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Flaxseed: An emerging functional food

Simranjeet Kaur

Abstract
Flaxseed, also known as linseed, is derived from the flax plant (*Linum usitatissimum*) and is highly regarded for its rich content of beneficial compounds. This oilseed is a valuable source of omega-3 polyunsaturated fatty acids, proteins, lignans, dietary fibers, and phytochemicals. Flaxseed has gained global recognition as a health food due to its diverse array of nutrients and bioactive components, including oil, fatty acids, proteins, peptides, fiber, lignans, carbohydrates, mucilage, and micronutrients. This comprehensive review discusses the extensive research conducted worldwide, encompassing in-vivo and in-vitro studies on human subjects and animal models, exploring the health benefits associated with different forms of flaxseed consumption. The consumption of flaxseed has been on the rise due to its potential positive effects on various health conditions such as inflammation, diabetes, cancer, and cardiovascular diseases. However, it is important to note that flaxseed also contains anti-nutritive and toxic compounds, including cyanogenic glycosides and phytic acids. Despite this, flaxseed finds application in a wide range of food and feed products, as well as non-food industrial uses, in the form of whole seeds, meals, flour, or oil.
This review delves into the benefits of incorporating flaxseed or its individual bioactive components for promoting health and addressing disease conditions. It also explores the functional properties of flaxseed that enable its utilization in food products, and highlights recent advancements in the development of food products incorporating flaxseed.

Keywords: Flaxseed, emerging functional food, *Linum usitatissimum*

1. Introduction
Flaxseed stands out as one of the most nutrient-dense foods available, owing to its exceptional nutritional profile. The use of flaxseed as part of the human diet dates back to the early 1990s, and it is now grown in approximately 50 countries worldwide (Edel *et al*., 2015; Marambe and Wanadsundara, 2017) [23, 44]. Flax (*Linum usitatissimum* L.) has been cultivated for thousands of years and is recognized as one of the oldest arable crop oilseeds, deriving its name from the Latin term for "very useful" (Goyal *et al*., 2018; Liu *et al*., 2018) [30, 41]. Flaxseed has earned the esteemed classification of a "superfood," denoting its natural origin, abundance of bioactive compounds, and wide array of health benefits. Including flaxseed in your diet can play a significant role in disease prevention, particularly those linked to inadequate nutrition (Bernacchia R. *et al*., 2014, Dzuvor *et al*., 2018) [7, 22].
The flaxseed is the richest source of bioactive compounds such as ALA, dietary fiber, protein, and lignan and these compounds have been shown to have positive effects on various aspects of health in animal and human studies as in controlling diabetes, improving cardiovascular health, etc. (Bechlin *et al*., 2019) [4].
Flaxseed boasts a remarkable n-6: n-3 fatty acid ratio of approximately 0.3:1, primarily attributed to its abundant alpha-linolenic acid (ALA) content. This advantageous ratio, coupled with the anti-inflammatory and antiproliferative properties of ALA, contributes to its potential as an anticarcinogenic agent, effectively thwarting the formation of malignant tumors and their subsequent metastases. Notably, the consumption of flaxseed-derived alpha-linolenic acid has been shown to have a positive impact on blood lipid levels, with significant reductions observed in plasma total cholesterol, LDL cholesterol, and VLDL cholesterol (Bernacchia R. *et al*., 2014 and Dzuvor *et al*., 2018) [7, 22]. Due to higher concentration of soluble dietary fibre flax seed helps in reduction in plasma triglyceride, low-density lipoprotein (LDL) cholesterol, plasma cholesterol, and atherosclerosis in rats through adequate consumption (Shim, Gui, *et al*. 2015) [72]. The water-soluble gum found in flaxseed can aid in weight regulation or loss when added to the diet (Liu *et al*. 2018) [41].
A variety of beneficial properties such as antihypertensive, anti-inflammatory, antioxidant and anti-diabetic effects are possessed by the proteins and cyclic peptides found in flaxseed

(Dzuvor *et al*. 2018) [22]. Additionally, flaxseed is gaining popularity as a superfood due to its ability to regulate gut microbiota and alleviate symptoms of several human diseases including cardiovascular diseases, diabetes, neurological disorders, menopause, skin disorders, gastrointestinal problems, and certain types of cancer (Parikh *et al*. 2019) [57].

Flaxseed has found broad applications in various industries, including food, cosmetic, medicinal, and feed industries (Bakowsk-Barczak *et al*., 2020; Bekhit *et al*., 2018) [3, 6]. The beneficial relieving effects of flaxseed in various illnesses is due to fats, proteins, lignans, and fiber, which have nutritive benefits. These constituents are also used to develop value-added products (Saka *et al*. 2022) [70]. The inclusion of flaxseed in various food products increases the functional property and behaves based on its biochemical composition. The flaxseed mucilage (FM), which has a strong ability to bind water and improve their stability, viscosity, and consistency, particularly in beverages (Puligundla *et al*. 2022) [60]. The antinutritional compound affects nutrient bioavailability and worsen health conditions. Anti-nutritive components, such as phytic acids, protease inhibitors, linatine, and cyanogenic glycosides (CGs) including neolinustatin, linustatin, lotaustralin, and linamarin, are present in flaxseed. The CGs releases hydrogen cyanide (HCN), a respiratory inhibitor that is converted to thiocyanates, which hinder iodine uptake from the thyroid gland and worsen iodine-deficiency illnesses like cretinism and goiter over time (Bekhit *et al*. 2018) [6]. Additionally, a significant substance called phytic acid has a detrimental effect on the absorption of essential minerals, including zinc, calcium, magnesium, iron, and copper (Bekhit *et al*. 2018) [6].

