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REVIEW

Flax and flaxseed oil: an ancient medicine & modern functional food

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Abstract Flaxseed is emerging as an important functional food ingredient because of its rich contents of α-linolenic acid (ALA, omega-3 fatty acid), lignans, and fiber. Flaxseed oil, fibers and flax lignans have potential health benefits such as in reduction of cardiovascular disease, atherosclerosis, diabetes, cancer, arthritis, osteoporosis, autoimmune and neurological disorders. Flax protein helps in the prevention and treatment of heart disease and in supporting the immune system. As a functional food ingredient, flax or flaxseed oil has been incorporated into baked foods, juices, milk and dairy products, muffins, dry pasta products, macaroni and meat products. The present review focuses on the evidences of the potential health benefits of flaxseed through human and animals' recent studies and commercial use in various food products.

Keywords Flaxseed · α-linolenic acid · Lignans · Health benefits · Bakery products

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Introduction

Flaxseed is one of the oldest crops, having been cultivated since the beginning of civilization (Laux 2011). The Latin name of the flaxseed is *Linum usitatissimum*, which means "very useful". Flax was first introduced in United States by colonists, primarily to produce fiber for clothing (Laux 2011). Every part of the flaxseed plant is utilized commercially, either directly or after processing. The stem yields good quality fibers having high strength and durability (Singh et al. 2011). Flax has been used until 1990s principally for the fabrication of cloths (linen) and papers, while flaxseed oil and its sub-products are used in animal feed formulation (Singh et al. 2011). There is a small difference in using the terms flaxseed and linseed. Flaxseed is used to describe flax when consumed as food by humans while linseed is used to describe flax when it is used in the industry and feed purpose (Morris 2008). In the last two decades, flaxseed has been the focus of increased interest in the field of diet and disease research due to the potential health benefits associated with some of its biologically active components. Flaxseeds have nutritional characteristics and are rich source of ω-3 fatty acid: α-linolenic acid (ALA), short chain polyunsaturated fatty acids (PUFA), soluble and insoluble fibers, phytoestrogenic lignans (secoisolariciresinol diglycoside-SDG), proteins and an array of antioxidants (Ivanova et al. 2011; Singh et al. 2011; Oomah 2001; Alhassane and Xu 2010). Its growing popularity is due to health imparting benefits in reducing cardiovascular diseases, decreased risk of cancer, particularly of the mammary and prostate gland, anti-inflammatory activity, laxative effect, and alleviation of menopausal symptoms and osteoporosis. This review is an attempt to cover the history of flax and flaxseed oil, its journey from being a medicine to a functional food source and its health benefits.

Functional elements of flaxseed

Flaxseed is one of the richest plant sources of the ω-3 fatty acid i.e. α-linolenic acid (ALA) (Gebauer et al. 2006; Tonon et al. 2011) and lignans (phytoestrogens) (Singh et al. 2011). The important flaxseed growing countries are Canada, China, United States, India and Ethiopia. Canada is the world's largest producer with a production of 0.42 million tonnes in 2010 (FAO 2012) and accounts for nearly 80 % of the global trade in flaxseed (Oomah and Mazza 1998). India ranks 4^{rth} with 0.15 million tonnes of total flaxseed production (FAO 2012). Total average world production of linseed during the last decade and in last 5 years by top 5 producer countries (2005–2010) is shown in Figs. 1 and 2, respectively.

Flaxseeds are available in two basic varieties: (1) brown; and (2) yellow or golden. Both have similar nutritional characteristics and equal numbers of short-chain ω-3 fatty acids. The exception is a type of yellow flax called *solin* (trade name *Linola*), which has a completely different oil profile and is very low in ω-3 fatty acids (Dribnenki et al. 2007). Brown flax is better known as an ingredient in paints, varnish, fiber and cattle feed (Drouillard et al. 2000; Kozlowska et al. 2008; Singh et al. 2011; Faintuch et al. 2011). Various edible forms of flax are available in the food market—whole flaxseeds, milled flax, roasted flax and flax oil. According to its physicochemical composition, flaxseed is a multicomponent system with bio-active plant substances such as oil, protein, dietary fiber, soluble polysaccharides, lignans, phenolic compounds, vitamins (A, C, F and E) and mineral (P, Mg, K, Na, Fe, Cu, Mn and Zn) (Bhatty 1995; Jheimbach and Port Royal 2009). The flaxseed composition is given in Table 1.

Flaxseed oil/lipids

Flaxseed is the richest plant source of the ω-3 fatty acid i.e. α-linolenic acid (ALA) (Gebauer et al. 2006). Flaxseed oil is low in saturated fatty acids (9 %), moderate in monosaturated fatty acids (18 %), and rich in polyunsaturated fatty acid (73 %) (Cunnane et al. 1993). Of all lipids in flaxseed oil, α- linolenic acid is the major fatty acid ranging from 39.00 to 60.42 % followed by oleic, linoleic, palmitic and stearic acids (Table 2), which provides an excellent ω-6:ω-3 fatty acid ratio of approximately 0.3:1 (Pellizzon et al. 2007). Although flaxseed oil is naturally high in anti-oxidant like tocopherols and beta-carotene, traditional flaxseed oil gets easily oxidized after being extracted and purified (Holstun and Zetocha 1994). The bioavailability of ALA is dependent on the type of flax ingested (ALA has greater bioavailability in oil than in milled seed, and has greater bioavailability in oil and milled seed than in whole seed) (Austria et al. 2008).

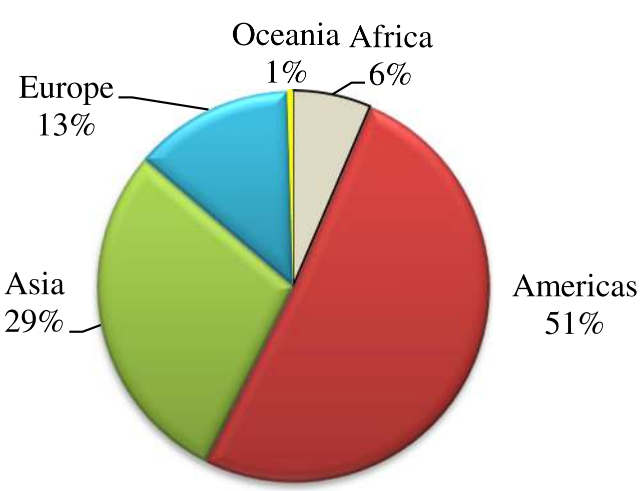

Fig. 1 Average production of linseed/flaxseed in the world (2000–2010)

Proteins

The protein content of flaxseed varies from 20 to 30 %, constituting approximately 80 % globulins (linin and conlinin) and 20 % glutelin (Hall et al. 2006). Flaxseed has an amino acid profile comparable to that of soybean and contains no gluten (Hongzhi et al. 2004; Oomah 2001). Although flax protein is not considered to be a complete protein due to the presence of limiting amino acid- lysine (Chung et al. 2005). It also contains peptides with bioactivities related to the decrease in risk factors of CVD (Udenigwe and Aluko 2010). Whole flaxseed, flaxseed meals and isolated proteins are rich sources of glutamic acid/glutamine, arginine (Oomah and Mazza 1993), branched-chain amino acids (valine and leucine) and aromatic amino acid (tyrosine and phenylalanine). The total nitrogen content in flaxseed is 3.25 g/100 g of seed (Gopalan et al. 2007).

