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A narrative review on nutraceutical, food and industrial applications of flaxseed (*Linum usitatissimum*. L)

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ABSTRACT

Flaxseed is a nutritional powerhouse, packed with essential nutrients such as omega-3 fatty acids, notably alpha-linolenic acid, Secoisolaricresinol diglucoside (SDG), lignans, protein, soluble fiber, and an array of phenolic compounds. This holistic nutritional profile makes flaxseed a remarkable dietary addition. A mere serving of flaxseed offers substantial protein, fiber, and omega-3 fatty acids, making it an ally in weight management, blood pressure regulation, and the reduction of cancer risk and inflammation. These health benefits make flaxseed an attractive choice for individuals seeking to improve their overall well-being. Flaxseed's appeal goes beyond its nutritional advantages. Its mild, nutty flavour and crispy texture make it a versatile ingredient that elevates the taste and consistency of a wide range of recipes. Whether sprinkled on yogurt, blended into smoothies, or used as a binder in baking, flaxseed's culinary applications are as diverse as they are delightful. Furthermore, flaxseed's potential uses extend into the food industry, aligning with Sustainable Development Goal 3, which promotes good health and well-being. The current applications of flaxseeds for attaining strategic solutions in areas of textiles, paper production, biofuels and health supplements is considered as an industrial novelty. Flaxseed's incorporation into food products contributes to the development of health-conscious and sustainable dietary options.

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Introduction

Linseed, scientifically named *Linum usitatissimum*. L but commonly known as flaxseed is a traditional plant belonging to the Linaceae family and often translated as 'extremely beneficial', boasts a rich history dating back to ancient civilizations. It is highly valued for its ability to provide both nutritious food and versatile fibers. This versatile crop has been cherished for centuries for its numerous nutritional and industrial applications. Interestingly, the term 'linseed' is commonly used in Europe to refer to the edible form of flax, while in North America, 'flaxseed' is the preferred term, reflecting regional language differences (Morya et al., 2022). Describing its appearance, linseed is recognized by its tall and slender stem, which can grow up to an impressive height of 60cm. This remarkable growth is a distinctive feature of the plant. The plant's lance-shaped

leaves have three prominent veins, measuring up to 4cm in length and 4mm in width. This remarkable plant is adorned with vibrant blue flowers, which can grow as large as 3cm in diameter. Within its fruit, you can find the prized flaxseed seeds, containing a rich store of nutrition and therapeutic benefits (Dzuovor et al., 2018; Gautam et al., 2022).

Linseed, grown worldwide, is a versatile plant that provides fiber, oil, medicinal remedies, and valuable nutrition. It has gained prominence in the realm of functional foods due to its rich content of phytochemicals, attracting attention for its potential to improve health (Sá et al., 2020). The recent excitement about flaxseed is driven by its potential health benefits, thanks to its abundance of omega-3 fatty acids, lignans, fiber, and protein (Gupta & Morya, 2022). These characteristics have been linked to numerous health benefits, including reducing inflammation, improving

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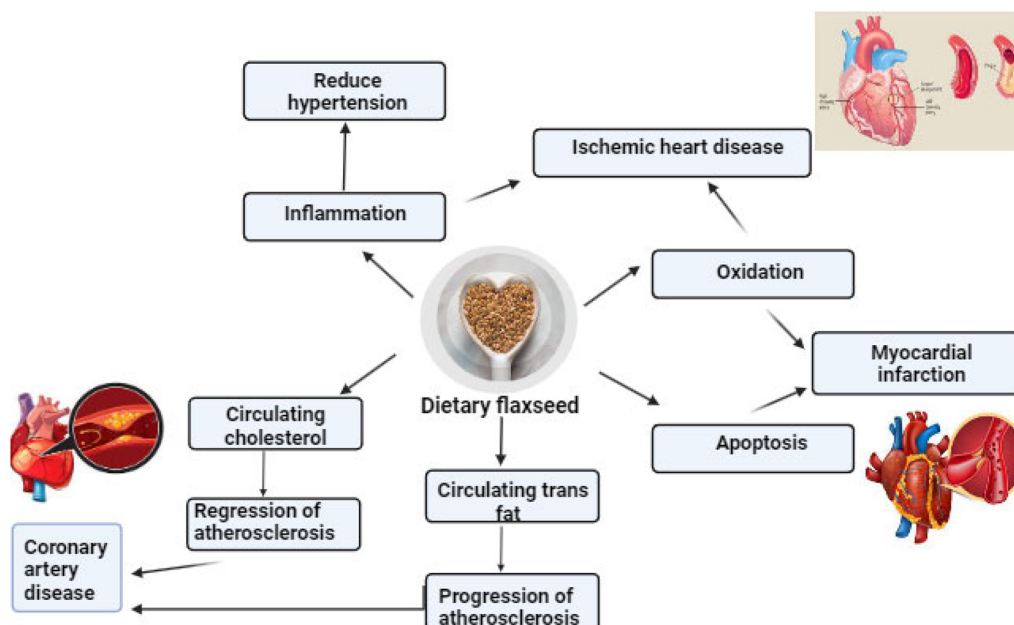


Figure 1. Effect of dietary flaxseed on maintaining cardiovascular health.