Fig 1: Health benefits promoted by flaxseed

2. Nutritional composition and main active biocompounds in flaxseed

Flaxseed's nutritional value is essential to grasp its significance in a balanced diet. However, its nutritional profile is subjected to considerable variability based on factors such as flaxseed type, cultivation conditions, processing methods, and analytical approaches, potentially influencing its nutrient content (Flax Council of Canada (FCC). Flax-a Health and Nutrition Primer; 2007) [26].

At its most basic level, flaxseed is composed of three distinct components: the germ, hull, and two cotyledons, which respectively account for 4%, 55%, and 36% of the seed's weight. The nutritional content of flaxseed, however, can vary depending on factors such as the variety of flaxseed and the environmental conditions in which it is grown, as well as the processing and analytical methods used. Generally, whole flaxseed contains approximately 3-4% ash, 4-8% moisture, 20-35% dietary fiber, 20-30% protein, 30-41% fat, and 1% simple sugars (Shim *et al*. 2014) [72].

Flaxseed is composed of various bioactive components, with the major ones being carbohydrates such as mucilage, oil, lignans, protein/peptides, and a small amount of CGs and linatine. In addition, flaxseed also contains minor components such as phytic acid, trypsin inhibitor, phenolics, minerals, cadmium, vitamins, and selenium, as noted in a study by Shim *et al*. (2014) [72].

Table 1: The composition (per kg) of whole flaxseed

Parameter	Amount (g/kg)
Total Fat (g)	42.16
C18:3 undifferentiated (g)	22.81
Protein (g)	18.29
Carbohydrate (g)	28.88
Ash (g)	3.72
Dietary fiber (g)	27.3
Moisture (g)	6.96
Energy (kcal)	534

***Source*:** (USDA, Agricultural Research Service, 2019). https://fdc.nal.usda.gov/fdc-app.html#/food-details/169414/nutrients

Main active biocompounds in flaxseed

1. Alpha-linolenic acid

Flaxseed is said to be one of the richest sources of fatty acids which are considered essential because they are necessary for the body, but the body cannot produce them on its own, and thus, they must be obtained through the diet (De Lorgeril M. *et al*. 2001) [19].

Flaxseed is composed of various types of fatty acids, with a significant amount of polyunsaturated fatty acids, especially ALA and linoleic acid (LA). ALA, which is an essential omega-3 fatty acid, is found in abundance in flaxseed and constitutes about 57% of total fatty acids. On the other hand, LA, which is an essential omega-6 fatty acid, makes up around 16.0% of total fatty acids in flaxseed. Hence, flaxseed is considered to be the richest source of ALA among all the plant-based foods. Both of these essential fatty acids are required by the human body but cannot be produced by the body (De Lorgeril M. *et al*. 2001) [19].

Alpha-linolenic acid (ALA) is an essential omega-3 fatty acid crucial for human health. It plays a vital role in the synthesis of docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), necessary for proper growth, development, and maintenance of the brain and skin. Flaxseed oil is a valuable ALA source. However, its limited conversion ratio to DHA and EPA presents a significant scientific challenge (Yang *et al*., 2021) [88].

ALA is an essential polyunsaturated fatty acid that cannot be synthesized by the human body and is necessary for normal growth, development, and maintenance, particularly for the brain and skin. Consumption of ALA has been linked to improved immunity and a reduced incidence of various conditions, including cardiovascular disease, cancer, diabetes, arthritis, and gastrointestinal tract disorders, due to its potent anti-inflammatory properties (Goyal *et al*. 2018; Kheira *et al*. 2019; Mosavat *et al*. 2018; Yadav *et al*. 2018; Zhu *et al*. 2020) [30, 38, 51, 87, 92].

The form of flaxseed consumed can impact the bioavailability of ALA, with flaxseed oil exhibiting greater availability than milled or whole seed forms. However, the high unsaturated fatty acid content of flaxseed makes it vulnerable to oxidative damage during processing, which poses a challenge to fully realizing its nutritional benefits (Yang *et al*. 2021) [88].

Table 2: Content of fatty acids in flaxseed oil (Morris *et al*. 2003) [49]

Parameters	Amount (g/100g)
Saturated fat	9.0
Monounsaturated fat	18.0
Omega-6 fatty acid	16.0
Omega-3 fatty acid	57.0

2. Lignans

A lignan is a type of phytoestrogen, which is a diphenolic compound found in many plant-based, fiber-rich foods such as grains (e.g., wheat, barley, and oats), legumes (e.g., beans, lentils, and soybeans), and vegetables (e.g., garlic, asparagus, broccoli, and carrots).

