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Nutritional Composition, Bioactive Compounds and Functional Properties of Flaxseed: A Comprehensive Review

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Abstract:

Flaxseed is one of the first cultivated oilseed crops and is known globally as one of the healthiest foods because of its high level of nutrients and many biologically active compounds in it. Nutritional properties of flaxseed range in ALA omega 3 fatty acid content, lignans, soluble and insoluble fibres, protein, vitamins, minerals, phenolic acids, flavonoids, carotenoids and phytosterols have been included in this summary of flaxseed's functions and healthy attributes. Flaxseed contains approximately 35 to 45 percent oil, 20 to 30 percent protein and 28 percent of the recommended daily allowance of dietary fiber; therefore, flaxseeds can be used as foods and/or nutraceuticals. The primary lignan of flaxseed is called secoisolariciresinol diglucoside (SDG) which has shown some degree of antioxidant, anti-inflammatory, cardioprotective (heart-protecting), anti-diabetic, and anti-cancer effects. The proteins found in flaxseed have well functional and therapeutic effects. The Omega-3 fatty acids act as regulating agents of the inflammatory and metabolic function of the body. Some micronutrients that are present in flaxseed are Ca, Mg, P, K, Zn and Vit E. Some antinutrients like cyanogenic glycosides and phytic acid present in flaxseed can be eliminated by different treatment techniques such as roasting, fermentation, extrusion and enzymatic treatment and thus enhance nutrient bioavailabity. The review, in its totality concludes that flaxseed is a unique functional food with promising applications in prevention of diseases and health promotion. Additional, large-scale human clinical studies are required to further validate its claimed health benefits for long-term treatment.

Keywords: Flaxseed, Omega-3 fatty acids, Lignans**,** Functional foods, Antioxidant activity

Introduction

Cultivated in ancient times throughout Asia, Africa, Europe, and America as one of the first oilseed crops grown by humans (Mueed et al. 2022 & Drozdowska et al. 2025), Flaxseed is an annual herb of the Linaceae family that has been used successfully for more than six thousand years. Once valued as a source of processing fiber for textiles,

and as a food and medicinal product, recent scientific investigations into Flax's many health benefits have revealed it to be one of the most extensively studied functional foods and the most studied nutraceutical product on the global market (Noreen et al. 2022 & Rodriguez-Leyva et al., 2019). Nutritionists are now classifying flaxseed as a "superfood", because it possesses an unusually rich and complex array of bio active components, that are linked with optimal health and wellness (Mueed et al. 2022). Flaxseed is one of the major sources of three classes of bio active components derived from plants: 1) alpha-linolenic acid (ALA) the principal plant-derived omega-3 PUFA; 2) secoisolariciresinol diglucoside (SDG) the principle lignan component of human diet; and 3) soluble mucilage and insoluble fiber (Edel et al. 2025 & Kajla et al. 2015). In addition to these major bioactive compounds flaxseed is rich in high-quality protein, peptides, carbohydrates, phytosterols, phenolic acids, tocopherols and multiple micronutrients such as potassium, magnesium, phosphorus, and the B vitamins (Mueed et al. 2022 & Noreen et al. 2023). With the omega-3 ALA at between 39 and 60 % of total fatty acids present in the oil obtained from the seeds, flaxseed exerts a widespread array of cardiometabolic benefits, ALA decreasing the serum lipid profile and triglycerides levels as well as the systemic inflammatory and vascular endothelial functions (Kajla et al., 2015 & Parikh et al. 2019). Epidemiological studies and clinical trials also indicated benefits of ALA intake in cardiometabolic risk factors such as decreasing both systolic (Systolic blood pressure was reduced by 2–15 mmHg, while diastolic blood pressure decreased by 1–7 mmHg (Ghazanfar et al., 2024) here the magnitude of the effects depended on the baseline cardiovascular disease (CVD) risk well as treatment dose and length. In vivo ALA is only converted into longer chain fatty acids EPA and DHA to a limited extent but this is considered important as it contributes to the production of anti-inflammatory prostaglandins and leukotrienes ((Lenártová et al., 2024). In quantitative terms, SDG-a major lignan precursor-is one of the most abundant dietary sources where the concentration ranges from 11.7 to 24.1 mg/g of seed depending on cultivar, crop and processing procedure (Corbin et al., 2024). On ingestion SDG is metabolized by colonic microflora sequentially into secoisolariciresinol (SECO), enterodiol (END), and enterolactone (ENL) which together are known as mammalian lignans or enterolignans, are weak phytoestrogenic agents, powerful antioxidant and interfere with numerous oncogenic signaling pathways (Corbin et al. 2024 & Ghosh et al. 2022). The consumption of SDG has shown to be protected against estrogen-dependent and estrogen-independent cancers, cardiovascular diseases, type 2 diabetes, metabolic syndrome and osteoporosis as demonstrated by both preclinical and clinical evidence (Ghosh et al., 2022 & Stepie et al., 2025). The fiber fraction of flaxseed has various important prebiotic, hypocholesterolemic, glycemic-regulatory and gastrointestinal motility-promoting activity owing to its content of soluble mucilage (20-40%) and insoluble cellulosic fiber (Mueed et al. 2022 & Noreen et al., 2023). The soluble fiber can form viscous gels in the intestinal lumen thus slowing down the digestion and absorption of glucose and impeding enterohepatic circulation of bile acids and the insoluble fraction stimulates selectively growth of Bifidobacterium and Lactobacillus species (Mueed et al. 2022 & Goyal et a., 2024). The current studies that research the interaction of three principal elements from flaxseeds (flaxseed fiber, lignans and ALA)

