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Comprehensive Review on Flaxseed: A Nutraceutical Wonder

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Abstract
With a long history, flaxseed (Linum usitatissimum) is used for many things, mainly for its incredible health benefits. As it is well-known for its profusion of nutrients and health benefits, including w-3 fatty acids and antioxidants, it is often consumed to reduce the risk of heart disease, cancer, and menopausal symptoms. Nowadays, flaxseed is recognised as a healthy dietary supplement with several advantages. Along with describing in detail the composition of flaxseed, this paper also focuses on various ways in which flaxseed is consumed. Flaxseed oil, being one form of consumption, is generally found to be more common, due to its various advantages as compared to other DHA oils, including antimicrobial, immunomodulatory effects, benefits against heart disease, etc. This paper also discusses the extraction of flaxseed oil, focusing mainly on mechanical pressing. Yet another form of consumption is flaxseed oil powder, and hence, this paper also discusses the microencapsulation process in detail by comparing various wall materials for the same.

Keywords: Flaxseed, Health Benefits, Functional Food, Nutraceuticals, Linolenic Acid

1. Introduction [1]

Flaxseed, one of the oldest crops, has been grown since the dawn of humanity. Flaxseed is scientifically known as Linum usitatissimum, which means "very useful" in Latin. Colonialists first brought flax to the United States with the intention of using the fabric to make clothing. Every component of the flaxseed plant is used economically, whether it is processed or not. The stalk produces solid and long-lasting fibres of excellent quality. Animal nutrition is made with flaxseed oil and its by-products. The words flaxseed and linseed have a slight difference in usage. Linseed is used to describe flax when it is used for industrial and feed purposes, while flaxseed is used to describe flax when people eat it as food. Due to the possible health benefits linked to some of its biologically active components, flaxseed has drawn more attention in the last 20 years in the field of diet and disease research. In terms of nutrients, linolenic acid (ALA), short-chain polyunsaturated fatty acids (PUFA), soluble and insoluble fibres, phytoestrogenic lignans (secoisolariciresinol di glycoside-SDG), proteins, and a variety of antioxidants are abundant in flaxseeds. Its rising popularity is a result of its health benefits, which include lowering the chance of cardiovascular diseases, cancer, especially of the mammary and prostate glands, as well as menopausal symptoms and osteoporosis. The two most common types of flaxseed are brown and yellow or golden. Both have an equivalent amount of short-chain w-3 fatty acids and comparable nutritional properties. Figure 1 below explains the journey of flaxseed from 8000 BCE, after its initial discovery, through the 19th century, up until the 2000s.

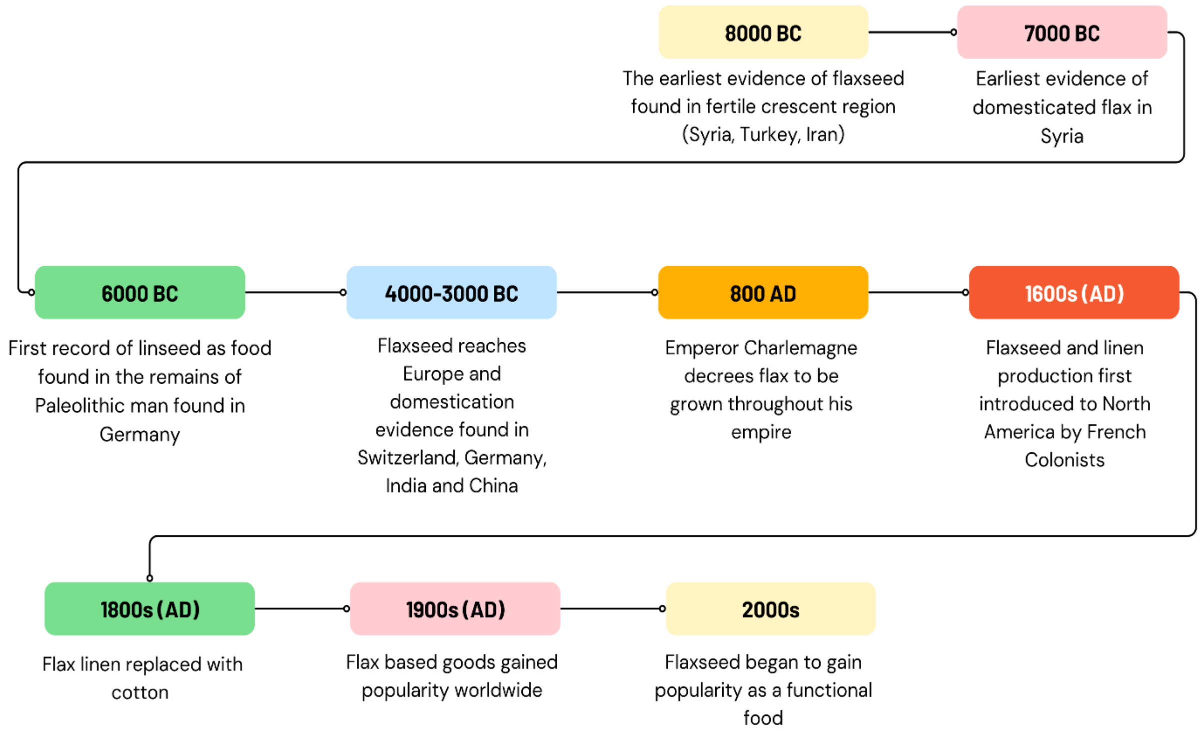

Figure 1: Timeline for Flaxseed [2], [3], [4]

Today, flaxseed is widely recognised as a nutritious food and dietary supplement. Research suggests that it may have a range of health benefits, including reducing the risk of heart disease, improving digestive health, and reducing inflammation.

2. Composition of Flaxseed [5]

The main components of flaxseed are fats, protein and dietary fibre, and its composition can vary based on genetics, cultivation environment and methods of seed processing. For example, an analysis of brown Canadian flaxseed revealed that it contained 41% fat, 20% protein, 28% total dietary fibre, 7.7% moisture, and 3.4% ash on average. This example sheds light on the differences in the composition of flaxseed mainly due to the cultivation environment. Flaxseed has grown popular in recent years as one of the most versatile functional foods, owing to the presence of predominantly three bioactive compounds: alpha-linoleic acid, dietary fibre and lignans.

2.1. Alpha-linoleic Acid

One of the major bioactive components of flaxseed, alpha-linolenic acid (ALA), serves as a leading source of w-3 fatty acids in vegetarian diets. Fatty acids are incredibly essential for the human body. However, the body cannot synthesise fatty acids due to the absence of the enzyme responsible for the production of fatty acids. As a result of this, the fatty acids need to be included as a part of the diet or in the form of a dietary supplement. Omega (w) fats are classified into two types: w-3 and w-6 fatty acids. Linolenic acid, eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) are three nutritionally essential w-3 fatty acids. All three fatty acids have proved to reduce the risk of cardiovascular diseases.

The Soxhlet and Supercritical CO_2 extraction methods were compared for flaxseed oil composition regarding ALA. The results showed that, compared to the Soxhlet extraction method (56.7%), supercritical CO_2 extraction yielded a higher average ALA content (60.5%).