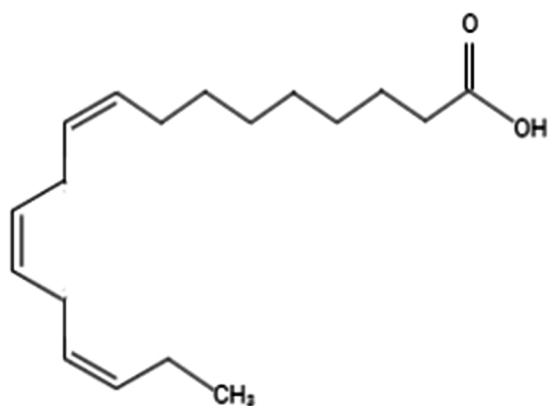


Figure 2. α – Linolenic acid.

cardiovascular health, and lowering the risk of certain cancers (Figure 1) (Rezaei et al., 2020; Awuchi et al., 2022).

Flaxseed stands out as one of the richest sources of α -linolenic acid (Figure 2), lignans, high-quality protein, and soluble fiber, highlighting its essential role in enhancing nutrition (Kumar & Goel, 2019). Furthermore, it also contains a substantial number of phenolic compounds, as illustrated in Figure 3. In addition to its nutritional benefits, flaxseed is highly regarded in the food industry for its potential as a functional ingredient. It can enhance the texture, flavor, and nutritional characteristics of a wide range of culinary creations (Taglieri et al., 2020). Apart from its uses in cooking, flaxseed has a wide range of industrial applications. The strong fibers obtained from flaxseed are used in making textiles and paper, while

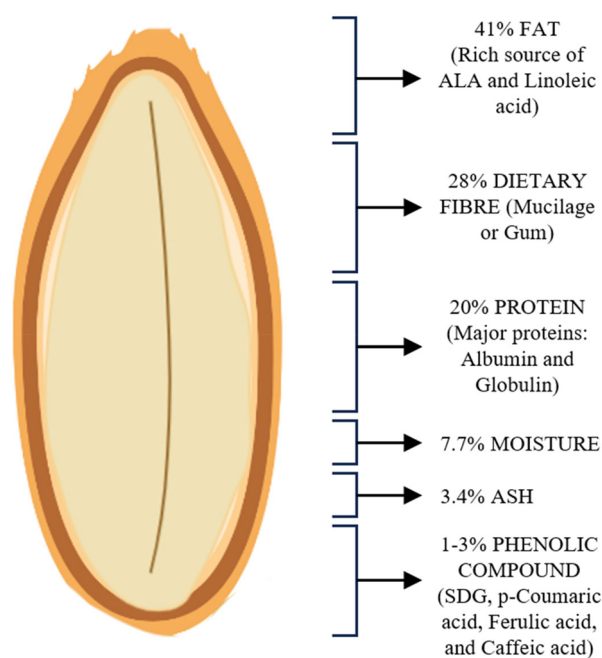


Figure 3. Nutritional composition of flaxseed.

flaxseed oil is utilized in producing paints, varnishes, and linoleum. These industrial applications enhance the economic value of this versatile crop, making it a profitable endeavour for farmers. However, realizing the potential of flaxseed in various industries comes with its own set of challenges. Adding flaxseed to food products presents logistical difficulties, including concerns related to formulation and integration (Drożłowska et al., 2020).

The circular economy and environmental stewardship ideologies are in line with the sustainable goal of achieving zero waste in the production and use of flaxseed and its by-products. To save waste, whole flaxseeds are used as much as possible in foods like bread, granola bars, and smoothies. Additionally, whole seeds can be planted in crop rotations (Taglieri et al., 2020). Optimization of the oil extraction procedure to reduce the loss of the by-product flaxseed meal is also implemented. Cold-press extraction is one technology that can cut waste while keeping more of the precious oil in the oil (Dunford, 2022). Flaxseed meal can be utilized in a variety of applications, including animal feed, dietary supplements for people, and waste-reduction in baking and cooking (Naz et al., 2019). It has a lot of fiber, protein, and good fats. Reducing waste and advance sustainability by recovering flaxseed fiber from the extraction procedure and using it to make biodegradable goods, textiles, or paper are another novel approach. Investigation on effective ways to extract lignans and other phytochemicals from flaxseed and its byproducts for use in the cosmetics and pharmaceutical industries while conserving resources has been documented in many studies (Ali et al., 2022). Creating and marketing biodegradable polymers and composites using flax fibers as an alternative to traditional resources to support a circular economy. Furthermore, adopting precision farming methods can enhance flaxseed harvesting, cut down on crop waste, and boost overall resource efficiency (Ilyas et al., 2023). To reduce waste and promote renewable energy, remaining organic waste materials, such as discarded flax plants, for the production of biogas or conversion into bioenergy are taken into account. Encouraging environmentally friendly farming methods can improve soil health and reduce waste from synthetic inputs, such as crop rotation and organic farming (Rostovtsev et al., 2023). More importantly, despite the fact that flaxseeds have many health advantages, they also include several antinutritional elements that, when ingested in excess, may be harmful to human health (Dahal & Koirala, 2020). It's crucial to remember that these substances can be processed or cooked away to a lesser extent and are normally not dangerous in moderate doses (Kataria et al., 2022). Compounds including phytic acid, oxalates, cyanogenic glycosides, lignans, and goitrogens have been reported in to have a negative impact when consumed improperly (Kataria et al., 2022). As a result, in the food industry, methods such as heat processing, boiling, soaking, fermentation, genetic modification, and enzymatic treatment are usually

employed to reduce the effect of such antinutritional compounds (Hao et al., 2020). It's crucial to consider that while lowering antinutritional compounds can be advantageous in some situations, it might not always be required or desired because some antinutrients may also have advantages for your health. The particular application and the desired result will determine the method to choose. In any situation, the food sector should prioritize rigorous monitoring of processing conditions and preserving the nutritional value of flaxseeds.