in influencing and modulating the gut microbiome development are substantial. In addition to its nutritional value as a favorable source of macronutrients and lignans, Flaxseed have also been reported to contain several bioactive secondary metabolites including phenolic acids (ferulic acid, caffeic acid and chlorogenic acid), flavonoids and phytosterols. Sitosterol, campesterol and stigmasterols (mainly) as well as cyclolino-peptides which are cyclic peptides that are notable for their immune suppressive, antioxidant, anti-fungal and anti-thrombotic properties (Drozdowska et al. 2025 & Dziadek 2023). Together, these components have a broad range of biological activities with anti-inflammatory, antimutagenic, antimicrobial, hepatoprotective, neuroprotective and anticancer properties and are considered multifunctional food ingredients(Noreen et al. 2023 & Dziadek 2023).The goal of this review is to: (i) describe the nutritional make-up of flaxseed; (ii) characterize the major and minor bioactive compounds including their identity, concentration ranges and structural properties; (iii) describe the functional properties and biological mechanisms of the demonstrated health effects of flaxseed; (iv) provide a critical appraisal of the clinical evidence regarding the role of flaxseed in the prevention and management of chronic non-communicable diseases (v) determine existing knowledge gaps and future research opportunities.

Proximate composition of Flaxseed

Three main forms of flaxseed that you can consume are whole flaxseed, ground flaxseed and flaxseed oil. Nelson protein fractions exist in various forms depending on the defatting treatment of flaxseed which can affect stability and bioavailability of flaxseed bioactive compounds (Nowak & Jeziorek, 2023). The outer covering (husk) of a flaxseed (Linum usitatissimum) sees a rugged, smooth and glossy surface with different hues ranging from dim brilliant to chestnut brown. According to Kajla et al. (2015), it has 15% in mucilage, and this outer layer is also called a seed coat. Besides their outer coat, flaxseeds are a good source of fats, complete proteins, dietary fibers and phenolic compounds (Lu et al., 2020). Flaxseed composition is influenced by a number of factors. The variations can be influenced by several parameters such as genetics, the environment in which they were grown and the seed preparation method used (Shams et al., 2022 & Choo et al., 2007). The composition shows a proximate value of 41% fat, 20% protein, 28% dietary fiber and averages 7.7 and 3.4 % moisture and ash for Canadian brown flaxseed (Barthet et al., 2003). Some varieties of flaxseed have been reported to contain more than 20% protein content which is higher than most other grains.

Macronutrients

Carbohydrates in Flaxseed

The carbohydrate content is 29% which the almost all of is fiber. The net digestive carbohydrate (carbohydrates-fiber) content is very low hence it can be called as a low carbohydrate food. The content of fiber in 2 teaspoons (20 g) of flax seeds is approximately 6 g which constitutes 15-25% of RDA for man and woman. From the total fiber content 20-40% is mucilage gums and 60-80% is non-gummy (cellulose and lignin) fiber in flax seed (Mohanty et al., 2024). There are two polysaccharide fractions which constitutes the polysaccharide fraction in flax seeds: neutral polysaccharide (arabinoxylan: 75%) and acid polysaccharide (rhamnogalacturonan: 25%). Arabinose, xylose, and Galactose was identified as one of the sugars presents in the neutral polysaccharide fraction, whereas L-rhamnose, D-galactose, D-galacturonic acid, and L-fucose were detected in the acidic

polysaccharide fraction. There were, however a significant variety in terms of both the types of monosaccharides and the relative amounts of various carbohydrate components in flaxseed grown from world's cultivated pools (Guo et al., 2022; Ms et al. 2021). The classification of the two different types of polysaccharide fractions is; FM neutral and acidic polysaccharide, based upon their net charge while arabinoxylans that consist of backbone (1,4)-xylan and thus make up the FM neutral fraction, do not contain uronate(s) at their C-6 position, while pectic substances would be classified as sugars in the FM acidic fraction making them to be classified as rhamnose, galactose, and galacturonic. The two polysaccharide fractions were compositionally different.

Nutrient in Flaxseed Table 1.

Composition	Quantity per serving (100gm)
Energy	534kcal
Protein	17-21.3g
Ash	3.42-45.8g
Total fat	36.8-45.8g
Neural arabinoxylan fraction	1.2g
Phamnagacluronan fraction	0.4
Sugar	1.5g
Total carbohydrate	28.9g
Fiber total Dietary	25.3-28.6g
Lignin	500-1000mg

(Pramanik et al., 2023)

Dietary fiber in flaxseed: composition, types and physiological effects

Flaxseed is a common food Flax seeds contain large amounts of dietary fiber (roughly 28% of total weight) in both insoluble and soluble forms (Kajla et al., 2015). Insoluble fibers in flaxseed consist of cellulose, hemicellulose and lignans. Approximately 3/1 of the total fiber consists of soluble fibers, mucilage or "gummy" things. Most of the mucilage resides in the epidermis and removing the seed coat removes a large quantity of the soluble fiber. There are many types of flaxseed fiber supplements being sold Flaxseed contains both soluble and insoluble dietary fibre, which contribute to its nutritional and functional properties (Kouamé et al., 2021)The total dietary fibre content of flaxseed is summarized in Table 2.