2.2. Lignans

Flaxseed is also one of the richest sources of lignans. Lignans are basically phytoestrogens, which are predominantly available in fibre-rich plants, cereals, legumes, vegetables, fruits, berries, and alcoholic beverages. Flaxseed contains 75-800 times the amount of lignans as cereal grains, legumes, fruits, and vegetables. The first plant lignans discovered in foods were secoisolariciresinol and matairesinol. Pinoresinol and lariciresinol are newer plant lignans that contribute significantly to total dietary lignin intakes.

Lignans are diphenolic compounds formed by the reaction of two coniferyl alcohol residues found in the cell walls of higher plants. The main lignan in flaxseed is secoisolariciresinol diglycoside (SDG), with minor amounts of matairesinol, pinoresinol, lariciresinol, and isolariciresinol. SDG levels in defatted flour range from 11.7 to 24.1 mg/g, while whole flaxseed flour contains 6.1 to 13.3 mg/g.

2.3. Dietary Fibre (Mucilage and Gum)

Dietary fibre refers collectively to the variety of plant substances that are not easily digested by the enzymes responsible for human digestion. Flaxseed meal is obtained in the following forms: crude, acid detergent, neutral detergent, and total fibres (cellulose, lignin and hemicellulose). Fibre content ranges from 22% to 26%, which is twice the percentage of high-fibre beans. A half ounce of dry whole flax seed provides 20% to 25% of your daily fibre requirements.

Flaxseed contains soluble and insoluble dietary fibres in varying proportions ranging from 20:80 to 40:60. The soluble fibre fractions are mucilage gums, and the significant insoluble fibre fractions are cellulose and lignin. Total fibre is made up of both dietary and functional fibre. Functional fibre is made up of nondigestible carbohydrates extracted from plants, purified, and added to foods and other products. Dietary and functional fibres are not digested or absorbed by the human small intestine and thus pass relatively undigested into the large intestine.

Work done by Cui W et al. 1994 [6], states that flaxseed mucilage is related to the hull of flaxseed and is essentially a gum-like material composed of acidic and neutral polysaccharides. The neutral fraction of flaxseed contains 62.8 %t xylose, while the acidic fraction contains mainly rhamnose (54.5 %), followed by galactose.

2.4. Protein

Flaxseed protein content has been reported to range between 10.5% and 31%. Madhusudhan & Singh, 1983 [7], stated that in India, Khategaon cultivars had a protein content of 21.9%. Similar to other vegetables, flaxseed proteins have techno-functional properties that affect their behaviour in a food system through interactions with other ingredients. Their hydration mechanisms primarily determine solubility and water-oil retention capacity. Differences in protein are mainly related to genetics and environment.

According to Soni et al. 2016 [5], it was observed that the protein content of dehulled and defatted flaxseed varied greatly depending on cultivar growth location and seed processing. Hull fraction has lower protein levels, and dehulling raises the protein level of flaxseed from 19.2% to 21.8%. Flaxseed proteins were found to be structurally more lipophilic than soybean proteins due to the influence of their polysaccharide composition, being 20% albumins of low molecular weight proteins (1.6S and 2S) and 80% globulins of high molecular weight proteins (11S and 12S). The main proteins found in flaxseed are albumin and globulin-type proteins. Flaxseeds are appreciably comparable to soybeans with respect to their amino acid profile and nutritional value.

3. Health Benefits

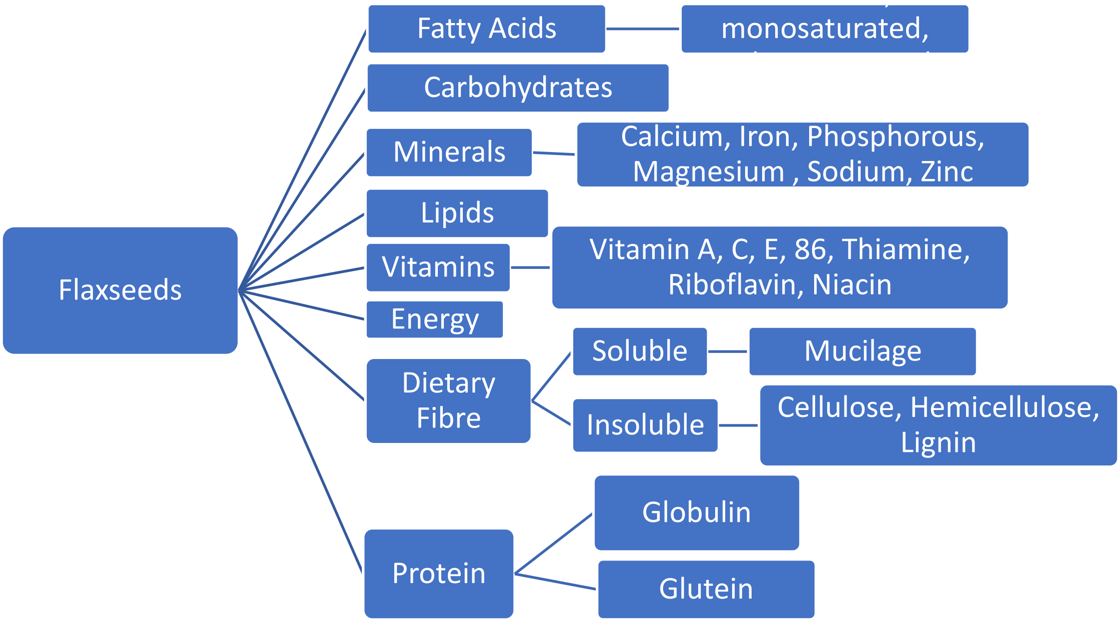

Figure 2: Nutritional profile of flax seed [8]

Figure 2 above gives a brief idea about the nutritional profile of flaxseed. Bierenbaum et al., 1993 [9], demonstrated that the antioxidant activity of flaxseed lowers both platelet aggregation and total cholesterol. It has previously been demonstrated that the flaxseed lignin Secoisolariciresinol Diglucoside (SDG) and the mammalian lignans Enterodiol (ED) and Enterolactone (EL) are potent antioxidants that prevent lipid peroxidation and DNA damage. It was determined that SDG and SECO's 3-methoxy-4-hydroxyl substituents were responsible for the lignan's antioxidant activity. Research has demonstrated the potential of flaxseed's secoisolariciresinol diglucoside to avert or postpone the onset of type 1 and type 2 diabetes.

According to Soni et al. 2016 [5], it was found that the long-chain polyunsaturated fatty acids have been shown to have immune modulatory effects, and further examined the role of PUFA consumption during pregnancy and early childhood and its influence on allergy and respiratory diseases. The potential protective role of allergy and respiratory diseases has been demonstrated by decreased consumption of omega-6-PUFAs in favour of more anti-inflammatory w3PUFAs (flax is rich in ALA, a biological precursor to w3-fatty acid) in modern diets.

By reducing cytokine production, which in turn reduces immunoglobulin E synthesis and T helper two-cell differentiation, w3PUFAs may change the balance of T helper cells. PUFAs can change gene expression, induce the metabolism of eicosanoids, and modify the cellular membrane.