There are various types of lignans including secoisolariciresinol diglycoside (SDG), matairesinol (Mat), pinoresinol (Pin), medioresinol (Med), lariciresinol (Lari), syringaresinol (Syr), sesamin (Ses), and 7′-hydroxymatairesinol, as stated by Umezawa *et al*. in 2003 [83]. Flaxseed is a potent source of plant lignans, with secoisolariciresinol diglucoside (SDG) being the most abundant type (Sicilia *et al*. 2003). Depending on the analytical method used, SDG is also known as secoisolariciresinol or SECO, which is the aglycone of SDG. In flaxseed, SDG occurs in two isomeric forms: (+)-SDG and (-)-SDG, with the former being the major isomer (Eliasson *et al*. 2003). Other lignans present in smaller quantities in flaxseed include matairesinol, isolariciresinol, lariciresinol, demethoxysecoisolariciresinol, and pinoresinol (Sicilia *et al*. 2003) [74].

Flaxseed is the richest source of SDG with a concentration of 7 mg/g, which is 75 to 800 times more SDG than any other foods. The concentration of flaxseed lignans can be influenced by factors such as variety, location, and crop year. Whole seed and ground flaxseed usually contain between 0.7% and 1.9% SDG, respectively.

The levels of other lignans (isolariciresinol, lariciresinol, pinoresinol, and matairesinol) in flaxseed are low. Flaxseed lignan has weak estrogenic and antiestrogenic activity and mainly participates in the metabolism of hormones (Bekhit *et al*., 2018 and Gerstenmeyer *et al*., 2013) [6, 29]. Many health benefits of flaxseed lignan, including anticancer, antidiabetic, anti-inflammatory, antihyperlipidemic, antiatherosclerotic, and antioxidative ability, have been reported (Aqeel *et al*., 2019; Figueiredo *et al*., 2017; Goyal *et al*., 2018) [2, 25, 30].

3. Dietary fiber

Flaxseed kernels are composed of both soluble and insoluble dietary fibers, which account for 20% of their weight (Ding and Cui, 2014). The level of flaxseed dietary fiber may range from 20 to 28% (Mercier *et al*., 2014) [47]. Like many other dietary fibers, flaxseed dietary fibers contain both soluble and insoluble fibers, as noted by Goyal *et al*. (2018) [30] and Liu *et al*. (2018) [41]. These fibers can potentially reduce the incidence of chronic diseases and maintain the balance of intestinal flora (Luo *et al*., 2018) [42].

Flaxseed fiber can be categorized as either dietary or functional fiber. Dietary fiber comprises of plant-based carbohydrates that are non-digestible. Functional fiber refers to non-digestible carbohydrates that have been extracted, purified, and added to various food and non-food products.

Table 3. Fiber content of flaxseed

Flaxseed form (1 tbsp)	Soluble fiber	Insoluble fiber
Whole flaxseed	0.6 - 1.2 g	1.8 - 2.4 g
Milled flaxseed	0.4 - 0.9 g	1.3 - 1.8 g

Source:http://members.ift.org/IFT/Research/IFTExpertReports/functionalfoods_report.html

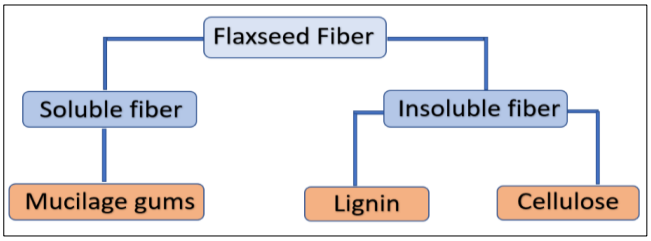

Fig 2: Classification of flaxseed fiber

The major fiber components found in flax are comprised of the following:

3.1 Cellulose: The cell walls of plants are primarily composed of cellulose, which is the main structural component.

3.2 Mucilage: Flaxseed is rich in mucilaginous gum, which makes up 8-12% of its seeds and is a gel-forming fiber that partially resists digestion as it moves through the gastrointestinal tract (Liu *et al*., 2018) [41]. Mucilage gum is a well-known functional fiber derived from flaxseeds, and is often used in laxatives and cough syrups (Flax Council of Canada, 2007) [26].

Flaxseed mucilage (also known as soluble flaxseed gum, SFG) is a low viscosity gel-forming fiber with potential applications as a fiber fortifier. SFG is mainly located in the outermost layer of the hull and accounts for 9.7% of the hull mass, although the composition and yield of SFG vary depending on extraction conditions and genotype (Qian KY *et al*., 2012) [62]. NFG represents approximately 27% of SFG and is primarily composed of arabinoxylans, with xylose (68.2%) and arabinose (20.2%) being the major components, along with minor amounts of galactose (7.9%) and glucose (3.7%). AFG is primarily composed of rhamnose (38.3%), galactose (35.2%), and fucose (14.7%), making it a rhamnogalacturonan.