Table: 2 Dietary fibers of flaxseed content

S.NO	Type of fiber	Dietary fiber amount(g/100g)
1	Soluble fiber	10
2	Insoluble fiber	30
3	Total dietary	40

(Gutte, Sahoo & Ranveer, 2015)

Flaxseed Proteins: Composition, Nutritional Quality, and Functional Properties

The primary protein source in flaxseed is classified as flaxseed globulin proteins or linseed proteins and their overall structure consists of five polypeptides. Conlinin (which is classified as the secondary protein source in flaxseed) is a polypeptide that also makes up about 66% of the total Flax Seed protein, while other proteins found in flaxseed comprise approximately 20-42% of the Flax Seed protein (Mueed et al., 2022a). Flaxseed has two main protein storage forms, one being a large salt-soluble and high molecular weight globulin (11 – 12S; 18.6% N content), and the other being a smaller water-soluble albumin (1.6-2S; 17.7% N content) (Chishty et al., 2016). Additionally there are vulnerabilities to low-molarity structural proteins as well (Waszkowiak & Mikołajczak, 2020). Bioactive peptides derived from flaxseed protein have both nutraceutical and therapeutic properties and support their usage as functional foods that promote good health. Being of plant origin flaxseed protein is considered environmentally and ecologically sustainable as opposed to animal-based proteins (Kauser et al., 2024)After extracting oil from flaxseed, the main by product flaxseed meal is an important source of protein of good quality and can be used for food and nutraceutical applications (Yang et al. 2023).

Table 3: Essential and Non-Essential Amino Acid Composition of Flaxseed

Essential Amino acids	(g/ 100g of flaxseed	Non-essential Amino acids	(g/ 100g of flaxseed)
Histidine	2.2	Aspartic acid	9.3
Threonine	3.6	Glutamic acid	19.6
Methionine	1.5	Serine	4.5
Valine	4.6	Proline	3.5
Isoleucine	4.6	Arginine	9.2
leucine	5.8	Tyrosine	2.3
Phenylalanine	5.9	Glycine	5.8
Lysine	40		
Tryptophan	1.8		
Conditional amino acid			
Proline	3.5		
Tyrosine	2.3		
Cysteine	1.1		

(Majhi et al., 2023)

Flaxseed Albumin: Biological Functions and Potential Health Implications

Albumin is a well-digestible water soluble protein that is abundant in food sources like egg whites and whey protein. Flaxseed protein is considered a valuable source of essential amino acids thereby contributing significantly to overall nutritional quality. The 2S albumin fraction of flaxseed, generally known as conlinin or colinin, represents the predominant water-soluble storage protein, and comprises about 40-42% of total seed protein. Conlinin has a relatively small molecular weight (16-17 kDa) and an alpha-helical structure, high in disulfide bonds (Ye et al., 2022). The

anticancer effect of flaxseed albumin has not been studied as extensively as flaxseed lignans and omega-3 fatty acids. However, there is limited information indicating albumin has antioxidant activity, with potentially anticancer capabilities. The importance of albumin in the maintenance of the immune system lies in the fact that it protects endothelial cells through antioxidant and immunomodulatory mechanisms (Nguyen et al., 2022). It is also the main plasma protein in the body and is required to maintain good nutritional state by providing essential amino acids for growth and cell division and for the synthesis of proteins required in many cellular processes; therefore reduced levels and compromised protein synthesis is linked to poorer outcomes and worse disease progression, including cancers (Lessomo et al., 2023). Albumin is also a transporting protein for fatty acids, hormones, vitamins and minerals which help maintain immune function and metabolic homeostasis; and Low serum albumin is often related to adverse outcomes and impaired nutritional transport (Van De et al., 2022).

Flaxseed Globulins: Structural Characteristics and Potential Bioactive Properties

The protein fraction comprising the largest proportion total protein present in flaxseeds are globulins, which is a family of proteins present in animal products, nuts and legumes. Globulin molecular weight in flax seeds, as found by Merkher et al., ranges typically between 252–298 kDa and the molecular weights of 11 S and 12 S globulins fractions are 252 and 298 kDa, respectively (Qin et al., 2022). Globulins have been noted for several physiological benefits that they impart, including an increased presence of immune cell lines and ability to increase resistance to disease. Globulins may also offer anti-cancer activity by enhancing the release of leukocytes against tumors (El-Saadany et al., 2022). Specifically, certain globulin protein fractions have proven to exhibit powerful antioxidant activities by scavenging free radicals and preventing cells from damaging free radical damage which is a precursor to cancer growth (Bochnak-Niedwiecka et al., 2022).

Polyunsaturated Fatty Acids (PUFAs) and Anti-Inflammatory Properties of Flaxseed

The oil content of flaxseed ranges from 35 to 45%, and it consists of 9 to 10% saturated fats (palmitic and stearic) (Martinchik et al., 2012). The remaining fat contains approximately 20% monounsaturated fat (oleic) and over 70% polyunsaturated fat (-linolenic acid, ALA) (Martinchik et al., 2012). Additionally, flaxseed has between 20 and 30% protein and has a high fibre content (as much as 28% dietary fibre) (Martinchik et al., 2012). In relation to the homeostatic and inflammatory pathways, polyunsaturated fatty acids (PUFA's) have an important role to play by regulating them and producing biologically active metabolites that may include lipid mediators as the result of transformation processes (Zarate et al., 2017). On the basis of position of first double bond from the end of carbon chain, PUFA are classified into omega-3 and omega-6 (Mariamenatu & Abdu 2021). Omega-6 (linoleic acid) and omega-3 (linolenic acid); are 2 kinds of PUFAs, needed in aqueous solution as mammals and poultry cannot synthesize them and they should be supplied by dietary means (Alagawany et al., 2021). Also, omega-3 FAs are not able to be converted into omega-6 FAs and vice versa. Upon ingestion, they are transformed into omega-6 AA from LA and omega-3 EPA and DHA from ALA by a bioconversion occurring via elongation and desaturation process (Shahidi