Other important studies [10], [11], [12], [13], [14],[15], found that, in animal models, flaxseed has been demonstrated to lower the incidence and early risk markers for colonic and breast cancer. Additionally, epidemiologic studies have demonstrated that lignin concentrations were significantly lower in omnivores and breast cancer patients and that the prevalence of breast cancer is lower in nations with a vegetarian diet. As a result, it is becoming increasingly clear that lignans have many advantageous qualities.

According to Frische et al., 2003 [16] and Flower et al., 2013 [17], it was found that without altering the premenopausal women's serum hormone concentration, flaxseeds dramatically enhanced the excretion of lignans in the urine, indicating that a mechanism other than a hormonal effect may have been responsible for the flaxseed's reported chemoprotective effects. The efficacy of lignans and other flaxseed compounds (ALA and fibre content) in easing menopausal symptoms in women with breast cancer, as well as their possible influence on the incidence or recurrence of breast cancer, were examined. After comparing all of the studies they looked at, the authors concluded that flax may be linked to a lower risk of breast cancer. Moreover, flax showed anti-proliferative properties in the breast tissue of breast cancer-risk women. The risk of death may also be lowered for those who have breast cancer.

4. Consumption of Flaxseed

Whole flaxseed, ground flaxseed, and flaxseed oil are the three most common forms of flaxseed that are suitable for human consumption. The type of flaxseed consumed determines how stable it is and what bioactive components it contains.

4.1. Flaxseed Oil [18]:

When it comes to ALA content, flaxseed oil is higher than flaxseed meal or whole seed. The flaxseed oil that is extracted has the highest oxidation sensitivity. Selecting unrefined flaxseed oil is crucial. It has a longer shelf life because it contains antioxidants like tocopherols and phenolic compounds. An opaque glass container kept in the refrigerator will keep flaxseed oil fresh for up to six months. Even at room temperature, flaxseed oil can oxidise in less than a week, at which point it becomes unsafe for human consumption. Flaxseed oil can be stir-fried at a moderate temperature, added to smoothies, cooked in muesli and used in homemade salad dressings and vegetable glazes.

4.2. Whole Flaxseed [19]:

Whole flaxseed can tolerate temperatures as high as 350 °C without losing any of its oxidative stability due to the presence of ALA. Thus, whole flaxseed should be kept for four to twenty months at room temperature in airtight containers in order to maintain its health-promoting properties. The hard, impermeable seed coats of flaxseed provide the lowest amount of ALA and SDG when consumed whole. While whole flaxseeds must be of the highest calibre, damaged seeds are more likely to develop rancidity, which can be identified by the seeds' musty "oil paint" stench. According to Best, 2004 [20], when used in place of up to 50% of the flour or bread crumbs in a batter, breading, or crust, whole milled flaxseed adds flavour and colour and holds up well under deep frying. Since flaxseed contains 35–45% oil, it is possible to omit an equivalent amount from any recipe calling for oil when flaxseed is also an ingredient.

4.3. Ground Flaxseed [19]:

Work done by Best 2004 [20] stated that since whole seeds were meant to pass through the digestive system, they must be cracked or ground in order to obtain their complete nutritional value. The flaxseed's sensitivity to oxidation is increased when the seed coat barrier is broken through grinding. Since ground flaxseed is more susceptible to oxidation than whole flaxseed, it should be used soon after being ground and kept in storage for a brief amount of time. When compared to whole flaxseed, the consumption of flaxseed oil and ground flaxseed led to noticeably higher plasma ALA levels.

According to Manthey et al. [21] and Menteş, 2008 [22], it has been demonstrated that using 15% w/w flaxseed flour increases the shelf life of fresh pasta by inhibiting microbial activity. The noodles treated with 15% w/w flaxseed flour inhibited the growth of mould. Also, adding 10% ground flaxseed to bread significantly increased its volume, specific volume, and Dallman degree and delayed the staling process. The same goes for eggs: 15 grams of ground flaxseed steeped in 45 millilitres of water for two minutes will replace one egg.

Ground flaxseed can be mixed into smoothies, baked goods, orange or other juices, and just about anything else. If ground or whole flaxseed makes up 6–8% of the dry ingredients in the recipe, it can be added to nearly any baked good. It gives bread, waffles, pancakes, and other products a nutty flavour.

5. Benefits Of Flaxseed Oil Over Other DHA Oils [23]

5.1. Risk Against The Heart

Research has indicated that the primary constituents of cold-pressed fish oil, eicosahexaenoic acid (EPA, 20: 5n-3) and docosahexaenoic acid (DHA, 22: 6n-3), are linked to a decreased risk of cardiovascular diseases, including arrhythmia, sudden cardiac death, and atherosclerosis. Rich in α-linolenic acid, flaxseed oil is thought to be a natural precursor of EPA and DHA. When fish oil and flaxseed oil are supplemented, the levels of EPA and DHA in the erythrocyte membrane rise at rates that are proportionate to the amount of the supplement. While DHA remained unchanged, supplementation with flaxseed oil increased EPA in the erythrocyte membrane to 133% ($P<0.05$) and docosapentaenoic acid (DPA, 22:5 3) to 120% ($P<0.01$) of the baseline level. In contrast, supplementation with cold fish oil increased both EPA and DHA to 300% ($P<0.001$) and 42% ($P<0.001$), respectively, in the erythrocyte membrane.

5.2. Metabolic Effects

In a clinical study, the effects of oils high in w3 fatty acids (ALA), like sunflower oil, on plasma lipids and low-density lipoproteins (LDL) were evaluated. In order to achieve dietary consumption ratios of w6: w3 PUFA of 0.5, 27.9, and 5.2, respectively, 57 men with an atherogenic lipoprotein phenotype (ALP) were randomly assigned to one of three diet regimens enriched with flaxseed oil (FXO: high ALA, number of participants = 21), sunflower oil (SOF: high linoleic acid, number of participants = 17), or fish oil (FO, number of participants = 19). These diet regimens were administered over a period of 12 weeks. The findings demonstrated that while DHA and EPA increased after fish oil ($P<0.001$), ALA and EPA relative abundance in erythrocyte membranes increased in the diet ($P<0.001$). There was a decrease in total plasma cholesterol (FXO -12.3%, $P=0.001$; SOF -7.6%, $P=0.014$; SO -7.3%, $P=0.033$), with FXO exhibiting the largest effect. It has also been reported that ALA derived from flaxseed oil has a positive impact on improving insulin resistance, treating obesity, and preventing diabetic retinopathy.

5.3. Effects on Skeletal Muscle and Bone Health

Consuming a range of w3 PUFA sources may help maintain bone health during the growth stage, according to an animal study. When compared to rats fed salmon oil, rats fed flaxseed oil, which is high in alpha-linolenic acid, demonstrated improvements in the bone microarchitecture. In conclusion, consuming flaxseed oil can enhance the lipid composition of skeletal muscle and support the health of the bones. Although more research is needed to compare the effectiveness of flaxseed oil with other w3 rich oils, it is evident that flaxseed oil can support bone health through a number of mechanisms, primarily the stimulation of osteogenesis.