Dietary fibers

Flax fibers are amongst the oldest fiber crops in the world. The use of flax for the production of linen goes back at least to ancient Egyptian times. Flax fiber is extracted from the skin of the stem of the plant. Total flax plant is approximately 25 % seed and 75 % stem and leaves (Lay and Dybing 1989). The stem or non-seed parts are about 20 % fiber, which can be extracted by chemical or mechanical retting. A flax fiber is a natural and biodegradable composite, which exhibits good mechanical properties and low density (Singh et al. 2011). Flax fiber is soft, lustrous and flexible; bundles of fiber have the appearance of blonde hair, hence the description "flaxen". It is stronger than cotton fiber but less elastic (Singh et al. 2011). Flax fiber is also a raw material for the high-quality paper industry for the use of printed banknotes and rolling paper for cigarettes and tea bags (Carter 1993).

Flax fibers include both soluble and insoluble dietary fibers. The proportion of soluble to insoluble fiber varies between 20:80 and 40:60 (Morris 2003; Mazza and Oomah

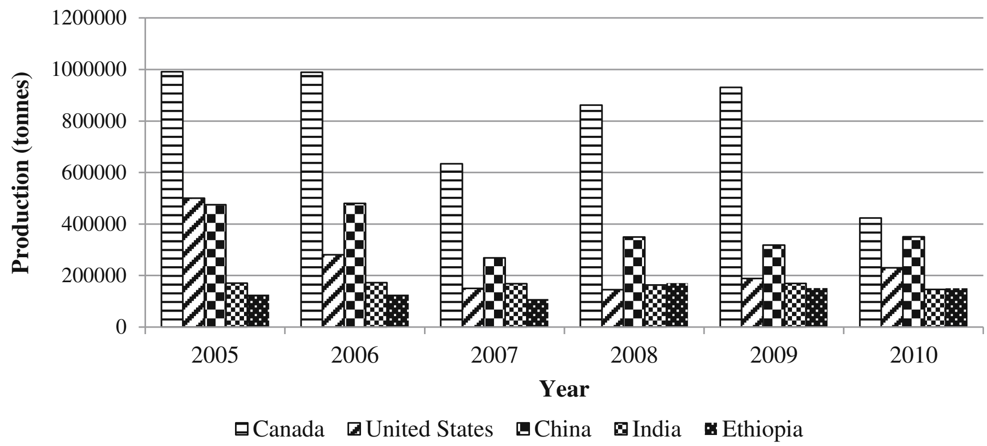

Fig. 2 Linseed/flaxseed production by top 5 producer countries (2005–2010)

1995). The major insoluble fiber fraction consists of cellulose and lignin, and the soluble fiber fractions are the mucilage gums (Vaisey-Genser and Morris 2003; Mazza and Biliaderis 1989). The mucilage can be extracted by water and has good foam-stabilizing properties (Mazza and Biliaderis 1989). Mucilage gums are polysaccharides that become viscous when mixed with water or other fluids and have an important role in laxatives (Singh et al. 2011). The optimal pH range for viscosity of flaxseed mucilage is 6–8, the pH environment in human intestines. Only 10 g of flaxseed in the daily diet increases the daily fiber intake by 1 g of soluble fiber and by 3 g of insoluble fiber. Insoluble fiber helps improve laxation and prevent constipation, mainly by increasing fecal bulk and reducing bowel transit time (Greenwald et al. 2001). On the other hand, water-soluble fiber helps in maintaining blood glucose levels and lowering the blood cholesterol levels (Kristensen et al. 2012).

Table 1 Chemical composition of nutrient and phytochemicals in flaxseed

Nutrients/bioactive compounds	Quantity/ 100 g of seed	Nutrients/bioactive compounds	Quantity/ 100 g of seed
Carbohydrates[a]	29.0 g	Biotin	6 mg
Protein	20.0 g	α-Tocopherol[b]	7 mg
Total fats	41.0 g	δ-Tocopherol[b]	10 mg
Linolenic acid	23.0 g	γ-Tocopherol[b]	552 mg
Dietary fiber	28.0 g	Calcium	236 mg
Lignans	10–2,600 mg	Copper	1 mg
Ascorbic acid	0.50 mg	Magnesium	431 mg
Thiamin	0.53 mg	Manganese	3 mg
Riboflavin	0.23 mg	Phosphorus	622 mg
Niacin	3.21 mg	Potassium	831 mg
Pyridoxin	0.61 mg	Sodium	27 mg
Pantothenic acid	0.57 mg	Zinc	4 mg
Folic acid	112 mg		

Source: Flax council of Canada (2007)

Values are adapted from http://www.flaxcouncil.ca/spanish/pdf/FlxPrmr-R11-Ch1_Span.pdf

[a] Values include dietary fiber

[b] Values in mg/kg of flaxseed lipids

Lignans

Plant lignans are phenolic compounds formed by the union of two cinnamic acid residues. Lignans are ubiquitous within the plant kingdom and are present in almost all plants (Tarpila et al. 2005). Lignans act as both antioxidants and phytoestrogens. Phytoestrogens can have weak estrogen activity in animals and humans. Flax contains up to 800 times more lignans than other plant foods (Mazur et al. 1996; Westcott and Muir 1996). Lignan content in flaxseed is principally composed of secoisolariciresinol diglucoside (SDG) (294–700 mg/100 g), matairesinol (0.55 mg/100 g), lariciresinol (3.04 mg/100 g) and pinoresinol (3.32 mg/100 g) (Tourre and Xueming 2010; Milder et al. 2005). Johnsson et al. (2000) reported SDG content in the range of 11.7 to 24.1 mg/g and 6.1 to 13.3 mg/g in defatted flaxseed flour and whole flaxseed, respectively. Besides lignans, other phenolic compounds found in flaxseed are p-coumaric acid and ferulic acid (Strandas et al. 2008). The SDG found in flax and other foods is converted by bacteria in the gut to the lignans- enterodiol and enterolactone which can provide health benefits due to their weak estrogenic or antiestrogenic, as well as

Table 2 Major fatty acids profile in flaxseed oil

Fatty acids	Percentage (%) (Range)
Palmitic acid (C16:0)	4.90–8.00
Stearic acid (C18:0)	2.24–4.59
Oleic acid (C18:1)	13.44–19.39
Linoleic acid (C18:2) (ω-6)	12.25–17.44
α-Linolenic acid (C18:3) (ω-3)	39.90–60.42

Sources: Choo et al. (2007); Bozan and Temelli (2008); Pradhan et al. (2010); Pu et al. (2010); Condori et al. (2011); Long et al. (2011); Zhang et al. (2011); Anwar et al. (2013); Guimaraes et al. (2013); Khattab and Zeitoun (2013) antioxidant effects (Adlercreutz 2007). Flax lignans have shown promising effects in reducing growth of cancerous tumors, especially hormone-sensitive ones such as those of the breast, endometrium and prostate (Tham et al. 1998).