Table 4: Composition of NFG and AFG (Qian KY *et al*., 2012) [62]

Composition of NFG	
Xylose	68.2%
Arabinose	20.2%
Galactose	7.9%
Glucose	3.7%
Composition of AFG	
Rhamnose	38.3%
Galactose	35.2%
Fucose	14.7%

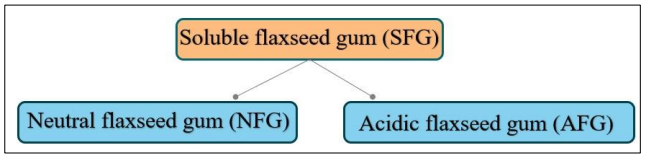

Fig 3: Classification of Soluble flaxseed gum (SFG)

Flaxseed gum (FG) has unique functional properties that can enhance the viscosity, emulsifying ability, rheology, and foaming ability of food products. The polysaccharide composition of FG is responsible for these properties. Hot water extraction is the most effective method for obtaining FG, which yields polysaccharides that have better stability, consistency, functional abilities, and commercial value. The properties of FG vary depending on the extraction method and plant variety used. Chemical or physical methods can also be applied to FG to modify its properties and achieve the desired purpose (Liu *et al*., 2018) [41].

4. Flaxseed Protein

Flaxseed contains a significant amount of protein, accounting for up to 23% of its total weight, and this amount increases to 35-40% in meal after oil extraction. Flaxseed protein has a balanced combination of amino acids, resulting in a high protein quality score of 82%, which is even superior to that of soybean (Wu *et al*., 2019) [86].

Variations in the content of protein in different flaxseed varieties can be attributed to both genetic factors and environmental conditions. The amount of proximate protein in dehulled and defatted flaxseed varies significantly depending on the cultivar, growth location, and seed processing methods used. The major proteins in flaxseed are albumin and globulin. Flaxseed protein is rich in arginine, aspartic acid, and glutamic acid, while lysine is a limiting amino acid (Chung M *et al*. 2005) [15]. The composition of flaxseed protein is given in table 5.

Flaxseed protein is not a complete protein, but it provides a similar nutritional value to soy protein, according to several studies (Bekhit *et al*., 2018; Marambe and Wanadsundara, 2017) [6, 44].

Table 5: Composition of flaxseed protein (Bekhit *et al*.2018) [6]

Amino acids	Flaxseed protein meal (g/100 g)
Alanine	4.59
Arginine	10.63
Asparagine	9.76
Cysteine	3.80
Glutamic acid	26.92
Glycine	6.14
Histidine	2.45
Isoleucine	5.21
Leucine	6.82
Lysine	4.18
Methionine	2.20
Phenylalanine	5.33
Proline	5.24
Serine	5.88
Threonine	4.19
Tryptophan	1.38
Tyrosine	2.94
Valine	5.17

Moreover, there is ample evidence to suggest that flaxseed protein has several health benefits, including anti-diabetic effects, anti-bacterial activity, angiotensin-converting enzyme inhibition, and antioxidant capacity (Franck *et al*., 2019; Marie *et al*., 2019; Nwachuku and Aluko, 2018; Wei *et al*., 2018) [46, 55].

5. Vitamins and minerals

Flaxseed is known for its high mineral content, particularly in phosphorus (650 mg/100 g), magnesium (350-431 mg/100 g), and calcium (236-250 mg/100 g), while containing only a small amount of sodium (27 mg/100 g). Flaxseed is also rich in potassium, with a content of 5600-9200 mg/kg. Increased potassium consumption has been associated with a decreased risk of blood platelet aggregation, free radicals in the blood, and stroke (Raghuwanshi V *et al*., 2019) [64].