To overcome these challenges, it is essential to improve processing methods and gain a better understanding of the inherent beneficial qualities of flaxseed. Potential solutions involve using enzyme treatments to enhance the functionality of flaxseed and employing extrusion processing techniques to enhance the flavor and texture of food products (Wei et al., 2018). In light of this, the purpose of this review study is to present a thorough and current overview of the industrial, food, and nutraceutical uses of flaxseed (*Linum usitatissimum* L.). This essay aims to investigate the several applications of flaxseed using a narrative style, including topics like its possible health advantages as a nutraceutical, its inclusion in different food items, and its multiple industrial uses. This study attempts to clarify the different ways that flaxseed can contribute to human nutrition, encourage sustainable agriculture practices, and spur innovation in food and industrial processes by summarizing existing research and exploring emerging trends.

Health benefits of flaxseed

Human lifestyles have changed significantly in recent decades, becoming more characterized by a higher intake of animal products and dietary fat. Plant-based flaxseed oil, which is abundant in omega-3 polyunsaturated fatty acids (PUFAs) and inexpensive, offers a heavy metal-free diet choice. Additionally, it offers protection against various diseases, such as diabetes, inflammation, and oxidative stress, by inhibiting the production of pro-inflammatory cytokines like TNF- α , IL-6, and IL-1 (Zhu et al., 2020). The nutritional benefits of various components found in flaxseed, such as its proteins, lignans, and fiber, have garnered increased attention in recent times. The remarkable bioactive compounds present in flaxseeds offer several health advantages, including their potential to treat and prevent diseases like cancer (Mueed et al., 2023; Awuchi & Morya, 2023). Flaxseed lipids, lignans, and fiber have shown various positive effects on health, as shown in Table 1. These effects include

Table 1. Various health benefits and the mechanism of flaxseed on human body.

Health benefit	Description	Mechanism	References
High in Omega-3 fatty acids	Flaxseed is one of the best plant-based sources of omega-3 fatty acids, which are important for brain function, heart health, and reducing inflammation.	ALA is converted into eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are important for brain function, heart health, and reducing inflammation	Mirmasoumi et al., 2018
Rich in fibre	Flaxseed is high in both soluble and insoluble fibre, which can improve digestive health, regulate blood sugar levels, and lower cholesterol.	Soluble fiber binds with water to form a gel-like substance that slows down digestion, while insoluble fiber adds bulk to stool and promotes regularity	Shim et al., 2022; Morya et al., 2022
May lower blood pressure	Flaxseed may help lower blood pressure in people with hypertension, potentially reducing the risk of heart disease and stroke.	High content of alpha-linolenic acid (ALA), an omega-3 fatty acid. Omega-3 fatty acids have been shown to improve blood flow and decrease the resistance of blood vessels, which can lead to a decrease in blood pressure	Toulabi et al., 2022
May reduce cancer risk	Some studies suggest that the lignans in flaxseed may have anti-cancer properties, particularly in reducing the risk of breast cancer.	Lignans may have anti-estrogenic effects that inhibit the growth of estrogen-dependent tumors, as well as anti-inflammatory and antioxidant effects that protect against cancer development	DeLuca et al., 2018
May Improve Cholesterol Levels	Flaxseed may help reduce LDL ('bad') cholesterol levels, which can lower the risk of heart disease.	Soluble fibre binds with water in the gut to form a gel-like substance that can trap cholesterol and bile acids, preventing their absorption into the bloodstream. This can lead to a decrease in blood cholesterol levels	Naik et al., 2018
May improve blood sugar control	The fibre in flaxseed may help regulate blood sugar levels and improve insulin sensitivity, which can be beneficial for people with diabetes.	Soluble fibre slows down the absorption of glucose into the bloodstream, while lignans may improve insulin sensitivity and reduce inflammation	Villarreal-Renteria et al., 2022
May reduce inflammation	The omega-3 fatty acids and lignans in flaxseed may have anti-inflammatory effects, which could be helpful for conditions such as arthritis and asthma.	Omega-3 fatty acids are known to have anti-inflammatory effects by reducing the production of pro-inflammatory cytokines and eicosanoids, as well as inhibiting the activation of inflammatory pathways	Askarpour et al., 2020

reducing inflammation, lowering cholesterol levels, decreasing lipids in the blood, preventing atherosclerosis, and regulating post-meal blood sugar and insulin levels. Furthermore, other components of flaxseed, such as proteins and peptides, exhibit beneficial biological properties within the body, including acting as antioxidants, reducing inflammation, controlling blood pressure, modulating the immune system, and managing glucose absorption (Dzuvor et al., 2018).