Minerals

In relation to composition of minerals, the contents of calcium, magnesium and phosphorus are highlighted (Bozan and Temelli 2008) being that a 30 g portion of the seed constitutes 7 % to 30 % of the recommended dietary allowances (RDAs) for these minerals. Proximate content of different minerals is shown in Table 1. Its potassium (K^+) content is high and comparable to those of recommended sources such as banana on a dry-matter basis. High K^+ intake is inversely related to stroke incidence, blood platelet aggregation, oxygen-scavenging free radicals in blood and vascular smooth muscle proliferation (Carter 1993).

Anti-nutritional factors

Despite having functional elements, flax is not totally free of anti-nutritional factors, such as cyanogenic glycosides (CGs). Flaxseed contains CGs and linamarin (acetone–cyanohydrin-beta–glucoside $C_{10}H_{17}O_6N$) in small amounts (Hall et al. 2006). Whole flaxseed contains 250–550 mg/100 g CG (Mazza 2008), of which linustatin and neolinustatin are the major components. Park et al. (2005) reported 207 and 174 mg/100 g seed of linustatin and neolinustatin, respectively in flaxseed. Upon seed damage, β-glucosidases are triggered and contribute to releasing the poisonous hydrogen cyanide (HCN). However, adequate processing of foodstuffs containing CG helps in reducing the potential risks associated with poisoning (Ernesto et al. 2002; Haque and Bradbury 2002). For example, more than 85 % of linustatin, neolinustatin were removed when flaxseed was heated for more than 2 h at 200 °C (Park et al. 2005). Flaxseed meal also contains 2.3–3.3 % phytic acid. Although phytic acid has been known in reducing bioavailability of micronutrients, recent research shows that phytic acid has antioxidant, anticancer, hypocholesterolemic, and hypolipidemic effects (Mazza 2008). Flaxseed meal also contains 10 mg/100 g Linatine (gammaglutamyl- 1-amino-D-proline) which induces vitamin B_6 deficiency (Mazza 2008). Ratnayake et al. (1992) and Dieken (1992) found that the linatine (a vitamin B_6 antagonist) in flaxseed did not affect vitamin B_6 levels or metabolism in people fed up to 50 g of ground flaxseed per day. It has been reported that flaxseed depressed vitamin E levels in rats only when fed at very high levels (Ratnayake et al. 1992). The cyanogenic glycosides in flaxseed raise thiocyanate levels in the blood very briefly, after which the levels drop, but even these levels are less than those of persons smoking tobacco (Zimmerman 1988).

Flax: a nutraceutical or functional food?

The words nutraceutical and functional food are wrongly interpreted to be one and the same, though there is a difference between the two. A functional food is one which is similar in appearance to a conventional food, consumed as a part of the usual diet, with demonstrated physiological benefits, and/or to reduce the risk of chronic disease beyond basic nutritional functions. While a nutraceutical is a product isolated or purified from foods that is generally sold in medicinal forms, not usually associated with foods (Health Canada 1998). A nutraceutical can be a part of functional foods while the latter has to provide essential nutrients often beyond qualities necessary for normal maintenance, growth and development. As flax is consumed in the form of whole/milled/roasted seeds, oil and flour as a food to provide basic nutrition as well as various health benefits in reducing cancer and cardiovascular diseases, lowering LDL-cholesterol and vasodilatory functions, flax can be considered as a functional food. On the other hand, various stable preparations of flax in the form of nutraceutical like neat oil, capsules and microencapsulated powder are available in market. Flax lignans- isolated SDG preparations are also commercially available as a dietary supplement (Chen et al. 2011b). Moreover, flaxseeds were also used as medicines in ancient times as cough remedy and to relieve the abdominal pain. Various medicinal preparations of flaxseed/oil are available in foreign markets, have been described under the next heading. Therefore, by keeping all these views in mind, flax can be considered a potential nutraceutical as well as functional food.

Flax: an ayurvedic and historical medicine

Humans have been eating flax for thousands of years. Ayurveda remains one of the most ancient and yet alive tradition practiced widely in India, Sri Lanka and other countries that have a sound philosophical and experimental basis (Patwardhan et al. 2004). *Atharvaveda* (around 1200 BC), *Charak Samhita* (Dash and Sharama 2001) and *Sushrut Samhita* (1000–500 BC) are main classics that give detailed descriptions of over 700 herbs. A scholarly description of the legacy of *Charaka* and *Sushruta* in contemporary idiom, best attempted with a commentary from modern medicine and science viewpoint, gives some glimpses of ancient wisdom (Valiathan 2003). Ayurveda and traditional Chinese medical system share many common approaches and have a long history of practice (Patwardhan et al. 2005). Ayurvedic literature describes more than 200 herbs, minerals and fats for skin care.

Flaxseed oil is believed to bring mental and physical endurance by fighting fatigue and controlling aging process. According to Ayurveda, flaxseed has properties like *Madhura*

Table 3 Medicinal uses of flax described in history

About 650 B.C.	• Hippocrates, the father of medicine, advocated flax for the relief of abdominal pains; And Theophrastus recommended the use of flax mucilage as a cough remedy.
About 1st century A.D.	• Tacitus praised the virtues of flax.
About 8th century A.D.	• Charlemagne considered flax so important for the health of his subjects that he passed laws and regulations requiring its consumption.
About 15th century A.D.	• Hildegard von Bingen used flax meal in hot compresses for the treatment of both external and internal ailments

Source: Flax council of Canada (2012) http://www.flaxcouncil.ca/english/index.jsp?p=what1&mp=what

(balances the skin pH), *Picchaila* (lubricous) *Balya* (improves tensile strength or elasticity of the skin), *Grahi* (improves moisture holding capacity of skin), *Tvagdoshahrit* (removes skin blemishes), *Vranahrit* (wound healing) and useful in *Vata* (skin) disorders including dryness, undernourishment, lack of luster/glow (Misra 1963). Flaxseed oil is rich source of essential fatty acids (EFAs): linoleic acid (ω-6) and α-linolenic acid (ω-3), which regulate prostaglandins synthesis and hence induce wound healing process. Deficiency of EFAs result in phrynoderma or toad skin, horny eruptions on the limbs and poor wound healing, etc. Flax preparations were widely used in medicine as an enveloping and wound-healing agent in the treatment of gastrointestinal disorders (Ivanova et al. 2011). In the Middle ages, flaxseed oil was administered as a diuretic for the treatment of kidney disorders (Moghaddasi 2011). Flaxseed was recommended as an antitumoral (in combination with sweet clover), pain and cough relieving, and anti-inflammatory remedy (Tolkachev and Zhuchenko 2000; Moghaddasi 2011). It was also used for the treatment of freckles (in a mixture with soda and figs) and nail disorders (with garden cress and honey) (Tolkachev and Zhuchenko 2000).