& Ambigaipalan 2018). They are incorporated into cellular membranes where they will act as substrates for the synthesis and release of a large variety of lipid mediators. Lipid mediators are synthesised and released by membrane-bound enzymes such as LOX, COX and CYP450 (Greene et al., 2011). These lipid mediators play significant roles in both induction and resolution of inflammation. Their pattern is modulated through dietary intake by omega-3 and omega-6 PUFA precursors (Serhan et al. 2015). Lipid mediators derived from both omega-3 and omega-6 PUFAs have a plethora of physiological mechanisms which modulate their action, with this area being particularly complex (Shearer & Walker, 2018), however they predominantly act as signalling molecules (vasoactive) with general anti-inflammatory and pro-resolving activities binding to G-protein coupled receptors including GPR32, GPR18, ChemR23, GPR37 and LGR6 respectively (Hallisey et al., 2020). One class of mediators are particularly important, lipid mediators derived from omega-3 polyunsaturated fatty acids (e.g. SPMs) due to their integral role in resolving inflammation (Arnardottir et al., 2021). Cytokines mediate central responses of the host to a number of physiological and pathological stimuli including inflammation, the pro-inflammatory cytokines play an important role in driving inflammatory process include TNF, IL-1 and IL-6 (Lee et al., 2021)

Table: 4 Poly unsaturated fatty acid

S. NO	Fatty acid	Quantity (g/100g)
1.	Al-linolenic acid	22.8
2.	Oleic acids	7.3
3	Linoleic acid	5.9
4	Palmitic acid	2.1
5	Stearic acid	1.3

(Majhi et al., 2023)

Micronutrient in flaxseed: Minerals, Vitamins and Antioxidant compounds

Flaxseed contains appreciable amounts of essential minerals, particularly calcium, magnesium, phosphorus and sodium (Kajla et al. 2015). Water soluble and fat soluble vitamin is in less amount in flax seed along with minerals (Kajla et al. 2015; Morris et al. 2005). Minerals is one of the important constitute of human body; its important role in biological function and human system like immune system and development and growth. Apart from carbohydrates, fats and protein macro nutrient and minerals and vitamin micro nutrient is available in flax seed. Among macro minerals in higher proportion are Potassium, Magnesium, Phosphorus and Sodium. And in case of micro minerals, iron and zinc is present in higher amounts. Mineral composition is of flaxseed, according to Noreen et al. (2023) has K (763.7mg/100g), P (581.5mg/100g), Mg (406.6mg/100g), Fe (5.13mg/100g), Zn (3.30mg/100g) is general inorganic minerals present in flax seed. The inorganic mineral profile of flax seed is presented in INSA Food Composition Database, 2024. Per 100g, flax seed has Sodium (11mg), potassium (470mg), Calcium (200mg), phosphorus (550mg), magnesium (350mg), iron (15mg), Zinc (7.8mg), Selenium (28g). Flaxseed contains both water soluble vitamins such as ascorbic acid, thiamine and riboflavin as well as fat-soluble vitamins. However, the concentration of water-soluble vitamins is generally lower than that of fat-

soluble vitamins in flaxseed. The vitamin composition of raw flaxseed per 100 g is presented below by INSA Food Composition Database, 2024: tocopherol (8.2mg), thiamine (0.79mg), riboflavin (0.25mg), niacin (7.9mg), vitamin B6 (0.79mg), folates (97g). Among the fat-soluble vitamins, vitamin E is present in higher quantity (569 mg/100g) in most form of tocopherol(552mg/100g) along with minor form of tocopherol (7mg/100g) and tocopherol(10mg/100g). The vitamin E has strong antioxidant activity to protect lipid and protein oxidation in cell structures and to balance sodium and may have cardiotrotective effects. Vitamin K is vital in normal blood clotting and approximately 0.3 mg per tablespoon of milled flax seed (Canadian Food Inspection Agency, 2024).

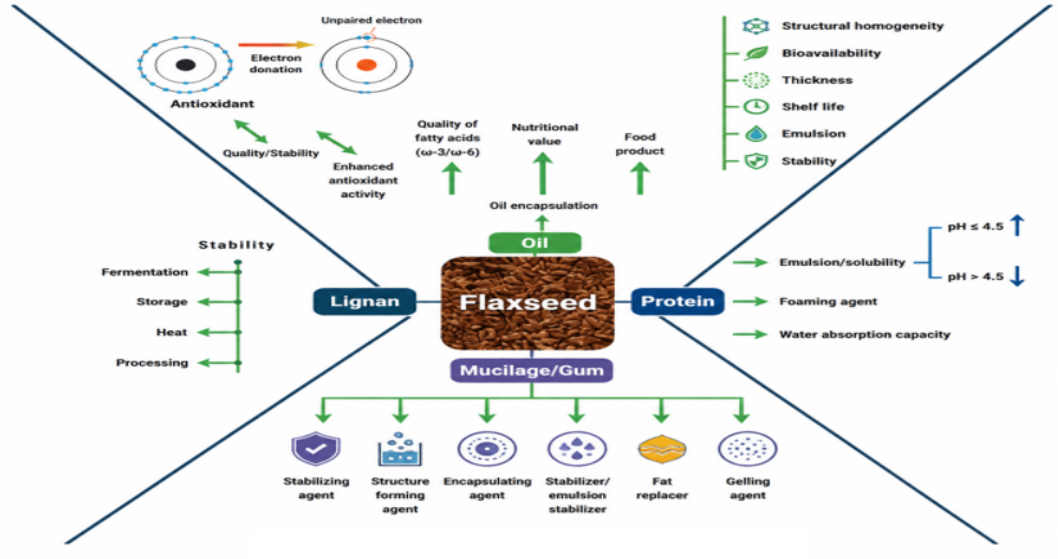
Table 5: Vitamin and Mineral of Flaxseed