5.4. Effects on Central Nervous System and Depression

DHA and EPA, two w-3 fatty acids found in fish oil, are vital for brain function and are also necessary for the construction of cell membranes. Numerous mood disorders have been linked to w3 fatty acids, according to reports. Fish consumption has been shown to have an inverse relationship with depression, according to epidemiological studies. Similarly, a flaxseed oil dietary supplement showed promise in the management of depression. It has been demonstrated that giving rats exposed to unexpected chronic stress 10% flaxseed oil improved both behavioural despair and anhedonia. Furthermore, in a rat model of postpartum depression, an Egyptian cultivar of flaxseed oil was reported to show significant antidepressant-like activity. Anxiety-like behaviours (improved plus maze, forced swim test, and open field test) were assessed in postpartum depression-induced rats, and the results showed that oral administration of flaxseed oil (270 mg/kg/day) for two weeks during the postpartum period improved anxiety and depressive symptoms.

5.5. Antimicrobial and Immunomodulatory Effects

The potential antimicrobial properties of natural products are widely acknowledged. Research has indicated that fish oil has anti-inflammatory properties and can be used to treat inflammatory conditions such as rheumatoid arthritis. Corresponding to this, flaxseed oil's anti-inflammatory, immunoregulatory, and antibacterial properties were evaluated; these effects were primarily attributed to its abundance of w3 PUFAs.

It has been suggested that consuming more flaxseed oil in the diet can lower immune function markers. It has been reported that increasing dietary supplements containing polyunsaturated fatty acids from flaxseed oil can improve acute pneumonia. Researchers looked at how supplementing with flaxseed oil affected the progression of Streptococcus pneumoniae and caused pneumonia in a mouse model. The animals' ability to colonise their lungs with S. pneumoniae was protected by long-term supplementation, as evidenced by the reduced histopathological involvement of lung tissue in the animals' lungs. Comparing supplemented infected mice to control mice, moderate pneumonia was found as opposed to severe pneumonia. Additionally, a reduction in inflammatory markers was noted. However, short-term supplementation did not appear to have any impact on lung colonisation.

Three groups of mice (n=60) were compared to evaluate the impact of w3 PUFA on apoptosis and macrophage phagocytic activity. The first group was fed cod oil, the second group was fed flaxseed oil, and the third control group was fed a regular diet.

The apoptotic and phagocytic activities of alveolar macrophages were assessed following a 9-week supplementation period. The groups fed sea cod oil and flaxseed oil showed a significant increase ($P<0.05$) in both bacterial uptake and intracellular killing of S. pneumoniae in their alveolar macrophages. Furthermore, upon interacting with the bacteria, alveolar macrophages from these groups exhibited a significant ($P<0.05$) decrease in apoptotic cells, whereas alveolar macrophages from the control group displayed the highest level of apoptosis. These findings confirmed that PUFA supplements in the diet can improve alveolar macrophages' capacity to phagocytose pathogens and decrease apoptosis.

6. Flaxseed Oil Powder

Flaxseed oil powder is a type of dietary supplement made by spray-drying flaxseed oil onto a carrier material, such as maltodextrin or sodium caseinate. This process creates a fine powder that can be added to foods and beverages or taken as a standalone supplement. Flaxseed oil powder is often used by people looking to improve their cardiovascular health, lower inflammation, support brain function, or promote healthy skin and hair. Flaxseed oil powder is typically made by first extracting the oil from flaxseeds using a cold-press or solvent extraction method. The oil is then spray-dried onto a carrier material, which can vary depending on the manufacturer. Maltodextrin is a common carrier used in flaxseed oil powders, as it is a neutral-tasting carbohydrate that can help to stabilise the oil and prevent it from oxidising. Other carriers that may be used include sodium caseinate, whey protein, or acacia gum.

Leading companies producing flaxseed oil powder [24], [25], [26], [27], [28]

1. Navitas Organics: A US-based company that specialises in organic superfoods, including flaxseed oil powder.

2. Healthworks: A US-based company that offers a range of superfoods, including flaxseed oil powder, that are sourced from organic and sustainably grown ingredients.
3. JustIngredients: A UK-based company that offers a range of food ingredients, including flaxseed oil powder, that are of high quality and sourced from sustainable suppliers.
4. Now Foods: A US-based company that offers a wide range of health supplements and food products, including flaxseed oil powder.
5. Indigo Herbs: A UK-based company that offers a range of high-quality, organic superfoods, including flaxseed oil powder.

7. Market Research [29]

The following graphs describe the overall market survey for Flaxseed in India. The market survey presented in this paper takes into account various parameters like flaxseed production in India, area of flaxseed harvest in India, product export value of flaxseed and its oil, flaxseed yield, flaxseed oil production, and import data for flaxseed and its oil.

Figures 3 and 4 below describe the trend of production of flaxseed (tonnes) along with the area of flaxseed harvest (ha) and the yield of flaxseed (100g/ha). From 2012 to 2018, the production of flaxseed remained consistent, ranging from 323000 to 326180 tonnes, with only marginal variations over the years, and subsequently suffered a drop in 2020. Roughly, the same trend is observed for the area of flaxseed harvest and the yield of flaxseed.