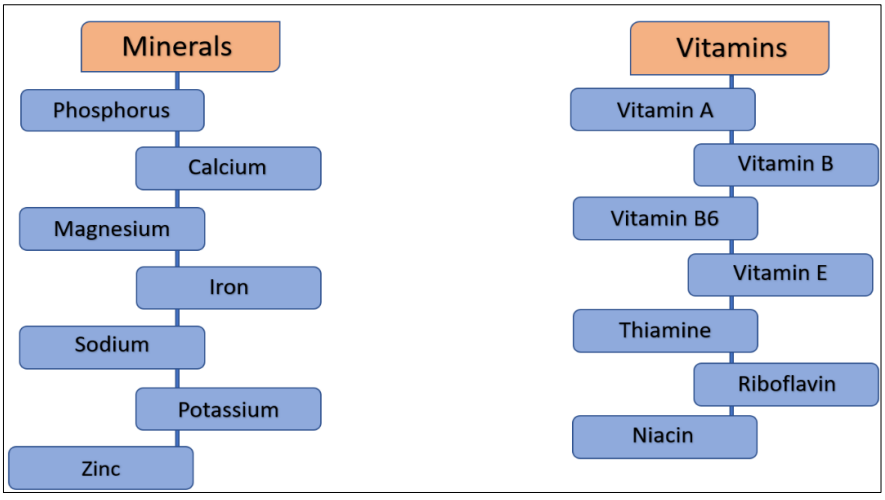

Fig 4: Minerals and vitamins in flaxseed

3. Health benefits

Flaxseed, a plant-based food source, is rich in healthy fats, fiber, and antioxidants, as indicated by Lee *et al*. (2021). In today's market, flaxseed is available in various forms, including seeds, oil, powder, and tablets, as mentioned by Shim, Gui, *et al*. (2015) [72]. Flaxseed fiber and supplements are commonly used to manage constipation and mitigate the risks associated with diabetes, cholesterol, heart disease, cancer, and other conditions, according to Shim *et al*. (2014) [72]. Lignans, antioxidants, fiber, protein, and polyunsaturated fatty acids such as ALA are some of the bioactive compounds found in flaxseed, as stated by Rubilar *et al*. (2010) [68].

Table 6: Studies conducted for specific health benefits of flaxseed and its components

Decreased risk of heart disease			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
α-linolenic acid, phenolic compounds, lignans, dietary fiber	Flaxseed pre-mixed in cookies	10g/day	Soltanian *et al*. 2019 [77]
	Flaxseed oil, roasted flaxseed, ground flaxseed, raw flaxseed	15-40g/day	Masjedi S. *et al*. 2021 [69]
	Ground flaxseed	30/day	Morshedzadeh *et al*. 2021 [50]
Hypotensive properties			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
α-linolenic acid, lignans, dietary fiber	Flaxseed powder	20-40g/day	Javidi *et al*. 2016 [34]
	Ground flaxseed	30g/day	Rodriguez-Leyva *et al*.2016 [67]
	Flaxseed powder	10-30g/day	Toulabi *et al*.2022 [81]
Hypoglycemic properties			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
Dietary fiber, α-linolenic acid	Flaxseed pre-mixed in cookies	10g/day	Soltanian *et al*. 2019 [77]
	Flaxseed powder	20-40g/day	Javidi *et al*. 2016 [34]
	Flaxseed powder	0-26g/day	Hutchins *et al*.2013
Wound healing properties			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
Omega-3 fatty acids	Flaxseed oil	1000 mg flaxseed oil	Soleimani *et al*. 2017
Skin beautifying properties			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
α-linolenic acid	Flaxseed oil	555,32 mg/capsule/day	Neukam *et al*. 2011 [54]
	Flaxseed oil	10ml/day in lotion	Hubbard, 2021 [32]

Anti-cancerous properties			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
Lignans, linoorbitides, α-linolenic acids	Extracted lignans	Flaxseed lignans + chemotherapeutic agents	Di, Y *et al*.2018
	Purified flaxseed lignans	-	Tannous, S.*et al*.2020 [80]
	Flaxseed oil	0.3-0.9% for 4-6 days	Buckner *et al*.2019 [10]
	Concentration of linusorb	80, 120, and 200 µM for 24 h	Zou *et al*.2019 [93]
	Concentrations of linoorbitides	-	Okinyo-Owiti *et al*.2015 [56]
Reduced risk of breast cancer			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
Lignans	Ground flaxseed	15g/day	Chang *et al*. 2019 [13]
Menopausal symptoms relieving properties			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
Lignans	-	5g/day	Cetisli *et al*.2015 [12]
	Flaxseed extract, ground flaxseed	90g/day	Colli *et al*.2012 [16]
Regulation of gut microbiota			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
Lignans, soluble fiber	Ground flaxseed	0.3g for each kg of body / day	Lagkouvardos, I. *et al*.2015 [40]
	Flaxseed mucilage	10g/day	Brahe *et al*.2015 [9]
Obesity preventing properties			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
Dietary fiber, flaxseed oil	Baked flaxseed	10 g of flaxseed pre-mixed in cookies twice per day for 12 weeks	Soltanian *et al*. 2018 [76]
	Flaxseed oil	4 mL/day	Ramos *et al*.2015 [65]
Soluble dietary fiber	Flaxseed fiber drink, flaxseed fiber bread	a diet with flaxseed fiber drink or with flaxseed fiber bread	Kristensen *et al*.2012 [39]
Anti-inflammatory properties			
Compounds	**Flaxseed form**	**Dosage**	**Reference**
Phenolic acids, tocopherols, linusorbs	Flaxseed oil	6g/day	Mirfatahi *et al*.2016 [48]
	Conc. linusorb	-	Ratan *et al*. 2020 [66]

4. Functional properties of flaxseed components

The addition of flaxseed significantly influences on the characteristics of products, such as colour, texture, storage stability and sensory etc. (Bekhit *et al*., 2018) [6]. Furthermore, impact of flaxseed enrichment on the quality of foods are highly depended on many factors, such as food systems, processing methods, and levels of the addition etc. Therefore, in order to minimize impact of flaxseed enrichment on the characteristics of products, the addition of flaxseed is generally controlled at a certain level.

4.1 Flaxseed oil

According to a study conducted by Condori and Chagman (Condori *et al*., 2020) [17], the addition of lycopene, a natural antioxidant, to flaxseed oil resulted in a significant improvement in its antioxidant capacity. The inclusion of

lycopene reduced the degradation kinetics of storage stability by 42%, effectively extending the shelf life of flaxseed oil by 31%. These findings suggest that lycopene holds promise as an effective method to enhance the oxidative stability of flaxseed oil, thereby preserving its quality for an extended period.