Ayurveda is too old than any history. After Ayurveda, historians wove the magic of flax into ancient historical times. Records show that the human race has eaten this seed since early times. The medicinal applications of linseed are mentioned in the works of Hippocrates, Qantes and Dioscorides as well as in medieval books on medicinal herbs in both Asia and Europe. Various medicinal and traditional uses of flax recommended by Hippocrates and other historians, and medicinal preparations available in market are shown in Tables 3, 4 and 5.

Health benefits

Flaxseed has potential health benefits besides the nutrition, due to mainly 3 reasons: first, due to its high content of ω-3 α-linolenic acid; Second, being rich in dietary soluble and insoluble fibers; and third, due to its high content of lignans, acting as anti-oxidants and phytoestrogens. ALA can be metabolized in the body into docosahexaenoic acid (DHA) (ω-3) and eicosapentaenoic acid (EPA) (ω-3). The health benefits of all ω-3 fatty acids (ALA, EPA and DHA) have been widely reported for several conditions including cardiovascular

Table 4 Traditional and medicinal uses of flaxseeds in various health problems

Flax form consumed	Preparation/Processing method	Traditional/medicinal health benefits
Flaxseed tea	Uncrushed flaxseeds are soaked in water for 30 min. Seeds are then removed while the water is warmed moderately	• Useful against dyspnoea, asthma, dysphonia, bad cough and bronchitis
Flaxseed drink	A teaspoon of flaxseed powder is put into a glass of hot water, brewed and drained. A cup of this water is to be taken daily.	• Helps out constipation
Flaxseed flour	Flaxseed flour 10-gram each for the concerned ailment is given a paste like consistency using honey, 30-40 g of this paste is swallowed on an empty stomach in the morning.	• Used against pulmonary tuberculosis, haemoptysis, splenomegaly and stomach ulcer. • Cures inflammations of intestines and abdominal pains. • Disinfects gastrointestinal tract. • Strengthens the nervous system. • Strengthens the memory. • Good in treating the impairment of concentration. • Good in the management of age-associated distractibility. • Ensures rapid healing of wounds through external use. • Protects the skin against getting dry. • Used in eczema and psoriasis diseases. • Exercises a positive impact on respiratory tract diseases. • Good in curing mental disorders. • Cures bad cough. • Used as mouthwash in oral cavity, throat and gingival disorders.

Source: Moghaddasi (2011)

Table 5 Some medicinal preparations based on flaxseed oil

Product/medicine name	Formulation	Actions
Essentiale (Germany)	Essential phospholipids, α-linolenic acid, pyridoxine, cyanocobalamin, nicotinamide, etc.	Stimulates the detoxicating function of liver; restores and maintains the structure of liver cells
Lipostabil (Germany)	Contains choline phospholipids, as well as α-linolenic and oleic acids.	A moderate vasodilatory action, normalizes the ratio of α-and β-lipoproteins in the blood
Essaven (Germany)	Contains phosphatidylcholine (linoleic acid, α-linolenic and oleic acids)	Help in painful fatigue of legs; muscle contusions and strains; and superficial vein disorders
Linetol (Russia)	Represents a mixture of linseed fatty acid ethylates, including oleic (15 %), linoleic (15 %) and linolenic (57 %) acids	In treatment of atherosclerosis and for external use in cases of skin burn and radiation damage
Efamol (Great Britain)	Capsules form containing linseed oil in combination with other oils and vitamin E	Shows a positive effect when used for the treatment of eczemas
Esoman-ointment (Great Britain)	Linseed PUFAs & hexachlorophane	Protect skin from aggressive agents such as acids, alkalis, formaldehyde and phenols

Source: Tolkachev and Zhuchenko (2000)

disease, hypertension, atherosclerosis, diabetes, cancer, arthritis, osteoporosis, autoimmune and neurological disorders (Simopoulos 2000; Gogus and Smith 2010) (Fig. 3). Flaxseed has also been reported to act as anti-arrhythmic (Ander et al. 2004), anti-atherogenic (Dupasquier et al. 2006, 2007), and anti-inflammatory (Dupasquier et al. 2007) agent in addition to improving vascular function (Dupasquier et al. 2006).

Health benefits of whole flax, flax flour, flax fibers and flaxseed oil

In treatment of diabetes mellitus

Increased blood sugar (Diabetes mellitus) is a major risk factor of cardiovascular diseases, which is defined as having a fasting plasma glucose level ≥126 mg/dl. Diabetes mellitus is characterized by hyperglycemia and associated with aberrations in the metabolism of carbohydrate, protein, and lipid that result in development of secondary complications (Mani et al. 2011). Of the 57 million global deaths in 2008, 36 million (63 %) deaths were due to non-communicable diseases (NCDs), out of which, diabetes was responsible for 1.3 million (3 %) deaths (WHO 2010), with the number likely to be doubled by the year 2030 (WHO 2009). More interesting fact is that one in 10 adults has diabetes according to a new report of WHO (2012). The number of people with diabetes increased from 153 million in 1980 to 347 million in 2008 (Danaei et al. 2011). India has the largest diabetic population and one of the highest diabetes prevalence rates in the world (Bjrok et al. 2003; King et al. 1998). It was estimated that in 2008, about 2 % of total deaths in India were due to diabetes (WHO 2011). Untreated diabetes can lead to cardiovascular diseases, kidney failure and blindness. A positive correlation was reported between the raised blood glucose level and the risk of cardiovascular diseases (Boden-Albala et al. 2008). Moreover, diabetes was tends to occur together with other risk factors such as obesity, hypertension, low HDL cholesterol and a high triglyceride level (Simmons et al. 2010; Lakka et al. 2002).

Dietary fibers, lignans, and ω-3 fatty acids, present in flaxseed have a protective effect against diabetes risk (Prasad et al. 2000; Prasad 2001; Adlercreutz 2007). Flaxseed lignan SDG has been shown to inhibit expression of the phosphoenolpyruvate carboxykinase gene, which codes for a key enzyme responsible for glucose synthesis in the liver (Prasad 2002). Supplementation of diet of type 2 diabetics with 10 g of flaxseed powder for a period of 1 month reduced fasting blood glucose by 19.7 % and glycated hemoglobin by 15.6 % (Mani et al. 2011). It could be due to lower content of glycemic carbohydrates and higher content of dietary fibers of flaxseed. Several small studies using a fasting glucose tolerance approach have found a reduction in postprandial blood glucose levels of women consuming flaxseed (Cunnane et al. 1993, 1995). Kelley et al. (2009) studied that when conjugated linoleic acid (0.5 %) and flax oil (0.5 %) was supplemented in diet of rats susceptible to obesity and diabetic tumors, a 20 % reduction in glycemia was observed. Kapoor et al. (2011) studied the effect of supplementation of flaxseed powder on diabetic human females. Patients were provided 15 and 20 g/day of flaxseed powder for a period of 2 months. Postprandial blood glucose levels were found to be decreased by 7.9 and 19.1 %, respectively. Similar results has also been reported by Nazni et al. (2006) who conducted a study on 25 diabetic subjects and supplemented flaxseed powder in bread