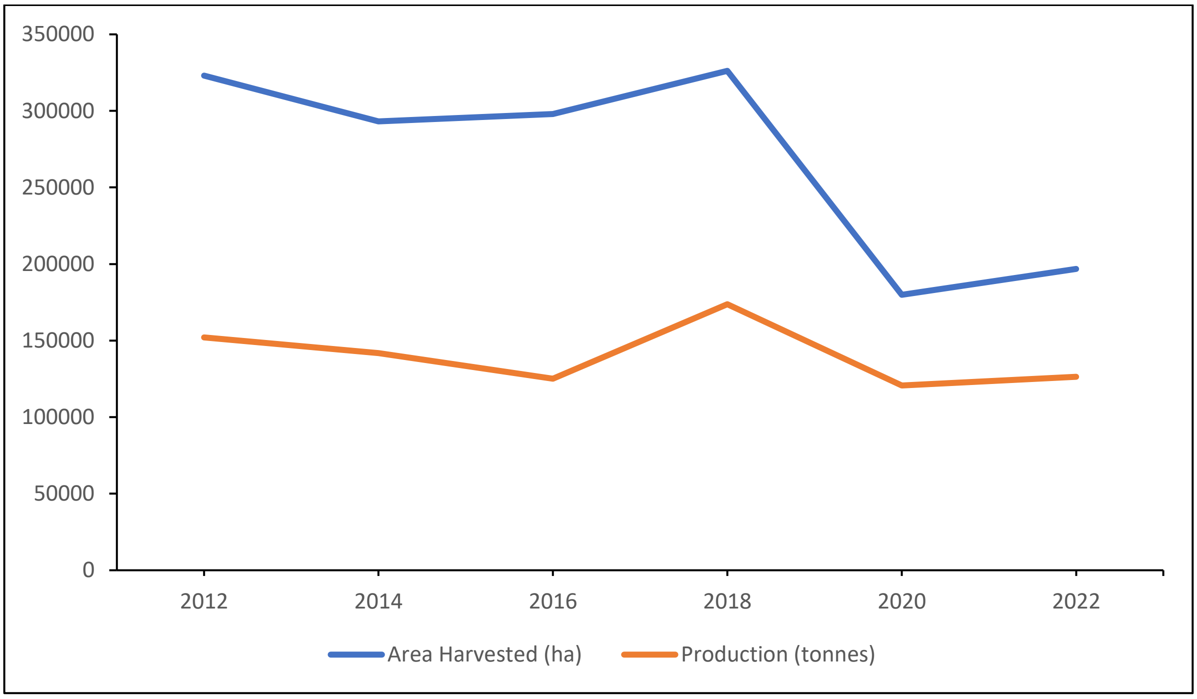

Figure 3: Area harvested and Production of Flaxseed

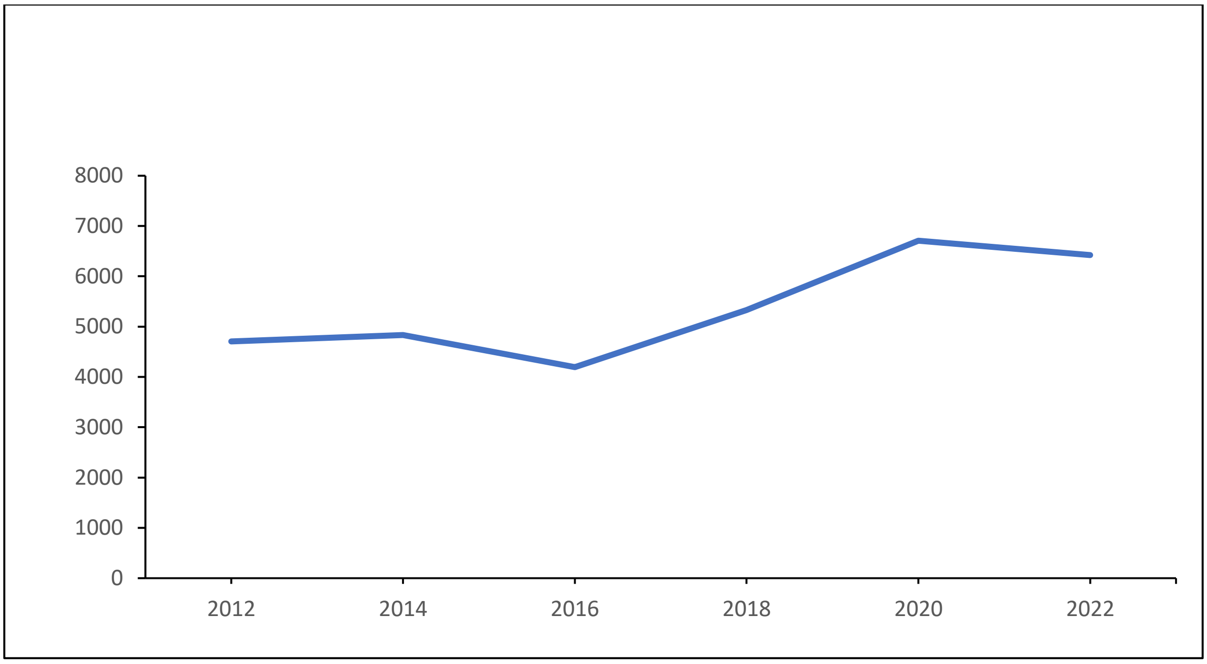

Figure 4: Yield of Flaxseed (100 g/ha)

Figure 5, shown below, sheds light on the flaxseed product export value (million USD). Starting from 2012 until 2020, the flaxseed export value experienced a steady rise with minimal variations and further increased, crossing the 25 million USD mark in 2022. Hence, it could be concurred that the product export value, based on the data available from 2012 to 2022, shows a potential to maintain its consistency for the coming years.

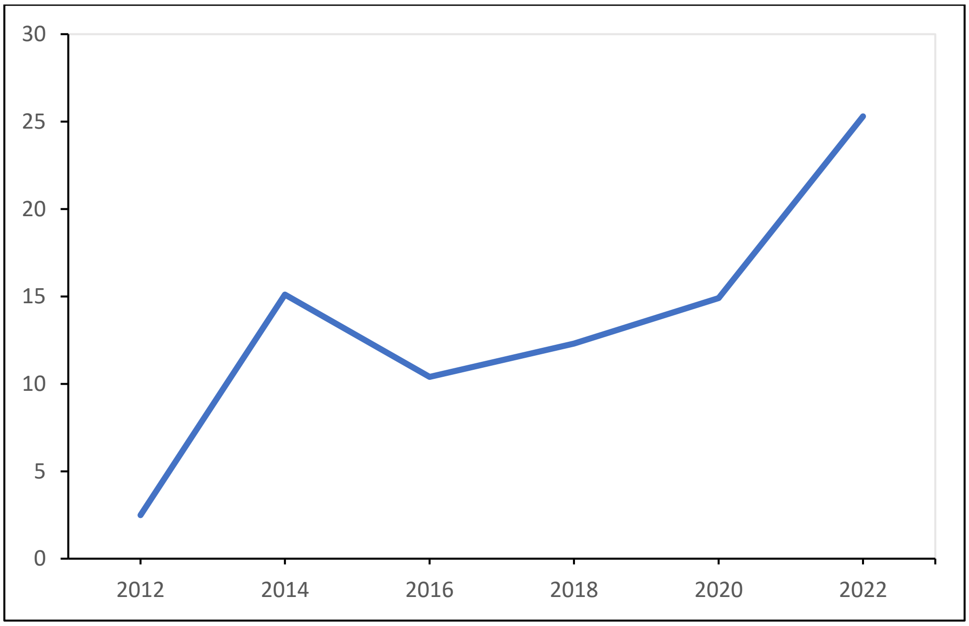

Figure 5: Product Exports Value of Flaxseed (million USD)

Figure 6 shows the flaxseed oil production in tonnes over the years 2012 to 2022. From the graph, it can be concluded that flaxseed oil production suffered a decline from 2012 to 2014, reaching a low of 33000 tonnes, with eventual improvement from 2016 to 2018. From 2018 onwards, flaxseed oil production is seen to have experienced a drastic decline.