In the modern era, the food and health sectors have been leveraging advanced techniques like nano-emulsion and microencapsulation to augment the bioavailability of ω-3 polyunsaturated fatty acids found in flaxseed. These technologies provide safeguarding measures to delicate components, shielding them from factors such as heat, light, oxygen, water, and digestive processes. Consequently, these approaches facilitate the efficient transportation of these components to designated target sites.

The utilization of nano-emulsion and microencapsulation techniques for enhancing the bioavailability of ω-3 polyunsaturated fatty acids from flaxseed has been investigated by Pham *et al*. (2020) [58]. Their study emphasizes the pivotal role played by these technologies in improving the delivery of these fatty acids to desired sites, thereby enhancing their bioavailability and potential health benefits.

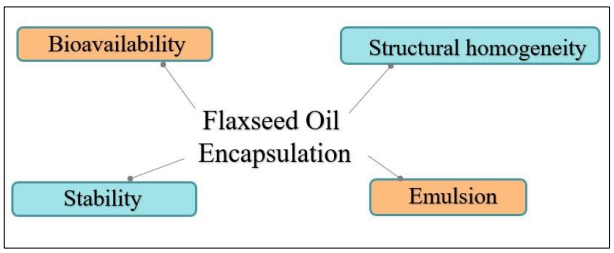

Fig 5: Properties of encapsulated flaxseed oil

4.2 Flaxseed protein

The increasing demand for plant-based proteins is driven by both health considerations and ethical concerns associated with animal product consumption. Flaxseed proteins have garnered attention as a desirable plant-based alternative to animal-derived proteins, particularly in the context of eggs, owing to their distinctive functional properties. Notably, flaxseed proteins exhibit a robust emulsification capacity (EC), allowing them to form stable emulsions in diverse food systems. This is achieved by forming a protective coating around oil droplets. It is important to acknowledge that the emulsification capacity of flaxseed protein can be influenced by factors such as heat, pH, and extraction methods. In a recent study conducted by Ye *et al*. (2022) [89], alkali solubilized flaxseed proteins displayed superior emulsification capacity compared to soy protein, gelatin, and whey protein.

Flaxseed proteins (FP) possess notable functional properties that contribute to their versatility in various food systems. One such property is their ability to form stable foams, exhibiting a consistent foaming capacity (FC) across a wide range of pH and temperatures. Another remarkable functional property of flaxseed proteins is their water and fat absorption capacity (AC), which refers to the protein's ability to retain water or fat in a food matrix without substantial structural damage. This property makes flaxseed protein suitable for use as a meat extender, as it helps prevent fat and weight loss during the cooking process. By leveraging its water and fat absorption capacity, flaxseed protein enhances the overall quality and succulence of meat-based products (Ye *et al*., 2022) [89].

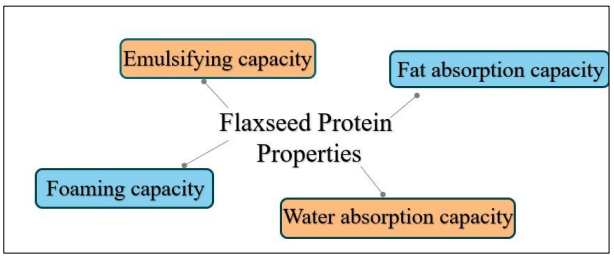

Fig 6: Properties of flaxseed protein

4.3 Flaxseed Mucilage

Flaxseed mucilage is gaining popularity as a steric stabilizer in salad dressings. Optimal stability of the emulsion was achieved using FM at a concentration of 0.75%, along with 2.5% salt and a pH of 4 (Stewart *et al*., 2000) [78]. In the meat industry, FM has shown promise as a binder due to its synergistic interactions with meat proteins, thermal stability, desirable storage modulus, and gel stability, even in high-salt environments (Chen *et al*., 2007) [14]. Its use in pork meat products has been found to enhance moisture retention, yield, and texture (Sun *et al*., 2011) [79]. Additionally, in meat sausages, a combination of flaxseed gum, carrageenan, and gellan gum has been used as a meat extender, resulting in improved texture, color, stability, water retention, and overall quality of the sausages during cooking (Zhou *et al*., 2010) [91].

FM has also found application as an additive in plant juices, dairy products, and flour-based items, contributing to properties such as thickness, emulsion stability, foam capacity, gelling ability, color, flavour, and nutrient retention (Qin *et al*., 2005; Zhang *et al*., 2020) [63, 90].