Anti-inflammatory, anti-oxidant and anti-diabetic mechanisms

Recent research has started to uncover the potential anti-inflammatory effects of omega-3 fatty acids, especially in the context of chronic metabolic conditions. Flaxseed oil (FO), which contains a substantial amount of alpha-linolenic acid (ALA) and is a rich source of plant-based omega-3 polyunsaturated fatty acids (PUFAs), has attracted considerable interest in this regard (Zhu et al., 2020). Several studies have highlighted the anti-inflammatory characteristics of flaxseed oil. Interestingly, research has shown that when combined with chronic exercise, omega-3 supplementation can have a synergistic effect, improving metabolic and molecular aspects in obese mice. This effect is particularly evident in the liver and involves the activation of anti-inflammatory signaling through the G Protein Coupled Receptor 120 (GPR120) (Gaspar et al., 2019). Furthermore, a study produced

encouraging findings, showcasing the effectiveness of flaxseed as a supplementary treatment for individuals with rheumatoid arthritis. Notably, the reduction in pain, which is a clinically important outcome, has the potential to decrease the need for non-steroidal anti-inflammatory drugs. This offers a valuable alternative for individuals dealing with this condition (Ghaseminasab-Parizi et al., 2022). The complex control of inflammation in Type 2 Diabetes Mellitus (T2DM) is now being linked to Interleukin (IL) 10, a versatile regulatory cytokine.

Furthermore, immune regulatory cells, especially regulatory T-lymphocytes (Tregs), are thought to have a crucial role in managing inflammation and maintaining a balance in the immune system in T2DM (Zhu et al., 2020). The anti-inflammatory effects often seen are primarily attributed to lignans and ALA, which are key components in flaxseed. Flaxseed's capacity to reduce pro-inflammatory factors like NF- κ B, reactive nitrogen species (RNS), and reactive oxygen species (ROS) plays a role in its anti-inflammatory and antioxidant properties.

Moreover, the way flaxseed works is in line with traditional anti-inflammatory medications. It hinders the generation of inflammatory agents on various fronts, encompassing cellular (such as NO, iNOS, PGE2, COX-2, TNF- α , and IL-6), systemic, and molecular (like NF- κ B) levels (Chera et al., 2022). This versatile approach to reducing inflammation underscores the potential of flaxseed as a natural and comprehensive

method for managing inflammation in different metabolic disorders.

Recent research has revealed the potential of flaxseed and its components in relieving symptoms of depression and anxiety, demonstrating effects similar to antidepressant medications. In studies conducted with rats subjected to ongoing stress, both flaxseed flour and flaxseed oil exhibited antidepressant-like effects (Akl et al., 2020). Flavanols, specifically those found in flaxseed, have been identified as factors contributing to these effects. Their consumption has been demonstrated to mitigate negative emotions. El Tanbouly et al. (2017) conducted an *in vivo* study that emphasizes the effectiveness of Egyptian flaxseed oil, specifically the G9 and G10 cultivars, in alleviating symptoms of depression and anxiety in female rats induced with postpartum depression (PPD). This research not only highlights the potential of flaxseed oil in managing mood disorders but also underscores its ability to address associated biochemical changes.

Furthermore, another study demonstrated that the consumption of flaxseed oil over a ten-week period can lead to an increase in Brain-derived Neurotrophic Factor (BDNF) levels in the bloodstream. Elevated BDNF levels have been linked to a reduction in depressive symptoms in women dealing with depression, suggesting the potential therapeutic value of flaxseed oil in mood disorders (Poorbaferani et al., 2020). The mechanism by which n-3 polyunsaturated fatty acids (PUFAs) affect depression appears to be linked to their ability to regulate Brain-derived Neurotrophic Factor (BDNF) activity. This influence on BDNF may help alleviate depression-like behaviors triggered by lipopolysaccharide (LPS) in animals, as suggested by the research. Remarkably, flaxseed oil has shown greater effectiveness compared to flaxseed flour in various tests, such as the sucrose preference test (SPT), and has even outperformed the conventional antidepressant escitalopram (Han et al., 2020).

Flaxseed is abundant in bioactive peptides and nutritious proteins, offering various positive nutritional effects. It's worth noting that this superfood includes essential amino acids like cysteine and methionine, which are well-known for their antioxidant properties (Mishra & Poonia, 2021). Antioxidants have crucial roles in protecting biological systems from the harm caused by free radicals. They perform various functions, including scavenging free radicals, reducing oxidative stress, chelating metal ions, quenching singlet oxygen, and activating antioxidant

enzyme systems (Alachaher et al., 2018). Flaxseed extract and its hydrolysate have become promising natural antioxidants suitable for a variety of food products, such as meat, mayonnaise, and dressings. Their ability to deliver antioxidant benefits within emulsion systems plays a significant role in prolonging the shelf life of these products. These antioxidants, which are derived from phenolic compounds, effectively counteract free radicals and are especially effective at preventing autoxidation (Akl et al., 2020; Awuchi et al., 2023). The presence of flaxseed Secoisolariciresinol diglucoside (SDG) is of a great importance as a notable component with significant antioxidant power (Parikh et al., 2019). The reason behind SDG's impressive antioxidant capabilities is its capacity to interrupt the chain of free radicals by providing hydrogen atoms, thereby suppressing oxidative harm. Furthermore, the high quantity of polyphenols in flaxseed, functioning as reductones, helps transform free radicals into more stable substances, effectively halting the progression of free radical chain reactions (Alachaher et al., 2018). Scientific studies have provided substantial evidence of the various beneficial effects of flaxseed in managing diabetes. Kezimana et al. (2018) reported significant results, including lowered HbA1C levels in individuals with type 2 diabetes, decreased insulin and leptin levels, and a remarkable 80% increase in the delay of diabetes onset.