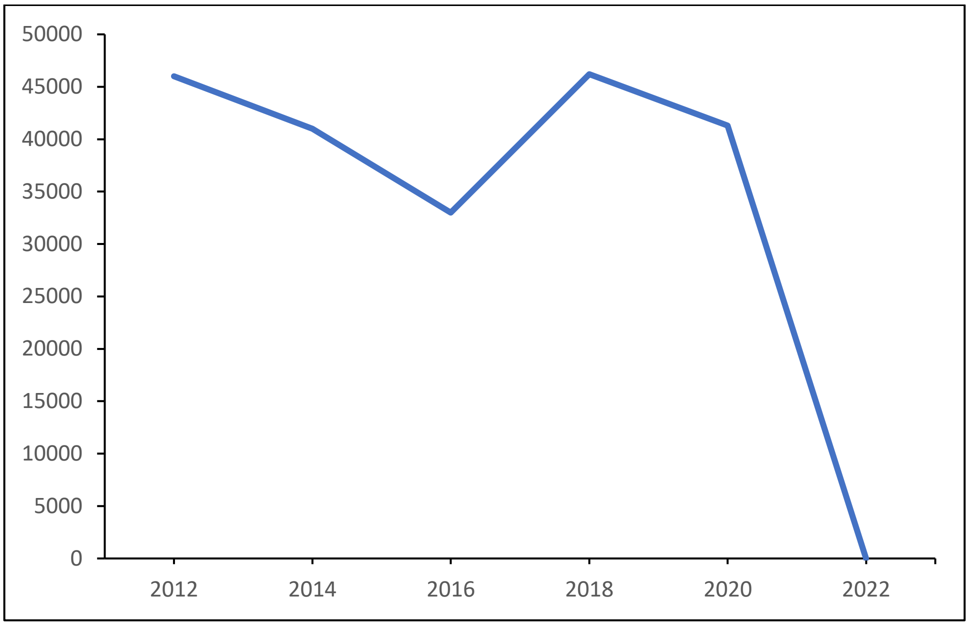

Figure 6: Linseed Oil Production in tonnes

Figures 7 and 8 describe the import data for flaxseed and flaxseed oil for the years 2012 to 2022 and 2008 to 2016, respectively. Germany and the Netherlands, from 2012 to 2022, were the only two countries that were the biggest consistent importers of flaxseed from India. The US majorly started importing flaxseed from India from the year 2018, and till 2022, the import value has remained consistent. In the case of flaxseed oil, Australia and the US turned out to be the biggest importers, whereas, relatively, the import from the UK was the least.

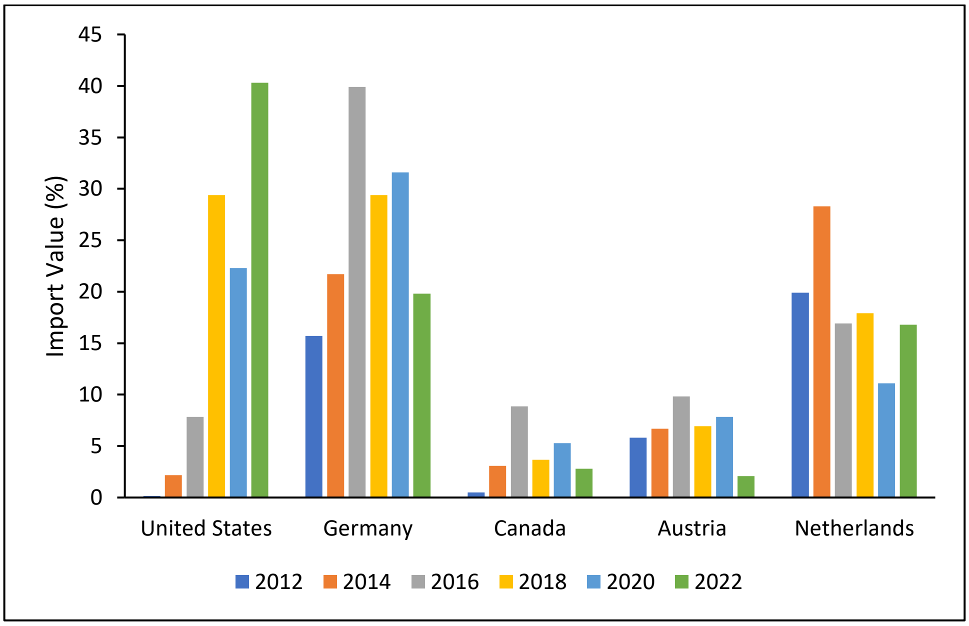

Figure 7: Import Data for Flaxseed

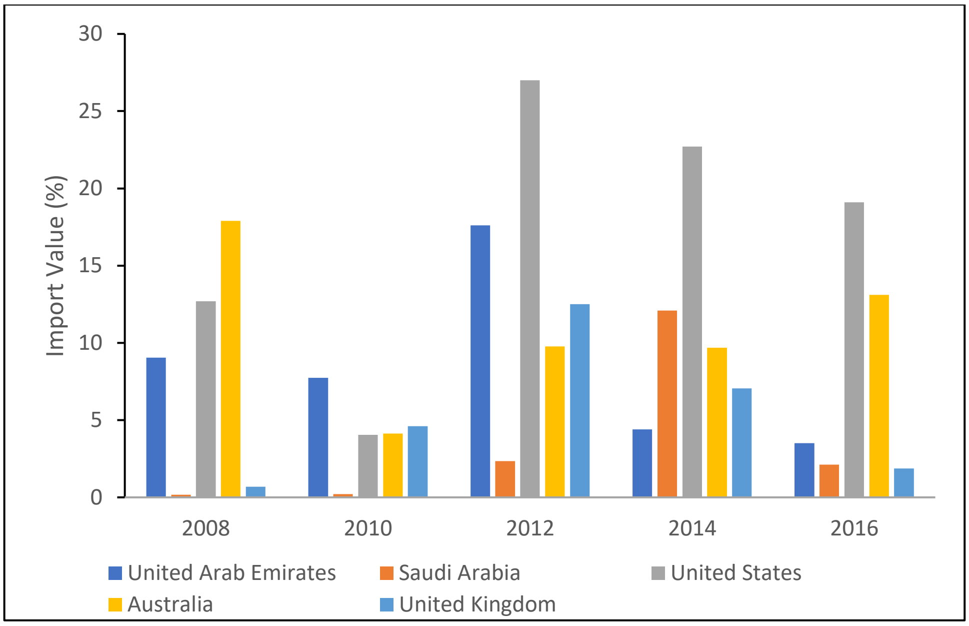

Figure 8: Import Data for Flaxseed Oil

Figure 9 describes the product export value of flaxseed oil from 2008 to 2018. The product exports value of flaxseed oil showed a rise from 2008 to 2010, with relatively less significant changes over the years till 2016.