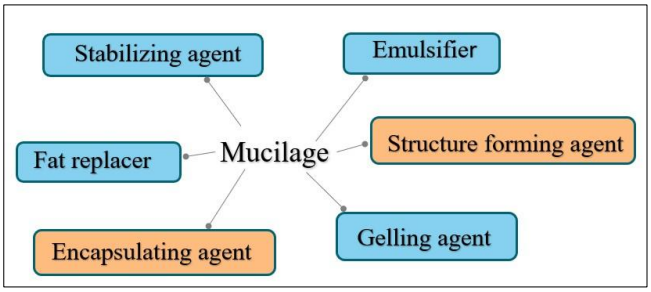

Fig 7: Properties of flaxseed mucilage/gum

4.4 Flaxseed Lignans

Flaxseed contains prominent macromolecules called lignans, with secoisolariciresinol diglucoside (SDG) being a key constituent. The presence of SDG in bread can be influenced by various factors, such as the amount of lignan or flaxseed meal added, the form of flaxseed used, and the specific bacterial or yeast cultures employed during the leavening process. Research has indicated that a significant proportion of SDG (approximately 73-75%) can be retained in bread samples, both in free form and as complexes. This suggests that SDG remains stable and withstands the heat generated during milling, fermentation, and cooking processes (Muir *et al*., 2000) [53].

Hyvärinen and Pihlava (2006) [33] conducted a study to assess

the stability of secoisolariciresinol diglucoside (SDG) in dairy products, including milk, cheese, yogurt, and whey drinks, under both cold and hot conditions. The findings revealed that SDG remained stable even when exposed to temperature changes during processes such as fermentation, pasteurization, and refrigeration. Similarly, Simbalista *et al.* (2012) [75] observed that bread enriched with whole flaxseed and defatted flaxseed flour maintained a high level of lignan content throughout various stages, including dough development, proofing, baking, and storage.

The studies indicate that lignans, including SDG, may undergo a recovery loss of 10-25% during cooking processes. However, by optimizing heating temperatures and considering factors such as flaxseed form, processing time, temperature, storage conditions, and microbial strains, it is possible to minimize this loss and preserve the SDG content in food products.

In addition, the research conducted by Hyvärinen and Pihlava (2006) [33] revealed that the secoisolariciresinol diglucoside (SDG) content in fermented foods like bread, cheese, and yogurt remained unchanged even after extended incubation periods with lactic acid bacteria strains commonly used as starters. This finding suggests that these fermented products can retain the desired nutritional benefits associated with SDG. Another study by Hall and Manthey (2005) [31] focused on the thermal stability of macaroni fortified with flaxseed. Their results showed that both SDG and alpha-linolenic acid (ALA) content remained intact throughout various heat treatments, including milling, drying, ultra-high temperatures, and shelf storage.

In another study conducted by Shim and Olivia (2014) [72], the storage stability of gluten-free flour, dough, and bread enriched with flaxseed meal was investigated at various cold temperatures (-23 °C, -18 °C, and 4 °C) over a four-week period. The findings revealed that the secoisolariciresinol diglucoside (SDG) content remained consistent throughout the study, suggesting that the processing and storage temperatures did not impact the stability of SDG in the products.

Collectively, these studies demonstrate the resilience of SDG in different food products and processing conditions, emphasizing the potential for preserving its beneficial properties during cooking, fermentation, and storage processes.

4.5 Flaxseed flour

Flaxseed flour is a commonly used ingredient in a variety of food products, either as a substitute for other ingredients or in varying proportions. The impact of flaxseed flour on food products is dependent on the quantity used. Its addition can lead to a decrease in the specific volume of breads due to its disruptive effect on the gluten structure. However, the dietary fibers present in flaxseed can enhance the dough's water retention capacity, resulting in dough expansion during cooking processes like baking. It is worth noting that incorporating flaxseed can also darken the colour of food products due to the natural dark and brownish color of flaxseed itself, as well as the occurrence of the Maillard reaction, which may impact consumer acceptance (Pourabedin *et al.*, 2017; Maidana *et al.*, 2020; Wandersleben *et al.*, 2018) [59, 43, 85]. Recent studies have explored the incorporation of both roasted and raw flaxseed flour and powder into various food products.

5. Incorporation of flaxseed components into food products

Flaxseed is a versatile ingredient that finds its way into a wide range of food products. It is commonly found in items like bread, cereals, granola bars, muffins, and cookies. Whether used in its whole seed form, ground into a powder, or as flaxseed oil, it adds nutritional value and enhances the texture and flavor of these products. Moreover, flaxseed has also made its way into dairy products such as yogurt, milk, and cheese, allowing consumers to enjoy the nutritional benefits it offers alongside their favorite dairy treats. In the realm of extruded products, such as snacks and breakfast cereals, flaxseed is often incorporated into the formulation. This inclusion not only adds a crunchy element but also boosts the nutritional content of these products. Beyond food, flaxseed oil serves industrial purposes and can be found in products like paints, varnishes, coatings, and linoleum. Its properties make it suitable for these applications, and it is derived from flaxseed. Additionally, flaxseed meal, which is a by product of oil extraction, is frequently utilized in animal feed. It serves as a source of omega-3 fatty acids and other beneficial nutrients for livestock, poultry, and even pet foods. By incorporating flaxseed into these various products, consumers can enjoy the associated health benefits, which include improved heart health, digestion, and potential anticancer properties. It is important to note, however, that the specific utilization and inclusion of flaxseed may vary depending on the product and the manufacturer. Table 7. Shows various recent food products developed by incorporating different flaxseed forms in varying proportion.