Kumaresan et al. (2018) conducted a study to evaluate the effectiveness of both prepared flaxseed milk and fermented soy milk as supplements for managing diabetes. These interventions were found to improve various diabetes-related factors, including weight loss, elevated blood sugar levels, and the HOMA-IR index, highlighting their potential as valuable tools in diabetes management. Oxidative stress induced by reactive oxygen species (ROS) is a key factor in diabetes development. Flaxseed, which is rich in Secoisolariciresinol diglucoside (SDG), possesses remarkable antioxidant properties that enable it to combat ROS and protect the liver from damage. This protective action not only slows down the progression of diabetes but also reduces the risk of diabetes-related complications. Moreover, the high content of soluble fiber and other bioactive components in flaxseeds plays a critical role in preventing and managing diabetes. These components influence insulin secretion and improve insulin function, contributing to the maintenance of normal blood glucose levels and lowering the risk of diabetes (Rehman et al., 2021; Bhavani et al., 2023).

Industrial application

Flaxseed has a wide range of applications, both in nutrition and industry. Each form of flaxseed has its distinct properties, as shown in Figure 4. Numerous industrial uses of flaxseed have been identified, and some of them are listed in Table 2.

Textile

One of the most significant industrial applications of flaxseed is in the textile sector. Flax fibers are highly valued for textiles due to their durability, longevity, and absorbent qualities (Azhar et al., 2020). Evidence of the use of flax fibres in textiles dates to ancient Egypt and spans thousands of years (Melelli et al., 2021). One of the earliest known fibres used by humans, flax fibres are derived from the flax plant's stem (Debnath, 2019). Flax fibers are an excellent choice for textiles because of their strength, durability, and absorbent properties. Linen fabrics are among the most common applications for flax fibers (Melelli et al., 2021). Fabrics like linen are made from the fibers of the flax plant. Linen is preferred in warm regions due to its durability, breathability, and ability to absorb moisture (Vârban et al., 2021). Bed linens, tablecloths, and napkins are just a few

examples of household textiles that are made from linen (Ighalo et al., 2021).

Another common use of flax fibers in textiles is the production of linen blends. Linen blends, also known as linen mixes, are created by combining flax fibers with other materials such as cotton or wool (Gębarowski et al., 2022). Linen blends are well-liked because they combine the robustness and endurance of flax fibers with the softness and comfort of other materials (Silva et al., 2018). Canvas, twine, and rope are among the specialty textiles produced from flax fibers. Flax fibers are an excellent choice for these types of fabrics due to their strength and durability (Muzyczek, 2020). Sails, tents, and awnings often make use of canvas crafted from flax fibers, while industries like construction and agriculture commonly use flax twine and rope due to their durability and strength (Bolcu & Stănescu, 2020). In the textile industry, flaxseed oil is also utilized alongside flax fibers (Debnath, 2021). Natural oil called flaxseed oil is made from the flax plant's seeds (Debnath, 2019).

Paper

The production of paper is one of the most major industrial uses for flaxseed (Chursina et al., 2019). Flax fibres are a great option for generating high-quality

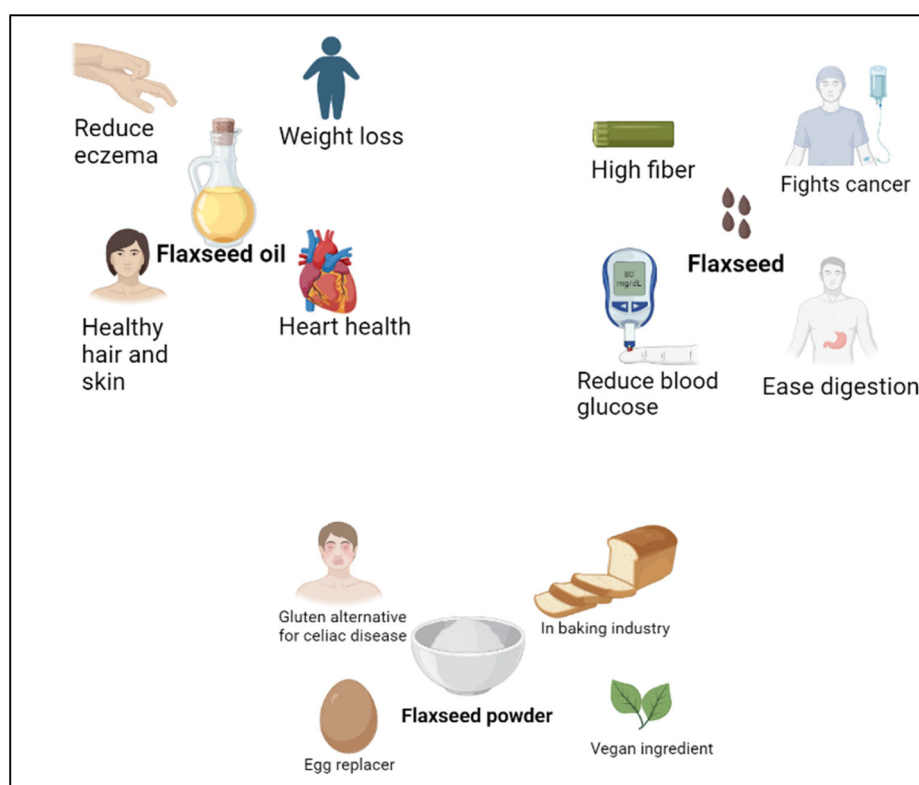


Figure 4. Various properties of flaxseed.