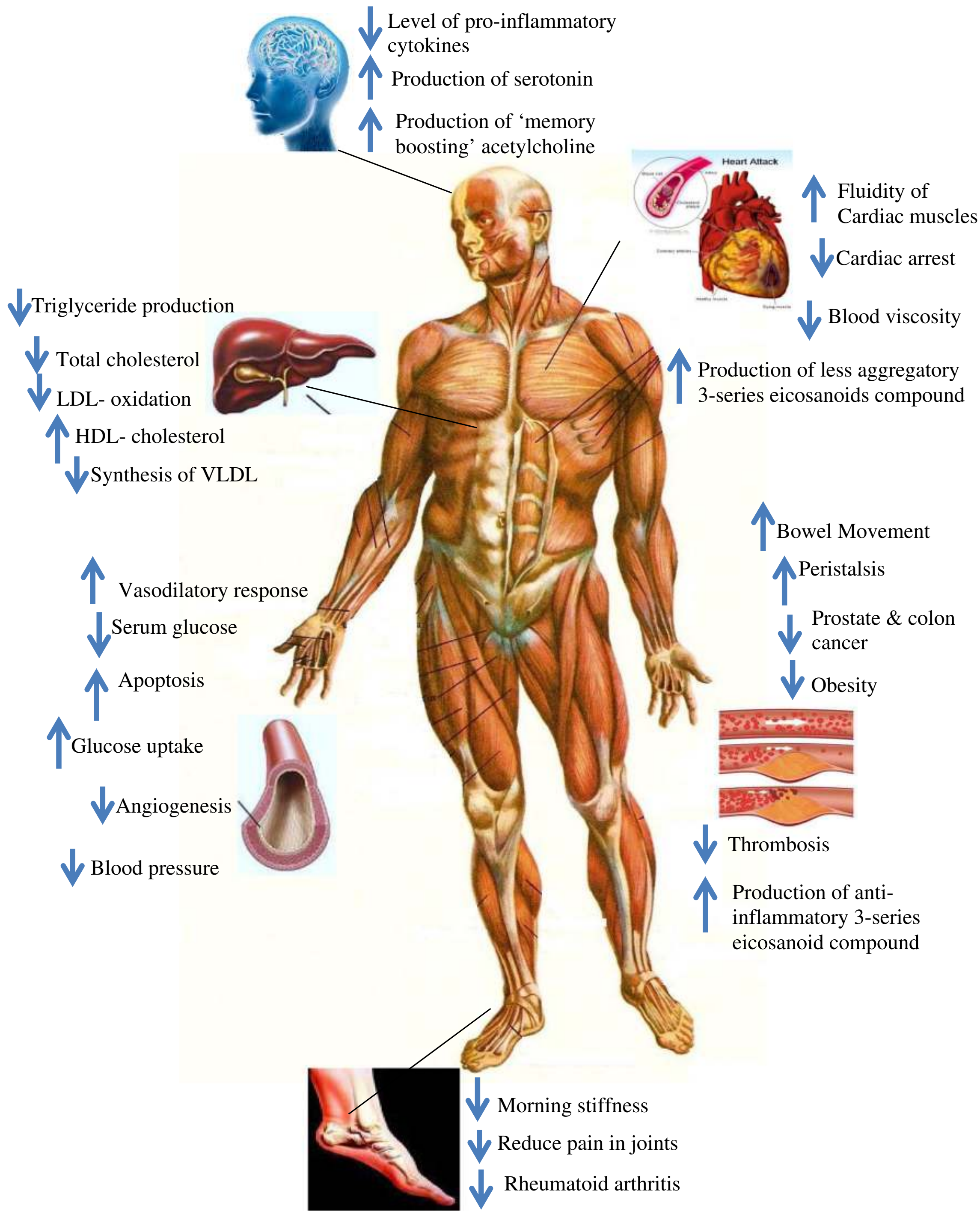

Fig. 3 Physiological effects imparted by functional elements of flaxseed (oil, fiber and lignans)

form for 90 days and reported a significant reduction in blood glucose levels after supplementation. However, Dodin et al. (2008) measured fasting serum glucose and insulin levels and reported no change after flaxseed supplementation. Similarly, ingestion of 10 g/day of flaxseed oil had no effect on fasting blood serum glucose and insulin levels (Barre et al. 2008). Utilization of flaxseed for glycemic control may also be associated to the decrease in risk of obesity and dyslipidemia, since these are risk factors for the development of diabetes and resistance to insulin (Wu et al. 2010; Morisset et al. 2009).

Tumor and cancer reducing effects

Interest in research on the association between flaxseed ingestion and risk of cancer emerged when epidemiologic evidences suggested a beneficial relationship. Research in laboratories has shown that flaxseed inhibits the formation of colon, breast, skin, and lung tumors and also reduces blood vessel cell formation in female rats, all suggesting a protective effect against breast, colon and ovarian cancer (Truan et al. 2012). Higher levels of insulin and insulin-like growth factor 1 (IGF-1) increase cancer risk by stimulating cell proliferation and increasing survival of DNA-damaged cells through antiapoptotic mechanisms (Sturgeon et al. 2011). Blood insulin has also been associated with increased risk of pancreatic and colorectal cancers (Pisani 2008). Various studies suggest that flaxseed added to the diet may lower circulating levels of insulin and IGF-1 (Woodside et al. 2006; Chen et al. 2011a). However, Sturgeon et al. (2011) reported that incorporation of 7.5 g of flaxseed daily for 6 weeks and 15 g of flaxseed for an additional 6 weeks into the diet of healthy postmenopausal women had little short-term effect on blood levels of IGF-1. Flaxseed has a breast tumor-reducing effect, possibly because of its high content of SDG lignan (Truan et al. 2012; Chen et al. 2011a; Chen et al. 2009; Saggar et al. 2010a, b; Wang et al. 2005). Enterodiol (ED) and enterolactone (EL) are produced from flax lignans in animal body. Because they are structurally similar to human estrogen-17β-estradiol (E2), they have binding affinity to estrogen receptors (ER) (Penttinen et al. 2007). Flaxseed and its SDG component have been shown to attenuate tumorigenesis through a reduction in cell proliferation and angiogenesis, as well as an increase in apoptosis via modulation of the estrogen receptor (ER)- and growth factor- signaling pathways (Saggar et al. 2010a; Chen et al. 2009). The potential breast cancer protective effect of flax lignans could be due to their weak estrogenic activity and antioxidant properties. Flaxseed oil with its exceptionally high ALA content was also shown to reduce human estrogen receptor-positive breast tumors (MCF-7) growth by 33 % compared to control (Truan et al. 2010). Chen et al. (2007) studied that the groups of mice that received 5 % and 10 % flaxseed in the diet for 8 weeks inhibited tumor growth by 26 % and 38 %, respectively. The researchers suggested the ability of flaxseed to help maintain more early stages of cancer is due to the fact that flaxseed contains the highest level of plant lignans, which have antioxidant activities (Hall et al. 2006) and have also been shown to alter estrogen metabolism, which may decrease ovarian cancer risk and improve health (McCann et al. 2007).