S.NO	Mineral	(mg/100g of flaxseed)	Vitamins	(mg/100g of flaxseed)
1	Calcium	236	γ-tocopherol	522
2	Magnesium	431	α-tocopherol	7
3	Phosphorous	622	δ-tocopherol	10
4	Potassium	831	Vitamin C (Ascorbic acid)	0.5
5	Sodium	27	Vitamin B (Thiamin)	0.5
6	Iron	5	Vitamin B2 (Riboflavin)	0.2
7	Zinc	4	Vitamin B3 (Niacin)	3.2
8	Manganese	3	Vitamin B5 (pantothenic acid)	0.6
9	Copper	1	Vitamin B6 (pyridoxine)	0.6
	Phenolic compounds		(mg/100g of flaxseed)	
1	Ferulic acid		10.9	
2	Chlorogenic acid		7.5	

(Majhi et al., 2023)

Bioactive compounds

These important health promoting compounds including lignans, phenolic acids, flavonoids, carotenes, phytosterols are shown in flaxseed (Linum usitatissimum L.) and lignans being the most bioactive. These bioactive constituents are considered to contribute significantly to the antioxidant, anti-inflammatory, anticarcinogenic and cardioprotective properties associated with flaxseed consumption. It is widely known that once consumed as a whole (with its array of bio-components), there is a synergistic effect from the components that leads to a health benefit (Mueed et al, 2022) further emphasizing its worth. The maximum content and richness of polyphenols and the highest antioxidant activity was also found in the defatted brown flax seed by Drozdowska et al. (2025), indicating the significance of consuming the whole seed. Flaxseed is a nutritionally rich seed that possesses bio-active compounds including linolenic acid (45-52% of the oil) together with lignans (mainly secoisolariciresinol diglucoside, SDG, up to 30 mg/g in the hulls), dietary fiber (28-40%), cyclolinopeptides (linusorbs), phenolic acids (ferulic, chlorogenic), phytosterols and proteins/peptides (Gao et al., 2024). acids (ferulic, chlorogenic), phytosterols, and proteins/peptides (Gao et al., 2024).



Figures 3: Functional properties of flaxseed bioactive compounds

(Mueed et al., 2022)

Lignans in flaxseed: Secoisolariciresinol Diglucoside (SDG) and Its Health Effects

Lignans are phytoestrogens that contain two phenylpropanoid units. One of the most common sources of dietary lignans is from flaxseed which has the highest amount of lignans in the food supply. The largest known amount of lignans is SDG or secoisolariciresinol diglucoside. According to a study by Mueed et al. (2022), flaxseed contains an average of 610 - 1300 mg/100 g of flaxseed which is several hundred times more than other common foods. After ingestion, SDG can be converted to another lignan called secoisolariciresinol by bacteria in the colon where it is further converted to ED and EL both of which have weak estrogenic and anti-estrogenic properties. Additionally both compounds possess remarkable antioxidant and affect several systems within the human body regarding enzymes (Hu et al., 2024). Lignans in flaxseed are synthesized by the phenylpropanoid pathway and secoisolariciresinol diglucoside formation occurs by the use of the enzyme pinoresinol lariciresinol reductase and the enzyme UGT74S1 involved in the step of glucosylation to secoisolariciresinol diglucoside (SDG) (Ghazalibiglar et al., 2018). Lignans in plant seeds and specifically secoisolariciresinol (SECO) and secoisolariciresinol diglucoside (SDG) have beneficial effects on human health; this can be partially explained by the antioxidant effect and the transformation in vivo to enterolignans (enterodiol and enterolactone) that can be easily absorbed by the intestinal wall and induce useful physiological processes. (Calado et al., 2018). In vivo experimental animal models (rat, mouse and rabbit) demonstrated the reducing effect of chronic disease development for cancer, diabetes mellitus, cardiovascular diseases etc by supplementation of SDG, in human the experimental and human clinical studies produced positive results for health benefits associated with SDG; further and larger Randomized Controlled Trials are needed to confirm the health effects of SDG supplementation in humans (Calado et al., 2018)A comprehensive review by Hu et al. (2024) outlined major health relevant

activity of SDG and its metabolites (see at fig 2):

- Antioxidant and free radical scavenging activities, as well as inhibition of lipid peroxidation and oxidative DNA damage.
- Anti-estrogenic and estrogenic modulatory effects and competing with binding of estrogen receptors, thus of particular interest in hormone sensitive cancers.
- Cardioprotective effects through decreased oxidative modification of LDL and attenuated progression of atherosclerotic plaques.
- Anti-diabetic effects and potential with ameliorated insulin sensitivity and reduced hyperglycemia in animal models.
- Inhibition of cellular signaling pathways, i.e., NF-B, PI3K/Akt with those involved in cancer cell proliferation and metastasis.
- Neuroprotective potential against mental stress and associated biomarkers.
- Anti-inflammatory effects through reduced inflammatory cytokines expression.

The majority of lignans present in flax seed are stored within the external seed coat (hull) and a high extraction yield is achieved by use of 50% aq ethanol in a 1:60 solid or liquid ratio using mild agitation (Mueed et al., 2022). Significantly, defatting of the seed substantially elevated the recovery of lignans and polyphenol yield per gram (Drozdowska et al., 2025).