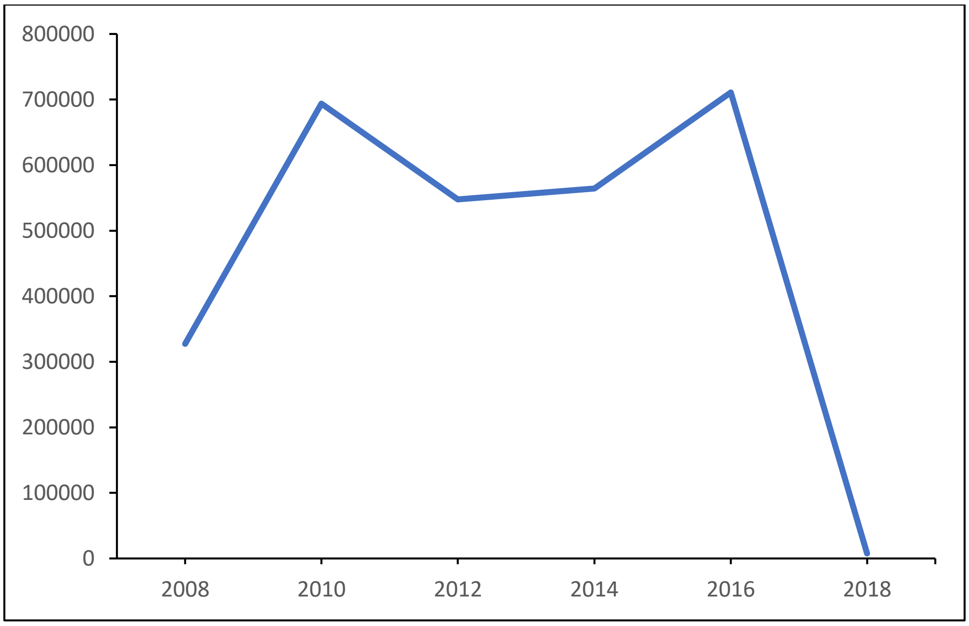

Figure 9: Product Exports Value of Flaxseed Oil

8. Applications:

The application of flaxseed can be mainly divided into two parts: Medicinal use and Use in food products. [1].

8.1. Medicines Derived from Flaxseed Oil

Flaxseeds have a wide variety of uses in different medicinal formulations, with products like Lipostabil, Essaven and Efamol. Medicines incorporating flaxseed in their formulation, along with their effects, are explained in the Table 1[1].

Table 1: Medicines Derived From Flaxseed Oil [1]

Product name	Formulation	Action
Essentials	α-linolenic acid, pyridoxine, cyanocobalamin, nicotinamide, and essential phospholipids	Stimulates the liver's detoxification process and repairs and preserves the structural integrity of liver cells.
Lipostabil	α-linolenic acid, oleic acids, choline phospholipids	It has a mild vasodilatory effect and restores the blood's ratio of α- to β-lipoproteins.
Essaven	phosphatidylcholine (linoleic acid, α-linolenic and oleic acids)	Assist with painful limb fatigue, muscular strains and contusions, and superficial vein disorders
Efamol	Linseed oil in capsule shape, combined with other oils and vitamin E	It has a favourable impact when used to cure eczemas

8.2. Commercial Utilisation of Flaxseed in Food Products [8]:

Flax seed is also widely used to add value to food products by their incorporation. Food items can have their value increased by adding ingredients, processing them, or adding packaging to them. The consumer finds value-added food products to be more appealing and practical than the initial commodity. Breakfast cereals, skim milk, ice cream, yoghurt, cheeses, extruded snacks, and others are instances of value-added products. Commercially, every part of the flaxseed plant is used, either straight or after processing, to create a variety of products with added value. When flax is used for human consumption, it is typically referred to as flaxseed, while when it is used in industry, it is referred to as linseed. Flaxseed (ground or milled) and flaxseed oil have been used as functional dietary ingredients in baked, dairy, extruded, snacks, and other goods. The commercial use of flax in different food products is tabulated below:

Table 2. Commercial Use of Flax [8]

Product name	Flaxseed form	Amount of supplementation (%)
Bagels	Milled flaxseed	23
Bagels/pretzel-type bakery	Flaxseed flour	5-15
Bread	Flaxseed flour	15
Bread	Raw and roasted ground	5-15
Chinese steamed bread	Flaxseed hull extracts	1
Yeast bread	Milled flaxseed (flour)	15-25
Taftoon bread	Coated and uncoated ground	5-25
Bread	Flaxseed flour	15-30
Pan bread	Roasted flaxseed flour	10-20
Unleavened flatbread	Total fat and partially	4-20
Pita bread	Flaxseed cake flour	5-20

Cereal bars	Flaxseed flour	6-18
Biscuits	Flaxseed flour	11-43
Biscuits	Flaxseed meal and oil	15 and 100
Biscuits	Flaxseed flour	20-40
Biscuits	Flaxseed flour	5-15
Sugar snap cookies	Barley, flaxseed, oats and	10-20
Cookies	Roasted flaxseed flour	5-30
Cookies	Flaxseed oil	5-50
Cookies	Flaxseed flour	0-18
Cookies	Roasted flaxseed flour	5-20
Cake and Cookies	Flaxseed flour	5-25
Carrot cake (gluten-free)	Flaxseed meal	9.48
Cake	Flaxseed flour	5-45
Muffins	Ground flaxseed	7.3-15.5
Muffins	Raw and roasted flaxseed	10-40
Muffins	Flaxseed flour	33-66
Muffins	Flaxseed meal	2-5
Pizza	Roasted flaxseed flour	10-20

Apart from these, there is also the usage of flaxseed in dairy products. Some of the most common uses are:

Table 3. Use of Flaxseed in Dairy Products [8]

Product name	**Flaxseed form**	**Processing method**	**Amount of supplementation**
Dahi (Indian Yogurt)	Microencapsulated flaxseed oil powder (MEFOP)	Fermentation	1-3%
Ice cream	Flaxseed oil	Freezing	0-12%
Cheese	Flaxseed lignan (SDG)	Pasteurisation and fermentation	One g/10L
Yoghurt	Flaxseed lignan (SDG)	Fermentation	100mg
Milk	Flaxseed lignan (SDG)	Heat treatment	1%
Whey drinks	Flaxseed lignan (SDG)	Pasteurisation	10 mg/100 ml
Butter	Flaxseed additive	-	0.8-1.6%

9. Extraction of Flaxseed oil

Recovery of oil from flaxseed is the crucial step in producing the most significant number of flaxseed products [30].Mechanical pressing and solvent extraction are very commonly used extraction methods. The problem with solvent extraction is that some solvent remains in the extracted oil, which is unacceptable to the organic market. Hence, solvent-extracted flaxseed oil has a limited use in the food industry [31].Traditionally, oilseeds were pressed mechanically to extract oil, but since this is time-consuming, energy-intensive, and produces inferior quality oil, alternative, environment-friendly oil extraction techniques have been developed [32].Prior to extraction, flaxseeds are usually dehulled, which improves the flavour, increases the protein content of the meal, and increases the oil yield. [33]. Dehulling removes the mucilage and crude fibre from the flaxseeds.

9.1. Mechanical Pressing for Oil Extraction

The ω-3 fatty acids are sensitive to heat, oxygen and light, and hence flaxseeds are usually cold-pressed. Although cold-pressed, there is a rise in temperature in the pressing chamber due to mechanical friction and developed pressure. Analysis of the Specific Mechanical Energy (SME) helps in estimating the heat generation and temperature increase while screw-pressing oilseeds. Higher SME signifies higher heat generation. Energy analysis in screw pressing whole and dehulled flaxseeds was conducted by [34]moisture content of whole flaxseed reduced from 12.6 to 6.3%. The SME requirement was higher for whole flaxseed than dehulled flaxseed. Moisture content in the flaxseed plays the role of lubricant, thus reducing frictional heat generation [31]. Although having a lubrication effect, the increase in moisture content and press head temperature reduces the oil recovery as reported by [35]. It also inferred a maximum press rate that was achieved for dehulled flaxseeds. The inverse relationship between moisture content and oil recovery was also confirmed by [36]. According to the study conducted on reducing the moisture content of the flaxseeds from 13.8 to 6.5%, the screw-pressed oil recovery increased from 44.4 to 73.3%, 36.4 to 76.6% and 45.4 to 81% for moisture-conditioned, steam and enzyme pretreated oil respectively. [37] pre-treated the flaxseeds with three enzymes, namely Viscozyme L, Kemzyme and Feedzyme, before cold pressing and observed that the oxidative stability and quality of extracted oil were much superior to the non-pretreated oil. Mechanically, the flaxseed is pressed multiple times. The effect of the application of multi-stage presses on flaxseed oil was studied by [38]. It was reported that the yield and quality of double-pressed flaxseed oil was superior to single-pressed oil. Pressing oil more than two times seemed to be uneconomical due to no much increase in oil yield.