Prevention of kidney diseases

Chronic kidney disease (CKD) is an important health problem among older adults and can lead to end-stage renal disease with its need for dialysis or transplantation for survival (Lauretani et al. 2009; Coresh et al. 2007). Due to the anti-inflammatory properties of ω-3 fatty acids, it has been suggested that these nutrients may protect the kidneys from damage in adults. PUFA supplementation was observed as reducing renal inflammation and fibrosis in animal models (Baggio et al. 2005). Gopinath et al. (2011) showed that increased dietary intake of long-chain ω-3 PUFA was inversely associated with the prevalence of CKD. Cicero et al. (2010) showed that long-term supplementation of omega-3 fatty acids was associated with a significant reduction in systolic and diastolic blood pressure. Hypertension is a risk factor for CKD; hence, the influence of long-chain n-3 PUFA on blood pressure may be a potential mechanism by which it protects the kidneys. However, a positive association between α-linolenic acid and moderate CKD was observed by Gopinath et al. (2011). One possibility behind the results could be lesser conversion of α-linolenic acid into EPA and DHA, which have been shown to be cardioprotective (Wang et al. 2006).

Reduction of dyslipidemia and cardiovascular diseases (CVD)

Serum lipid profile is directly related to the risk factors of cardiovascular diseases. It is the most intensely investigated effect studied in animals and humans after supplementation of flax in diet. Studies with flaxseed and its bioactive components have been performed with postmenopausal women, showing positive effects, including hypocholesterolemic and antidiabetic effects of supplementation (Patade et al. 2008; Bloedon et al. 2008). The effects of flaxseed on risk factors for CVD in studies performed on animals are similar to those conducted in humans. Rats, mice, and rabbits presented positive responses for biochemical parameters, indicating the hypocholesterolemic activity of flaxseed, generally related to the greater fecal content of lipids (Kristensen et al. 2011, 2012; Hassan et al. 2012; Park and Velasquez 2012; Khalesi et al. 2011; Mani et al. 2011; Cardozo et al. 2010; Barakat and Mehmoud 2011; Leyvaa et al. 2011). However, there remains controversy in relation to effect on the high-density lipoprotein (HDL) fraction. Gillingham et al. (2011) reported reduced levels of HDL fraction in human serum after consuming flaxseed oil in diet for 28 days. Similarly, researchers have also reported reduced or no change in HDL fraction in different animals (Faintuch et al. 2011; Patade et al. 2008; Prim et al. 2012). When type 2 diabetic patients were fed defatted flaxseeds for 2 months, patients showed significant reduction of plasma glucose, improvement in plasma lipid profile and significant reduction of lipid peroxidation (Mohamed et al. 2012). Dietary flaxseed may also offer protection against ischemic heart disease by improving vascular relaxation responses and by inhibiting the incidence of ventricular fibrillation (Jennifer et al. 2010). However, Vedtofte et al. (2011) reported that higher intake of ALA was not significantly associated with decreased risk of ischemic heart disease among women or men. Some of the recent clinical studies regarding the consumption of whole flaxseed, flax flour or oil and their physiological effects are shown in Table 6.

Table 6 Recent clinical reports showing lipid profile and other health effects of flaxseed consumption in diet

Experiment	Model system	Significant findings	References
Consumption of 5 g of flax fibres daily for 1 week in form of bread and drinks	Young healthy adults	Faecal excretion of fat increased by 50 %. Flax bread and Flax drink reduced the Total & the LDL-cholesterol by 7 & 9 and 12 & 15 %, respectively.	Kristensen et al. (2012)
Consumption of 5 g of flaxseed gums per day for 3 months	Type-2 diabetics	Total and LDL-cholesterol were reduced by 10 and 16 %, respectively.	Thakur et al. (2009)
15 % flaxseed meal enriched biscuits were fed for 8 weeks	Hypercholesterolemic rats	Cholesterol & triglyceride level decreased from 456.66 & 173.84 to 183.92 & 102.67 mg/dl, respectively. LDL and VLDL decreased from 199.46 & 34.95 to 84.08 & 20.53 mg/dl, respectively. While, HDL increased from 38.95 to 64.37 mg/dl.	Hassan et al. (2012)
100 % flaxseed oil was used as shortening in preparation of biscuits, which were fed for 8 weeks	Hypercholesterolemic rats	Cholesterol & triglyceride level decreased from 456.66 & 173.84 to 170.48 & 96.79 mg/dl, respectively. LDL and VLDL decreased from 199.46 & 34.95 to 74.79 & 19.34 mg/dl, respectively. While, HDL increased from 38.95 to 66.09 mg/dl.	Hassan et al. (2012)
Flaxseeds were consumed to see its effect on appetite -regulating hormones; lipemia and glycemia.	Young men	Decreased triglyceride levels (postprandial lipemia), Higher mean- ratings of satiety and fullness	Kristensen et al. (2011)
Flaxseed powder enriched diets were consumed for 12-weeks to check body weight and lipid profile	Rats	Rats fed with high fat & high fructose diet along with 0.02 % flax powder showed decreased levels of TG, total cholesterol and LDL-cholesterol from 100, 69 and 10 to 96, 63 and 9 mg/dl, respectively	Park and Velasquez (2012)
Feeding of basal diet & basal diet supplemented with 1 g flaxseed lignan per kg for 8 weeks	Mice	Reduction in breast tumor cell proliferation (or growth) without affecting the size of tumor	Truan et al. (2012)
7.5 g per day of ground flaxseed was consumed for 6 weeks and 15 g per day for an additional 6 weeks	Postmenopausal women	Flaxseed supplementation did not impact circulating levels of IGF-1, IGF-BP3, or C-peptide, which increase cancer risk by stimulating cell proliferation and increasing survival of DNA-damaged cells	Sturgeon et al. (2011)
Animals were fed with 10 %, 20 % & 30 % of raw and heated flaxseed in the basal diet for 30 days	Rats	Total cholesterol level got significantly reduced in all flaxseed groups and HDL- cholesterol got significantly increased in 20 % raw; 30 % raw and heated flaxseed groups. Significant reduction in LDL-cholesterol level was only observed in 30 % raw flaxseed groups	Khalesi et al. (2011)
Diets containing 2·7 % flaxseed, 4·5 % fibre and 3·7 % ALA were fed for 10 weeks.	Mice	The median number of adenomas in the small intestine was 54 & 37 for control & flaxseed groups, respectively. Compared with controls (1·2 mm), the adenoma size was smaller in the flaxseed (0·9 mm) fed group	Oikarinen et al. (2005)
Animals were fed the basal diet (control) and ω-3 rich flax cotyledon's fraction (82 g/kg), respectively for 8 weeks	Mice	Flax diet reduced the cell proliferation; suppressed insulin growth factor (IGF)-1R and the growth of breast tumour	Chen et al. (2011a, b)
Non-fiber beverage, Flax drink -flax fiber extract (2.5 g) and flax tablets	Human	Flax drink increased the sensation of satiety and fullness compared to Control and also a significant decrease in subsequent energy intake was observed after the Flax drink compared to Control (2,937 vs. 3,214 kJ)	Ibrugger et al. (2012)
Isoenergetic diets were consumed for 28 days each containing approximately 36 % energy from fat, of which 70 % was provided by flaxseed oil	Hypercholesterolemic subjects (Human)	Compared with control, total, LDL & HDL-cholesterol levels were reduced by 11, 15.1 & 8.5 %. LDL:HDL ratio by was reduced by 7·5 %	Gillingham et al. (2011)
Diet rich in flaxseed oil was given for 10 days and then a single dose of Cisplatin (6 mg/kg body weight) was administered intraperitoneally while still on diet	Rats	Dietary supplementation of flaxseed oil in Cisplatin (CP)-treated rats ameliorated the CP-induced hepatotoxic and other deleterious effects	Naqshbandi et al. (2012)