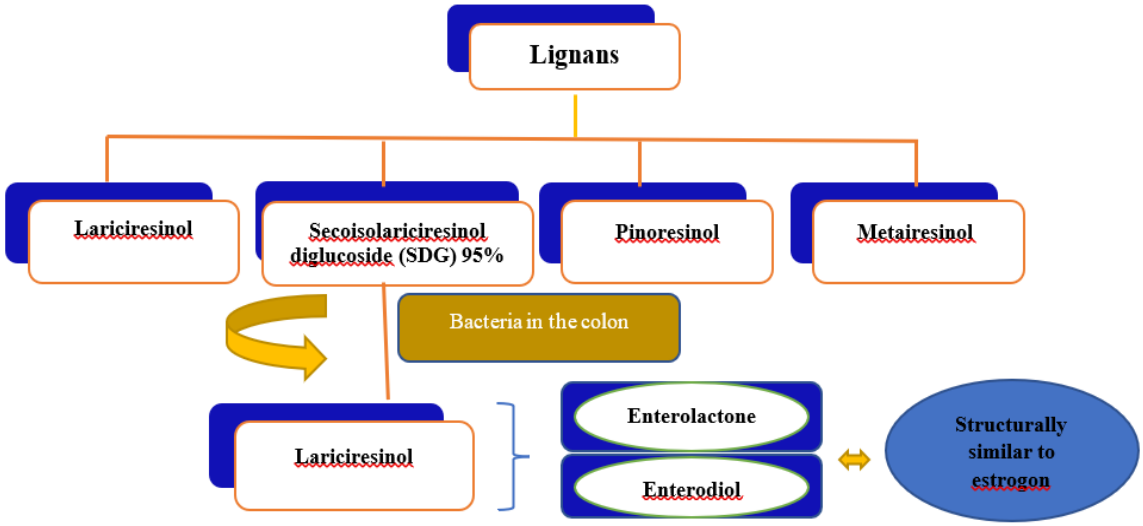


Figure 2: Metabolism of lignans in flaxseeds

(Calado et al., 2018)

Phenolic Acids

Flaxseed contains abundant phenolic acids, primarily hydroxycinnamic acid derivatives, including ferulic acid, sinapic acid, p-coumaric acid, caffeic acid, as well as hydroxybenzoic acid derivatives such as p-hydroxybenzoic acid and vanillic acid. The concentration of these phenolic acids varies depending on the flaxseed genotype (brown or black varieties), agronomic conditions,

processing methods, and whether the oil has been extracted from the whole seed (Mueed et al., 2022). While whole seed typically contains fewer free phenolic acids compared to oil it must be noted that when the oil is extracted these compounds are more available in the oil fraction. It has been reported that sinapic acid and ferulic acid are the predominant phenolic acids in flaxseed, although their concentrations vary considerably. polyphenols between different varieties of flaxseed. The antioxidant ability of sinapic acid is known to be high and it also inhibits lipid oxidation in food products. In vitro, ferulic acid displays anti-mutagenic and anti-proliferative activity (Antoniszczak et al., 2025). The phenolic acids present in flaxseed can contribute to the overall radical scavenging capacity by having the presence of hydroxyl groups and can break the chain reaction of lipid peroxidation. According to a detailed review by Imran et al., on the phytochemistry of Linum usitatissimum, "Natural phenolic compounds in flaxseed oil work synergistically with tocopherols and phytosterols in eliciting a multiple mechanism free radical scavenging action leading to an increase in their stability and bioactivity over that which would be expected from their individual presence (Bekhit et al., 2018).

Flavonoids

Flaxseed possesses diverse flavonoids: flavonols (kaempferol, quercetin, quercitrin, and quercetagetin), flavanones (naringenin) and isoflavones. Flavonoid content in the seed exhibits an inverse relationship with total protein content and a weak positive correlation with oil content. (Imran et al., 2023). Moreover, there are several phytochemicals (i.e. Bioactive flavonoids and various pigments) present in large concentration in flaxseed. It can be concluded that oil produced from flaxseed could be upgraded in term of quality and thermal stability providing diverse health benefits if combined with other oil seed source (Suri et al., 2023). Gut microbiota play role to modify bioavailability and biological activity of flaxseed flavonoids; that is, gut bacteria i.e. Lactobacilli and bifidobacteria metabolize the original flavonoid glycosides into aglycone forms i.e. Quercetin, kaempferol, naringenin, which can be easily absorbed (Landete, 2022).

The main flavonoids in flaxseed according to Antoniszczak et al. (2025) are kaempferol and quercitrin and the amount of these varies with different cultivars. Functionally flaxseed flavonoids display their antioxidant properties through either electron donation metal chelation or enzyme inhibition. Anti-inflammatory effects were observed through the inhibition of NF-κB activation and the decreased production of pro-inflammatory mediators such as TNF, IL-6, and COX-2. Additionally, quercetin and kaempferol showed antiproliferative activity against several cancer cell lines in vitro, including the MCF-7 breast cancer cell line (Drozdowska et al., 2025). The amount of isoflavones present in flaxseed is relatively low compared to soy but is one of the main reasons for its phytoestrogenic activity as they work alongside the oestrogenic effect produced by the lignans. The concurrent administration of flaxseed with probiotic-containing dairy products may increase metabolism of the flavonoid precursor and hence its bioactivity, Imran et al. (2023).