10. Microencapsulation of Flaxseed Oil

The best encapsulation efficiency was achieved by the emulsions made with the modified starch, proving that Hi-Cap 100 is a superior encapsulating agent. Particles made with this wall material demonstrated an encapsulation efficiency of 75%, which is regarded as a good result, even at the highest oil concentration (40%). Encapsulation efficiency was negatively impacted by oil concentration. The amount of surface oil that was not encapsulated increased with increasing oil concentration, indicating a decrease in encapsulation efficiency [39].

Higher peroxide values were generally associated with higher oil loads. This is connected to the reduced protection against lipid oxidation caused by the low encapsulation efficiency attained under these circumstances. A lower encapsulation efficiency implies a higher concentration of flaxseed oil on the particle surface. Compared to encapsulated oil, this nonencapsulated oil is far more prone to lipid oxidation when exposed to oxygen [39].

Table 4. Comparison of Different Wall Materials for Microencapsulation [39], [40], [41]

Wall Material	**Material Sourcing**	**Emulsion Preparation**	**Encapsulation Efficiency (EE)**	**Oxidative Stability (meq peroxide / kg of oil)**
Gum Arabic	Instantgum BA, Colloides Naturels Brazil, Sao Paulo, Brazil	The method is described in [39]	Concentration range (%) / Encapsulation efficiency (%) 10 / 92.87 20 / 77.08 30 / 53.56 40 / 39.93	Concentration range (%) / Oxidative Stability 10 / 3.2 20 / 3.7 30 / 3.67 40 / 4.11
Whey Protein Concentrate WPC80	Alibra, Campinas, Brazil		Concentration range (%) / Encapsulation efficiency (%) 10 / 68.42 20 / 58.51 30 / 47.06 40 / 38.08	Concentration range (%) / Oxidative Stability 10 / 1.4 20 / 1.5 30 / 1.6 40 / 2.11
Modified Starch HiCap100	National Starch, Sao Paulo, Brazil		Concentration range (%) / Encapsulation efficiency (%) 10 / 97.21 20 / 92.26 30 / 87.31 40 / 75.23	Concentration range (%) / Oxidative Stability 10 / 0.53 20 / 1.0 30 / 1.3 40 / 1.91
Flaxseed Mucilage Nanofiber	Brown flaxseeds (Linum usitatissimum) and cold-pressed flaxseed oil from the local market in Isfahan, Iran.	The method is described in [40]	Concentration range (%) / Encapsulation efficiency (%) 10 / 87.8 20 / 85.9 40 / 82.7	For the oil concentration range as follows: 10%, 20%, 40% over a period of 0 to 16 storage days, the peroxide value (meq O2 / kg of oil) is [17]: 8.26, 20.21, 23.48, 46.96, 26.75, 26.46.
n-LPI	The Crop Development Centre (Saskatoon, SK, Canada) and Bioriginal Food and Science Corp. (Saskatoon, SK, Canada) supplied the flaxseed oil and whole green lentil seeds (CDC Greenland).	The method is described in [41]	Concentration range (%) / Encapsulation efficiency (%) 10 / 65.38 20 / 55.28 30 / 46.87	The peroxide values of flaxseed oil coated with n-LPI, over a period of 0 to 35 storage days, the peroxide value (meq O2 / kg of oil) is [18]: 1.36, 4.62, 14.16, 25.98.
u-LPI			Concentration range (%) / Encapsulation efficiency (%) 10 / 65.14 20 / 54.32 30 / 44.71	
h-LPI			Concentration range (%) / Encapsulation efficiency (%) 10 / 57.45 20 / 45.19 30 / 33.17	

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The study observed that nanofibers containing 10, 20, and 40% (w/w) flaxseed oil had encapsulation efficiency values of 87.8, 85.9, and 82.7%, respectively. The Encapsulation Efficiency values of the nanofibers at various loaded Flaxseed Oil concentrations did not differ significantly ($p > 0.05$). It was hence concluded that the combination of PVA and flaxseed mucilage successfully entrapped oil in the nanofibers and covered all of the flaxseed oil droplets during the emulsion's production. The kind of core, the makeup of the wall materials, the distribution of droplet sizes in the emulsions, and the ratio of the wall materials to the core all have a significant impact on the loading capacity and encapsulation efficiency. [40]

The study observed that n-LPI (native and pretreated lentil protein isolate) material had a higher EE (EE ~55.84%), followed by u-LPI (heated and un-hydrolysed lentil protein isolate) (EE ~54.7%) and h-LPI (heated and hydrolysed lentil protein isolate) (EE ~45.27%) [41]. Research on oil encapsulation, cited in this study, has consistently shown that an increase in the oil load within the encapsulated powder is associated with a rise in surface oil content and a fall in EE. [41] .

11. Conclusion

Flaxseed (Linum usitatissimum) has a long history and is used for a variety of purposes, including food and textiles. Well-known for its abundance of nutrients and health advantages, such as antioxidants and w-3 fatty acids, it is frequently eaten to lower the risk of cancer, heart disease, and menopausal symptoms. Flaxseed is now acknowledged as a beneficial dietary supplement with a range of health benefits. This paper explains the composition of flaxseed and discusses its health benefits, which range from antimicrobial effects to effects on bone health, metabolic effects, etc. A thorough market analysis has been done based on the figures from the years 2012-2022, further identifying the import opportunities and current market trends for India. Along with addressing the applications of flaxseed, this paper also sheds light on the conventional extraction method – mechanical pressing. Also, it compares several wall materials for their use for microencapsulation, along with the effects these wall materials have on encapsulation efficiency and oxidative stability.

Abbreviations

ALA – alpha linolenic acid
PUFA - polyunsaturated fatty acids
SDG - secoisolariciresinol di glycoside
EPA - eicosapentaenoic acid
DHA - docosahexaenoic acid
ED - Enterodiol

EL - Enterolactone
SECO – Secoisolariciresinol
LDL - low-density lipoproteins
ALP - atherogenic lipoprotein phenotype
FXO – Flaxseed Oil
SFO – Sunflower Oil
P – Plasma Cholesterol value
SME - Specific Mechanical Energy
EE – Encapsulation Efficiency
LPI – Lentil Protein Isolate

Nomenclature

α – alpha (position of first carbon atom that is attached to the functional group)
β –beta (position of the second carbon atom from the functional group)
w - omega

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