Table 6 (continued)

Experiment	Model system	Significant findings	References
Flaxseed powder (60 g/day, 10 g ALA) was administered in a double-blind routine for 12 weeks	Obese population	Total cholesterol level decreased from 197.2 to 179.4 mg/dl. LDL & HDL decreased from 122.3 & 50.9 to 106.6 & 47.9 mg/dl, respectively. While, VLDL increased from 25.8 to 26.6 mg/dl	Faintuch et al. (2011)
Full fatty and partially defatted flaxseed flour @ concentration of 4-20 % supplemented diet was fed for 1 week in form of unleavened flat bread	Albino rat	12 % full fat & 16 % defatted flaxseed flour increased TD from 79.4 to 81.45 & 84.6; NPU from 44.3 to 49.4 & 54.65; PER from 1.51 to 1.8 & 1.87; and BV from 55.79 to 60.65 & 64.6	Hussain et al. (2012)
Low-fat muffins supplemented with 500 mg flax lignan were fed for 6 weeks	Postmenopausal women	A significant decrease (0.88 to 0.80 mg/L) in C-reactive protein (CRP) was observed in test women	Hallund et al. (2008)
30 g/day of flaxseeds were consumed in diet for a period of 3 months	Hypercholesterolemic postmenopausal women	Dietary flaxseed supplementation lowered the total and LDL-cholesterol level, approximately by 7 % and 10 %, respectively. However, the levels of HDL and triglyceride remained unaltered	Patade et al. (2008)
Diet was supplemented daily with 10 g of flaxseed powder for a period of 1 month	Type 2 diabetics	Blood glucose level reduced by 19.7 %. A favorable reduction in total cholesterol (14.3 %), triglycerides (17.5 %), LDL-cholesterol (21.8 %), and an increase in HDL-cholesterol (11.9 %) were also noticed	Mani et al. (2011)
Ground linseed was added in diet for 27 days (from day 29, till day 56)	Hypercholesterolemic rabbit	Total Cholesterol & LDL-cholesterol levels were reduced from 16.76 & 15.96 to 10.06 & 10.74 mg/L, respectively. There was no significant difference in serum HDL-cholesterol and TAG between the two groups	Prim et al. (2012)
25 % flaxseed based diet was consumed by mothers during lactation. At weaning, pups received the same diet for 170 days	Rats	A reduction in total cholesterol levels from 63.43 to 45.71 mg/dL and triglycerides from 79.86 to 54.29 mg/dL was observed, without any alteration in HDL	Cardozo et al. (2010)
40 g/day of ground flaxseed-containing baked products were fed for 10 weeks	Human	Flaxseed significantly reduced LDL-cholesterol at 5 weeks (by 13 %), but not at 10 weeks (by 7 %) and lipoprotein by a net of 14 %. In men, flaxseed reduced HDL-Cholesterol by a net of 16 % and 9 % at 5 and 10 weeks, respectively	Bloedon et al. (2008)
One group was fed high cholesterol diet (2 g/100 g) and other was fed same diet supplemented with flax/pumpkin seed mixture in ratio of 5:1	Rats	When compared with hypercholesterolemic group, flax group showed reduced levels of total cholesterol (220.35 vs 120.48 mg/dL), triacylglycerols (100.93 vs 77.99 mg/dL), VLDL-C (20.19 vs 15.59 mg/dL), LDL-C (171.83 vs 65.37 mg/dL), while increased level of HDL-C from 28.33 to 39.51 mg/dL	Barakat and Mehmoud (2011)
Flaxseed oil was fed in basal diet @ 6.4 % for 165 days	Trout	Sensory evaluations showed the preference for the taste of the flaxseed oil-enriched fillets to the control fillets	Simmons et al. (2011)

LDL low density lipoprotein; *VLDL* very low density lipoprotein; *HDL* high density lipoprotein; *TG* triglycerides; *TD* true digestibility; *NPU* net protein utilization; *PER* protein efficiency ratio; *BV* biological value

Prevention and treatment of obesity

Traditionally, obesity-related disease conditions have been often treated and/or prevented using many plant materials including flax (Singh et al. 2011; Santos et al. 2010). Flaxseed fibers form highly viscous solutions upon hydration, which is similar to those observed for other gums (Goh et al. 2006). Particularly viscous fibers appear effective in suppression of hunger (Wanders et al. 2011; Kristensen et al. 2011). Soluble nonstarch dietary fibers of flaxseed mucilage are multi-branched hydrophilic substances, forming viscous solutions that delay gastric emptying and nutrient absorption from the small bowel.

In obesity, leptin may be under-expressed by the adipose tissue in response to a consistently high caloric diet, or, leptin receptors may be down-regulated, thus leading to high plasma leptin levels (Dubey et al. 2006). Leptin is a protein encoded by the *obese* gene, named for the phenotype of the double knockout mouse (McCullough et al. 2011). These mice experience no satiety, and thus eat continuously when fed ad libitum, leading to severe diet-induced obesity. It decreases the secretion of neuropeptide Y (NPY) which is a potent appetite stimulator. McCullough et al. (2011) reported that consumption of flaxseed significantly increased plasma and adipose levels of ALA. Leptin protein levels were elevated in animals taking diet supplemented with 10 % flaxseed. Changes in leptin expression were strongly and positively correlated with adipose ALA levels and inversely correlated with risk of atherosclerosis.

Natural treatment of bowel syndrome

In Western societies, constipation remains a major health problem mostly due to refined diet. It is well known that a sufficient amount of dietary fiber is a cornerstone in the prevention and treatment of constipation (Tarpila et al. 2005). The metabolism of flaxseed fiber can be stated as with any dietary fiber. Dietary fiber as a natural way to manage irritable bowel syndrome made it the first line treatment for this condition during 1970s and 1980s. Cunnane et al. (1995) studied the influence of consuming 50 g flaxseed per day for 4 weeks on several indices of nutrition in 10 young healthy adults. Various reviews and articles have described comprehensively the effects of flax fiber, including gastrointestinal (GI)-motility, constipation, glucose tolerance, hypocholesterolemic effect and fermentation (Mani et al. 2011; Kristensen et al. 2011, 2012).