Table 2. Industrial application of flaxseed.

Application	Description	Product	Industry	Reference
Food	Flaxseed is used as a nutritional ingredient in food products such as breads, cereals, and snack bars. It is also used as a vegan egg substitute in baking.	Flaxseed oil, Flaxseed powder	Food	Campos-Vega et al., 2020.
Weight management	The high fibre content of flaxseeds can contribute to a sensation of fullness and aid with weight management.	Flaxseed powder	Food	Morya et al., 2022
Textile industry	Flaxseed is used in the production of textiles and industrial materials due to its strong, durable fibres. It is also used in the production of biodegradable plastics and packaging materials.	Flax fibre	Textile, Composite Material	Cassuto et al., 2022; Morya et al., 2022
Animal feed	Flaxseed meal is used as a feed supplement for livestock due to its high protein content and omega-3 fatty acids.	Flaxseed meal	Agriculture	Xu et al., 2022
Cosmetic	Flaxseed oil is used in cosmetic and personal care products due to its moisturizing and anti-inflammatory properties. It is commonly used in skin creams, hair conditioners, and body lotions.	Flaxseed oil	Beauty, Personal Care	Fale et al., 2022
Biofuel	Flaxseed oil can be used as a feedstock to produce biodiesel, a renewable energy source.	Flaxseed oil	Energy	Ganesan et al., 2022
Paper production	Flax fibres are used in paper production to create a stronger and more durable paper.	Flax fibre	Paper	Santana & Tavares, 2022
Industrial coatings	Flaxseed oil is used in the production of coatings due to its quick-drying and hardening properties.	Flaxseed oil, flaxseed mucilage	Coatings, paints	Mirbahoush et al., 2019
Construction	Flax fibres are used in construction to create insulation and strengthen building materials.	Flax fibre	Construction	Lascano et al., 2020
Soil remediation	Flax is used in phytoremediation to remove heavy metals from soil.	Flax plant	Environmental	Khan et al., 2023
Fuel additives	Flaxseed oil can be used as a fuel additive to reduce emissions and improve engine performance.	Flaxseed oil	Automotive, Energy	Sharma et al., 2022
Medical	Flaxseed oil is used in medical products such as anti-inflammatory supplements and topical treatments for skin conditions.	Flaxseed oil	Medical	Ebrahimi et al., 2021
	Flaxseeds include lignans, which have anti-cancer potential.	Flaxseed	Medical	Flower et al., 2014

paper since they are robust, long-lasting, and absorbent (Bayart et al., 2021). Evidence of the use of flax fibers in paper production can be traced back to ancient Egypt, making it one of the oldest known fibers employed by humans. These fibers are obtained from the stems of the flax plant and have been utilized for generations (Haile et al., 2021). They are an excellent choice for producing high-quality paper due to their strength, durability, and absorbent properties (Pathak & Sharma, 2021). One of the prevalent applications of flax fibers in the paper industry is in the production of specialty papers, including cigarette papers and tea bag papers (Crini et al., 2020). Flax fibers are utilized in the production of cigarette papers due to their strength, durability, and ability to burn evenly. Additionally, flax fibers are employed in the manufacturing of printing papers and currency (Dudarev, 2022). They are commonly used to produce currency because of their strength, durability, and high-density characteristics. Furthermore, they possess excellent anti-counterfeiting properties (Mbakop et al., 2018). They are environment friendly and can be easily disposed of due to biodegradable property (Abo Elgat et al., 2020).

Paint

The creation of paint is one of its important industrial uses. Several paints require flaxseed oil as an

ingredient, and producers are drawn to it by its distinctive qualities (Özcan and Uslu, 2022). The seeds of the flax plant are used to make the natural oil known as flaxseed oil. Due to its well-known drying qualities, flaxseed oil is a perfect component for oil-based paints (Yasmeen et al., 2018). Flaxseed oil goes through a process known as polymerization when it is exposed to air, which causes a tough, protective layer to form. The paint's endurance and protection for the painted surface are provided by this film (Azhar et al., 2020). The low toxicity of flaxseed oil makes it one of the key benefits of utilizing it to make paint (Gupta et al., 2022). While making paint, flaxseed oil provides a natural and sustainable substitute for synthetic binders (Seralthan & Baskaran, 2020). It is well recognized that synthetic binders include hazardous substances that can be bad for the environment and for people's health (Sharma et al., 2022).

Another well-known for its superior colour retention abilities is flaxseed oil (Hadzich & Flores, 2019). Flaxseed oil contributes to the improvement of the colour and vitality of paint when utilized in its manufacturing. Flaxseed oil is a popular option for producers who wish to create high-quality, long-lasting paints due to its distinct chemical makeup. The capacity to enhance the flow and levelling of the paint is another benefit of utilizing flaxseed oil in the manufacture of paint (Tasneem et al., 2022). Due to

its low viscosity, flaxseed oil spreads readily and uniformly over the painted surface. It is simpler for painters to obtain a uniform and smooth finish because to this characteristic (Karpova et al., 2021). Another widely used component in varnishes and wood finishes is flaxseed oil (Irin et al., 2020). The exceptional penetration capabilities of flaxseed oil-based varnishes allow them to offer great protection by penetrating deeply into the wood grain (Qamar et al., 2019). Finishes made with flaxseed oil are renowned for their longevity and ability to endure adverse weather conditions (Debnath, 2021).

