.org/10.5650/jos.ess22181

Zhang, T., Zhang, Z., & Wang, X. (2023b). Composition and antioxidant ability of extract from different flaxseed cakes and its application in flaxseed oil. *Journal of Oleo Science, 72*(1), 59–67.

Zhang, S., Chen, Y., McClements, D. J., Hou, T., Geng, F., Chen, P., Chen, H., Xie, B., Sun, Z., Tang, H., Pei, Y., Quan, S., Yu, X., & Deng, Q. (2023c). Composition, processing, and quality control of whole flaxseed products used to fortify foods. *Comprehensive Reviews in Food Science and Food Safety*, *22*(1), 587–614. https://doi.org/10.1111/1541-4337.13086

Publisher's Note