Carotenoids

Carotenoids comprise the largest group of organically produced pigments responsible for coloring of flaxseed. Carotenoids exist as reds oranges and yellows and can also act as provitamin A substances (Fan et al., 2023). Carotenoids are lipophilic, yellow-orange and red pigments that are pre-vitamins A and powerful antioxidants in cellular

membranes. Significant concentrations of carotenoids are present in flaxseed of which carotene is most abundant and possesses greatest provitamin A activity. Carotenoid content has been previously determined to be 0.7–3.0mg/100 g, varying based on seed varietal, soil type, crop season and postharvest handling (Mueed et al., 2022). Thus of all carotenoids the;-carotene has shown to be most efficient compound of provitamin A. Carotenoid concentrations in flaxseed have been reported to range from 0.7 to 3.1 mg/kg of the total seed weight. The provitamin-carotene has been previously determined to be at concentrations of approx 77mg/kg of flaxseed weight. Furthermore, flaxseed oil has shown increased concentrations of lignans, novel chlorphylls, and carotenoids are present in the oil phase (Fan et al., 2023). The health benefits of flaxseed carotenoids go beyond their role as provitamin A. Together with tocopherols present in oil, carotene and related xanthophylls aid to protect lipid-rich cellular compartment via scavenging of singlet oxygen and peroxyl radicals, thereby supplementing tocopherols' radical-scavenging activity. Indeed, Imran et al. (2023) demonstrated that, the carotenoids along with other relevant antioxidant compounds present in the flax seed oil play a protective role synergistically against the oxidation of PUFAs, more specifically-linolenic acid. The anti-cancer health benefit of carotenoids in flax seed has also been suggested. Antoniszczak et al. (2025) reviewed some evidence showing that dietary carotenoids are linked to a decreased risk of various epithelial cancers through the regulation of cell cycle progression and the induction of apoptosis in preneoplastic cells. Although present in lower concentrations in flaxseed, lutein and zeaxanthin have been reported to contribute to the prevention of age-related macular degeneration, indicating potential ocular health benefits associated with the regular consumption of flaxseed.

Phytosterols

Phytosterols are triterpenoids and similar to cholesterol in structure, possessing a cyclopenta phenanthrene tetracyclic ring system that possesses C-28 or C-29 side chains. They play a vital role in maintaining the structure and functional integrity of plant cell membranes and are abundantly found in oilseeds such as flaxseed. To date there have been over 250 individual compounds of phytosterols isolated from plants (Gajewska et al., 2024). Oilseeds, especially flaxseed and flaxseed oil, are known to be good sources of phytosterols and have been studied extensively to characterize these compounds as they possess known anti-cancer and cholesterol lowering properties.

Phytosterol Profile of Flaxseed

The six main types of phytosterol in flaxseed oil have been identified by GC-MS analysis (Gas Chromatographic Mass Spectrometry) in addition to being discussed by Madhagy et al (2023) the major phytosterols in flaxseed oil are: Beta-sitosterol (60% of total phytosterols), campesterol (24% of total phytosterols), stigmasterol (7% of total phytosterols), with small amounts of delta-5-avenasterol (total amount is 2% of total phytosterols) and 4-methylenecycloartenol (2% of total phytosterols (Kakade, 2024). The maximum amount of total phytosterols was found in cold pressed flaxseed oil (11.8 g/kg), as roasting flaxseed oil at 120°C and 160°C reduced this amount to 11.3 g/kg and 9.65 g/kg respectively, which attests to the thermal sensitivity of phytosterol fractions (Madhagy etal, 2023). Lepage (2010) reported that β-sitosterol was found to reach its maximum accumulation at 830 mg/100 g oil, campesterol at 564 mg/100 g oil and stigmasterol at 265 mg/100 g oil during early stages of seed development (7 days

after flowering) with a decrease toward with maturity.

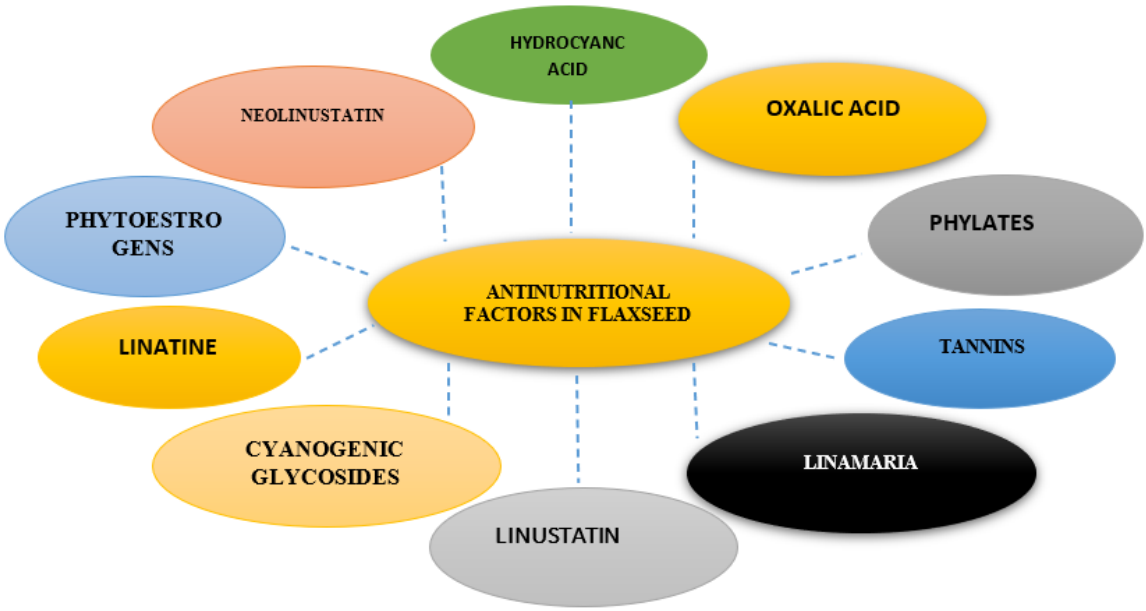
Interactions with Other Flaxseed Bioactives

Phytosterols in flaxseed do not exert their effect alone, rather they act synergistically with other bioactive compounds. Gupta et al. (2023) mentioned that all the natural phenolics, phytosterols and tocopherols of flax seed oil formed a mutually reinforcing antioxidant system. Phyotosterols maintain oxidation stability through preventing unsaturated fatty acids of cell membrane and lipid droplets from peroxidation, therefore they work together with the direct radical scavenging function of lignans, phenolic acids and flavonoids at a matrix level to emphasize consumption of whole flax seed or less processed flax seed products.