Biofuels

Biofuels are sources of clean energy that come from living things including plants, animals, and microorganisms. One such biological substance that finds major industrial use in the creation of biofuels is flaxseed (Jaikumar et al., 2021). Oil, the main component used in the manufacturing of biodiesel, is abundant in flaxseed (Mandal & Kundu, 2021). The process of chemically transforming vegetable oils, like flaxseed oil, into a fuel that can run diesel engines yields biodiesel, a renewable fuel (Ahmad et al., 2019). Transesterification, a procedure used to create biodiesel from flaxseed oil, entails combining the oil with an alcohol, such as methanol, while a catalyst, such as sodium hydroxide, and is present (Asokan et al., 2021). The low viscosity of flaxseed oil makes it one of the key benefits of using it to make biodiesel. Compared to many other vegetable oils, such as soybean or rapeseed oil, flaxseed oil has a lower viscosity, making it simpler to process and refine (Gupta et al., 2021). Also, the cetane number of flaxseed oil, a gauge of its ignition quality, is high. Better engine performance is the result of the gasoline igniting more quickly and effectively with a high cetane number (Budhraj et al., 2022).

Biodiesel made from flaxseed oil is also a sustainable substitute for regular diesel fuel. When compared to conventional diesel fuel, biodiesel emits much fewer greenhouse gases because it is a renewable fuel source (Stavropoulos et al., 2023). Moreover, because biodiesel contains less sulphur, it emits less of the dangerous atmospheric pollutant sulphur dioxide (Danish et al., 2020). Biodiesel made from flaxseed oil is also a sustainable substitute for regular diesel fuel. When compared to conventional diesel fuel, biodiesel emits much fewer greenhouse gases because it is a renewable fuel source. Moreover, because biodiesel contains less sulphur, it emits less of the dangerous atmospheric pollutant sulphur dioxide (Jaikumar et al., 2021).

Food industrial application

Firstly, flaxseed is widely used as a nutritional ingredient in the food industry. Flaxseed oil is commonly used in salad dressings, margarine, and other food products as a source of healthy omega-3 fatty acids. Flaxseed powder is used as a nutritional supplement and a vegan egg substitute in baking. Flaxseed is also used in breads, cereals, and snack bars due to its high fibre and protein content (Ndou et al., 2018).

Dietary supplements

Due to its many health advantages, flaxseed is a fantastic dietary supplement that has become more well-known in recent years (Zanussi et al., 2019). Flaxseed is a great food for people who want to improve their general health because it is high in fibre, protein, and vital fatty acids (Belc et al., 2020). Flaxseed's high fibre content is one of the main advantages of using it as a dietary supplement (Abbaspour et al., 2020). Flaxseed includes soluble and insoluble fibre, which helps lower cholesterol levels, encourage regular bowel movements, and minimise the risk of colon cancer. Flaxseed's fibre also encourages feelings of fullness, which can help with weight loss (Dresseno et al., 2018).

Vegans and vegetarians should eat flaxseed since it is a superior source of protein. All the essential amino acids required for optimum health are present in the protein found in flaxseed (Morshedzadeh et al., 2019). As a dietary supplement, flaxseed can aid in increasing protein consumption, which is necessary for preserving and gaining muscle mass. Alpha-linolenic acid (ALA), an omega-3 fatty acid, and other important fatty acids are abundant in flaxseed (García-Hernández et al., 2022). The consumption of omega-3 fatty acids is necessary for optimal health and is linked to a lower risk of heart disease, stroke, and several types of cancer. Flaxseed can help raise omega-3 fatty acid intake and enhance general health when taken as a dietary supplement (Saleh et al., 2019).

Baking industry

There are several straightforward ways to incorporate flaxseed into baked goods. One approach is to finely grind flaxseed and then blend it into the batter or dough (Ahmad et al., 2021). These methods can improve the nutritional profile and texture of baked goods. Another option is to substitute flaxseed oil for other oils or fats in the recipe, which can enhance

both the flavor and nutritional content of the baked items. In vegan baking, flaxseed can also serve as a replacement for eggs. Ground flaxseed can be used in recipes instead of eggs because it forms a gel-like consistency when mixed with water (Bryant & DeClue, 2021). This approach can potentially reduce the fat and cholesterol content in baked goods while preserving a comparable texture and structure (Viana et al., 2023). Due to its numerous health benefits and versatility, flaxseed has gained popularity as an ingredient in the baking industry. Many baked goods, including bread, muffins, cookies, cakes, and more, can incorporate flaxseed.

Flaxseed bread is a popular baked product where the bread batter includes ground flaxseed (Wirkijowska et al., 2020). Flaxseed bread serves as a nutritious alternative to conventional bread, boasting high fiber content and essential fatty acids. Additionally, it is gluten-free, making it an excellent choice for individuals with celiac disease or gluten intolerance (Saka et al., 2022). Celiac disease (CD), a chronic condition characterized by immune-mediated damage to the small intestine, develops in individuals with specific genetic predispositions when they consume dietary gluten (Kumari & Morya, 2021).

Flaxseed cakes, which incorporate ground flaxseed into the cake mix, offer a delicious and nutritious alternative to traditional cakes (Taglieri et al., 2020). These cakes serve as a wholesome and satisfying dessert choice due to their abundance of fiber, protein, and essential fatty acids. Flavors like lemon, vanilla, or fresh fruit can be used to create a variety of delicious flaxseed cakes (Cakmak et al., 2021).