Fig 8: Various kinds products developed by flaxseed components incorporation

Table 7: Various recent food products developed by incorporation of different flaxseed components

Bakery and confectionary products			
Product name	**Flaxseed component**	**Supplementation**	**Reference**
Functional bread	Flaxseed oil	Hybrid microcapsules of flaxseed oil (2 g/mL)	Kairam, Kandi & Sharma (2021) [35]
Gluten free pizza dough	Flaxseed flour		Sapozhnikov, Kopylova, Gurova & Bolshakov (2021) [71]
Cupcake	Flaxseed sprouts powder	2%	Cakmak, Mama & Yilmaz (2021) [11]
Synbiotic dark chocolate	Fermented flaxseed	(6 g flaxseed inoculated with 109 cfu/mL of lactic acid bacteria followed by 4 days incubation	Waghmode, Gunjal & Patil (2020) [84]
Dairy products			
Product name	**Flaxseed component**	**Supplementation**	**Reference**
Yoghurt	Flaxseed powder	2.36 %	Mousavi, Heshmati, Daraei Garmakhany, Vahidinia & Taheri (2019) [52]
Yoghurt	Flaxseed powder	1 %	Marand, Amjadi, Marand, Roufegarinejad & Jafari (2020) [45]
Low fat yoghurt	Flaxseed flour	0.5%	Foutohi & Manafi Dizaj Yekan (2021) [27]
Yoghurt	Extruded flaxseed powder	2%	Ahmad *et al*. (2020) [1]
Meat products			
Product name	**Flaxseed component**	**Supplementation**	**Reference**
Fish burger	Flaxseed flour	10%	Duman (2020) [21]
Other products			
Product name	**Flaxseed component**	**Supplementation**	**Reference**
Panjiri	Flaxseed flour	10%	Karwasra, Kaur, Sandhu, Siroha & Gill (2021) [37]

6. Anti-nutritive compounds

While compounds such as cyanogenic glycosides and linatine exist within flaxseed, they have been identified as potential toxic substances. However, it's important to note that no toxicity has been reported in clinical studies involving dietary supplementation of flaxseed. Cyanogenic glycosides, including linamarin, linustatin, neolinustatin, lotaustralin, and amygdalin, are nitrogenous secondary metabolites found not only in flaxseed but also in other food items like apples, spinach, and cassavas (Parikh *et al*.2018, Bolarinwa *et al*.2015, Touré *et al*.2010, Cressey *et al*. 2019) [57, 8, 82, 18]. When ingested, these glycosides are converted by intestinal beta-glycosidase into cyanohydrin, which subsequently decomposes into hydrogen cyanide. This conversion process is facilitated by two distinct enzymes: linustatinase and linamarase β-glucosidase (Cressey *et al*.2019) [18].

Hydrogen cyanide, which can lead to acute cyanide poisoning and pose risks to the respiratory and nervous systems, has been associated with certain compounds found in flaxseed (3). However, studies have shown that the consumption of 15-100 grams of flaxseed does not result in increased plasma cyanide levels above the baseline (Cressey *et al*. 2019) [18]. Among the cyanogenic glycosides in flaxseed, linustatin and neolinustatin are considered to be the least producers of cyanide compared to others. This is due to the presence of a gentiobiose moiety in flaxseed glycosides that requires hydrolysis to glucose. The resulting cyanohydrin formed during metabolism is highly stable, resisting spontaneous decomposition into hydrogen cyanide (Cressey *et al*. 2019) [18].

Ingesting 1-2 tablespoons of flaxseed theoretically produces around 5-10 mg of hydrogen cyanide, which is unlikely to cause toxicity for several reasons. Firstly, acute toxicity typically requires a dose of 50-60 mg of cyanide. Secondly, the human body has the ability to routinely detoxify up to 100 mg/day of cyanide (Parikh *et al*. 2018, Touré *et al*.2010) [57, 82]. Additionally, cooking heat can destroy cyanide (Kajla *et al*.2015) [36]. Human studies with a daily intake of 50 grams of flaxseed did not show an increase in urinary thiocyanate levels (Parikh *et al*.2018) [57]. Based on these findings, it would be highly unrealistic to consume 1 kilogram of flaxseed daily in order to experience cyanide toxicity.

7. Conclusion

Increasing people are aware of the importance of flaxseed due to the presented bioactive compounds such as ALA, lignan, protein dietary fibre etc. Flaxseed is versatile, easy, and cheap to include in a human diet. It may be a natural form of supplementation of many essential nutrients. From the review of the scientific literature, it is possible to unequivocally confirm the effectiveness of flaxseed supplementation in improving human health. Further studies are needed to clearly establish the recommended portion of flaxseed consumption to bring into effect its biological activities. There is need to understand the impact of the incorporation of flaxseed on the macroscopic structure and mechanical characteristics of the products, and find the balance between nutrition and sensory value of products so that they are acceptable and also provide health benefits.

8. References

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