Antinutritional factors in flaxseed and their potential health impact impacts

Flaxseed (Linum usitatissimum L.) is widely recognized for its distinctive nutritional profile, characterized by high concentrations of alpha-linolenic acid (ALA), lignans, dietary fiber and protein. Due to the presence of these bioactive constituents, flaxseed has gained considerable attention as a functional food ingredient with potential health-promoting properties, including cardioprotective and anti-inflammatory effects (Kauser et al., 2024).Despite the several benefits, flaxseed contains multiple antinutrients-mainly cyanogenic glycosides, phytic acid, protease inhibitors, tannins, and linatine which can potentially impact nutritional quality and health risk in high consumption or inefficient processing (Mueed et al., 2022b). Recent works are being carried out to study the characters of these antinutrients, their toxicity mechanism and methods of their removal to make flaxseed product safe and with improved nutritional value (Huang et al., 2023; Mueed et al., 2022b). Processing methods including fermentation, extrusion, roasting, germination, enzyme treatment, etc., had already been reported and achieved effective removal of antinutritive substances while retain or improving their functionalities (Sa et al., 2025). The flax seed contains some antinutritive elements which has adverse effect to the human body and the percentage is described below as in fig 3. These antinutritive factors include Plasmo trypsin myoinositol phosphate, cadmium and cyanogenic glucosides etc. Their excess will be toxic and higher level of their levels leads to various human disorders. The irritability of the nervous system, human disorders and disorders of the nervous system produce cases Cyanogen. The amount of the cyanogen advances step by step and can be devoured by people that produce cyanates Bernacchia et al. (2014). Phytic acid, a common antinutritional factor in flaxseed meal reduces the protein and mineral bioavailability of a composite food. Flax seed meal is higher in antioxidants and unsaturated fatty acids. The treatment to dephytinize the flax seed flours was carried out by phytase application and fermentation. In order to increase the nutritional value of noodle, undehphytinized and dephytinized flax seed flours were used in noodles from 0% to 30%. Thus, it is concluded that dephytinized flax seed flour up to 20% can be successfully used to produce functional noodles of the desired quality. Phytase-treated noodles had lower phytic acid levels than those processed through fermentation. Showed strong antioxidant activity (Yaver, 2023). Flax seed has antinutritive compounds such as phytic acid and cyanogenic glycosides (Nesbitt et al., 2010). undesired; in fairly large amounts even though flaxseed contains all the healthy ingredients. These compounds travelling through the intestinal tract can be converted in turn to Hydrogen Cyanide (by the action of intestinal glucosidase) and thence to

thiocyanate, which blocks the absorption by the thyroid gland of iodine. This is referred to as iodine deficiency, leading to goiter and even cretinism. Thermal processing such as autoclaving or microwave baking of the seeds (Olombrada et al., 2023) allows for enhancement, presence mixing to remove phytic acid and undesirable components. Flax seeds should, therefore, be much more nutrient-complete than antinutritive compounds and there are many methods employed in the modern process to remove maximal amounts of antinutritive compounds (Tiwari et al., 2025).



Figures: 3 Antinutritional factors in flaxseeds

Conclusion

Flaxseed (Linum usitatissimum) is an oil seed crop which is nutritionally rich in oils as well as have a high potential to be used as functional food, nutraceutical. It is a rich source of bio active ingredients that are contained in the seeds, such as omega-3 fatty acids and non-contentious compounds including lignans, dietary fibers, proteins, vitamins (especially B series), minerals (Calcium and Iron content affect iron metabolism in growing children); phenolic compounds; flavonoids and phytosterols exhibiting wide ranges of biological activity responsible for antioxidant, anti-inflammatory, cardioprotective, anti-diabetic, antimicrobic and anticancer effects. Combining the effects of these bio-active components together may increase the health therapeutic value of the flax seed, and can also be utilized as a preventive and treatment tool against various chronic non communicable diseases. Moreover, its food value can be enhanced by adding protein and dietary fiber in food formulations, with better effects on the digestion and metabolism regulating process (Maurya and Kushwaha., 2019). Anti nutritional compounds like cyanogenic glycosides, tannins, phytic acid could be one of the limiting factors. However modern food processing methods like fermentation, roasting, extrusion and enzymatic methods, can reduce the anti-nutritional activity, thus

can retain its nutritional characteristics. So it could be exploited for formulating the functional, fortified and health therapeutic food formulations. However more research needs to be conducted on the mechanism underlying bio-activity, bio-availability of nutrients present

Al-Madhagy, S., Ashmawy, N.S., Mamdouh, A. et al. A comprehensive review of the health benefits of flaxseed oil in relation to its chemical composition and comparison with other omega-3-rich oils. Eur J Med Res **28**, 240 (2023). https://doi.org/10.1186/s40001-023-01203-6 in it and also on the clinical effectiveness.

Al-Madhagy, S., Ashmawy, N.S., Mamdouh, A. et al. A comprehensive review of the health benefits of flaxseed oil in relation to its chemical composition and comparison with other omega-3-rich oils. Eur J Med Res **28**, 240 (2023). https://doi.org/10.1186/s40001-023-01203-6

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