Flaxseed crackers are made with dough that includes ground flaxseed, resulting in a nutritious and crispy snack option (Nassef et al., 2023). They can serve as an excellent alternative to regular crackers, which often contain excessive salt and unhealthy fats, thanks to their high fiber and essential fatty acid content. Various flavors and spices like garlic, rosemary, or cumin can be used to create tasty flaxseed crackers (Yawale et al., 2022).

Flaxseed Muffins are another popular baked treat that incorporates ground flaxseed into the recipe (Kumari & Khetarpaul, 2019). They offer a nourishing and satisfying option for breakfast or snacks due to their high fiber, protein, and essential fatty acid content. One can use various flavors and ingredients like blueberries, chocolate chips, or nuts to create delicious flaxseed muffins (Sunwar, 2022).

Table 3. Future prospects of flaxseeds in various novel advancements.

Nutraceutical advancements	Functional foods	Flaxseed can also be included in functional meals and supplements that target particular health issues, such as weight management, digestive health, and cardiovascular wellbeing.	Raghuwanshi et al., 2019
	Bioactive compound isolation	To further understand their modes of action and potential therapeutic applications, researchers can concentrate on extracting and identifying particular bioactive components within flaxseed.	Mueed et al., 2023
	Personalized nutrition	Incorporating a person's genetic make-up and health condition into dietary recommendations could be made possible by advances in nutrigenomics.	Capcanari et al., 2021
Food industry	Plant-based products	Flaxseed has the potential to be a prominent ingredient in baked products, dairy substitutes, and meat substitutes thanks to the growing demand for plant-based cuisine.	Lira et al., 2023
	Clean labelling	As a natural source of fiber, omega-3 fatty acids, and antioxidants, flaxseed can help clean-label products meet customer expectations for natural, minimally processed ingredients.	Alexandri et al., 2022
	Noval product development	Food scientists can experiment with the creation of new foods, beverages, and condiments made from flaxseed.	Oomah, 2020
Industrial application	Biodegradable materials	Flax fibers can be used to create biodegradable polymers and composites, which will address environmental issues with traditional plastics.	Akhila et al., 2023
	Biofuel production	Diversifying renewable energy sources and lowering greenhouse gas emissions may be made possible through research into flaxseed as a potential feedstock for biofuels.	Bujnovský et al., 2020
	Phytochemical extraction	It is possible to extract phytochemicals from flaxseed for use in medicines, cosmetics, and other industrial purposes.	Noreen et al., 2023
Sustainable agriculture	Crop improvement	Development of flaxseed varieties with superior features, such as greater production, disease resistance, and improved nutritional value, may result from ongoing research in crop breeding and genetic engineering.	Bayat et al., 2022
	Crop rotation and agroecological practices	In crop rotation systems, promoting the use of flaxseed can improve soil health, lower the demand for chemical inputs, and promote sustainable agriculture.	Sainju et al., 2020
International collaboration and trade		Collaboration between nations can enable the transfer of knowledge and technology, encouraging international trade in goods derived from flaxseed and fostering economic development.	Pourchasse, 2019
Consumer education and awareness		The food and nutraceutical industries can see improved customer demand and product development by raising knowledge of the nutritional and health benefits of flaxseed.	Urbisz et al., 2021

Flaxseed cookies are a delightful and nutritious treat because their cookie batter includes ground flaxseed. These are an excellent alternative to regular cookies, which often contain excessive sugar and unhealthy fats, thanks to their high fiber and essential fatty acid content (Karakurt et al., 2022). Cookies made with flaxseed can be crafted in a range of flavors, including peanut butter, oatmeal, and chocolate chip varieties (Ahmad et al., 2020).

Future prospects

Future prospects for flaxseed (*Linum usitatissimum* L.) include a variety of intriguing options in the food, industrial, and nutraceutical sectors. Some of the crucial areas for research and development in the future have been proposed in Table 3.

Conclusion

The recent years have shown the advantages of using flaxseed in various therapeutical and industrial applications. The nutritive value of flaxseed has been applied for the development of functional foods and therapeutic agents which are essential for overall health and the prevention of chronic diseases such as osteoporosis, cancer, and heart disease. Incorporating flaxseed into your diet can be a simple and delicious way to boost your nutrition. However, the use of flaxseed in the food industry is somewhat limited due to its strong flavor, which can be undesirable in certain food products. Managing the potent taste of flaxseed has been a challenge, leading to various approaches such as substituting flaxseed oil for whole flaxseed or using microencapsulation techniques to mask the flavor. Due to its wide range of uses in numerous industries, flaxseed is of major industrial significance. Flaxseed has long been a significant resource, used in everything from the creation of paints and varnishes to the production of textiles like linen. Its oil is also utilized to strengthen composite materials and is a crucial component in the manufacturing of biofuels. Flaxseed's adaptability extends to agriculture, where it helps improve soil quality and offers nutrient-rich animal feed. Flaxseed has a position in the world of health and wellness as a source of functional foods and dietary supplements. Flaxseed continues to be an important and sustainable resource that meets both human and industrial demands thanks to its environmentally favorable qualities, strong nutritional content, and flexibility to a variety of industries. Flaxseed's importance is projected to increase as sectors look for

more ecologically friendly and sustainable solutions, bolstering its position in the industrial landscape.

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Disclosure statement

The authors declare no conflict of interest.

Notes on contributor



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