Health benefits of flax proteins

Concerning the protein fraction, flax is not actually used as a source of food protein but used in animal feed as a cheaper material (Rabetafika et al. 2011). Recent reports have shown various techno-functional properties (Wang et al. 2010a; Mueller et al. 2010a, b; Green et al. 2005) and health benefits of flaxseed proteins. A study about flaxseed protein have shown the benefits of flaxseed proteins in coronary heart disease, kidney disease and cancer (Oomah and Mazza 2000; Wang et al. 2007, 2009). Flax protein contains abundant arginine and glutamine (Oomah and Mazza 1993), which are very important in the prevention and treatment of heart disease (Gornik and Creager 2004), and in supporting the immune system (Avenell 2006). Flaxseed contains bioactive peptides, such as cyclolinopeptide A, which have strong **immunosuppressive** and **antimalarial** activities, inhibiting the human malarial parasite *Plasmodium falciparum* in culture (Bell et al. 2000). A number of studies have shown that flaxseed proteins possess potential for therapeutic applications (Table 7). For example, peptides derived from enzymatic hydrolysis of flaxseed proteins inhibited angiotensin I–converting enzyme (ACE) activities, and also displayed in-vitro **antioxidant** activities (Omoni and Aluko 2006; Marambe et al. 2008). Peptide mixture from flaxseed with high levels of branched-chain amino acids, and low levels of aromatic amino acids have shown antioxidant properties by scavenging 2,2-diphenyl-1-picrylhydrazyl radical (DPPH), and **antihypertensive** properties by inhibiting the ACE activity (Udenigwe and Aluko 2010).

Commercial utilization of flaxseeds in food products

Functional food revolution

Functional foods are those that provide a specific health benefit to the consumer over and above their nutritional value. Functional foods are relatively recent developments that meet a strengthening consumer demand for foods that enhance health and wellbeing. According to a new report by Global Industry Analysts, Inc. the global market for functional foods and drinks is projected to reach exceed $130 billion by the year 2015 (Global Industry Analysts 2010). According to Leatherhead Food Research (2011) statistics, global functional food market in different sectors is shown in Fig. 4. The

Table 7 Biological/functional properties of flaxseed proteins

Function of flax protein	Effects/Mechanism	Reference
Antifungal	Act against food spoilage fungi *Penicilliumchrysogenum, Fusariumgraminearum & Aspergillusflavus*	Xu et al. (2006, 2008)
Antioxidant	Hydrolyzed flaxseed proteins exhibited antioxidant property by scavenging 2, 2-diphenyl-1- picrylhydrazyl radical, superoxide radical & hydroxyl radical	Xu et al. (2008); Udenigwea et al. (2009)
Antihypertensive	Inhibits angiotensin I-converting enzyme	Udenigwe and Aluko (2010)
Cholesterol lowering effect	Due to their bile acids binding activity	Marambe et al. (2008)
Anti-diabetic	Because flax proteins can interact with fiber and mucilage; And also by stimulating the secretion of insulin	Oomah (2001)
Anti-thrombic	Flax proteins- hirudine&linusitin	Tolkachev and Zhuchenko (2000)
Anti-tumor	Due to presence of low lysine/arginine ratio	Oomah (2001)

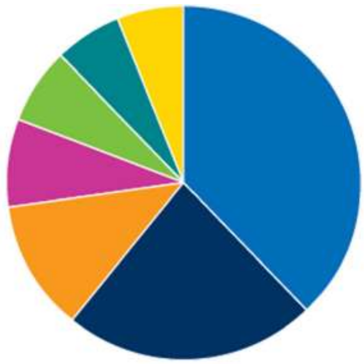

Fig. 4 Global functional foods market by sector, 2010 (% value)

United States market dominates (>30 % of the total global market) and is showing a sustained growth of ~14 % per year, while its ~8 % per year across the world (Smithers 2008). In this large marketplace, the food industry is demanding economical, high-quality, novel and substantiated ingredients. In such a setting, flaxseed being rich in ω-3 fatty acids, lignans and fibers provide the industry with an excellent choice in developing the value-added food products. With the increasing rate of obesity and other chronic diseases in western societies, flax products are increasingly used as functional foods and nutraceuticals (Hasler et al. 2000; Lemay et al. 2002; Ogborn et al. 2002; Watkins et al. 2001). In recent years, as people have become more concerned about health, demand for flax in food and beverages, functional foods and dietary supplements has risen dramatically both in the U.S. and other countries. For example, Mintel's Global New Products Database (GNPD) reported that in 2005, 72 new products were launched in the United States that listed flax or flaxseed as an ingredient (Wilkes 2007). In the first 11 months of 2006, there were 75 new products launched enriched with flax or flaxseed (Wilkes 2007). Interest in flax and other ω-3-containing foods heightened further in May 2003 when the White House issued a letter to the U.S. Department of Agriculture (USDA) and the U.S. Food and Drug Administration (FDA) that asked them to promote the intake of ω-3 fatty acids in the diet (Wilkes 2007).

Estimated intakes of whole and milled flaxseed, ALA and fibers

After reviewing various clinical studies regarding the health effects of flax elements, it can be concluded that flax in different forms can be consumed but the dietary intakes are equally important. The intended uses of whole and milled flaxseed are determined to generally recognized as safe (GRAS) (Jheimbach and Port Royal 2009). FDA previously authorized the addition of flaxseed to foods at up to 12 % levels by weight, and this may be taken as a representative maximum addition level for most foods (Jheimbach and Port Royal 2009). While it may be technologically and organoleptically feasible to add a somewhat higher proportion of flaxseed to a few food products, for many products even 12 % flaxseed addition is likely to be unattainable. Using the Reference Amounts Customarily Consumed (RACC) established by FDA, addition levels of 12 % by weight can be converted to g/serving by multiplying the RACC by the intended addition percentage. Various recommended levels of flaxseed in food products are shown in Table 8.

For optimal health, many government and public health authorities recommend increasing ω-3 fatty acids in diet. In fact as early as 1990, Health Canada recommended an ω-6 : ω-3 fatty acid dietary ratio of 4:1 to 10:1 (Health and Welfare Canada 1990). Supplemented products for clinical trials need to contain an amount and type of flaxseed that will significantly increase the levels of ALA in the blood over and above the recommended daily amount of 1.6 g/d for males and 1.1 g/d for females (Health Canada 2009; U.S. Department of Agriculture and U.S. Department of Health and Human Services 2010). Flaxseed contains approximately 23 g ALA per 100 g (USDA 2010) and thus, the recommended dietary amounts can be obtained by consuming about 9 g of flaxseed per day. Various expert committees recommended dietary intakes of ALA according to Table 9. The mean intake of dietary fibers among several European countries is 22 g/d,

Table 8 Intended addition levels of flaxseed by weight and per serving

Food category	RACC[a] (g)	Maximum flaxseed content[b] (g/serving)
Bread	50	6.0
Biscuits, bagels, tortillas	55	6.6
Doughnuts, muffins	55	6.6
Pancake/waffle mix	40	4.8
Pasta (dry weight)	55	6.6
Multi grain flours or meal	30	3.6
Breakfast cereals	30	3.6
Cookies	30	3.6
Nuts & seeds	30	3.6
Cheeses	30	3.6
Salad dressing	30	3.6
Mayonnaise	15	1.8
Margarine, table spreads	15	1.8
Yoghurt	225	27.0

Source: Jheimbach and Port Royal (2009)

[a] Reference amount customarily consumed (21 CFR § 101.12)

[b] Based on addition of flaxseed at 12 % by weight of the food

Table 9 Recommendations of α-linolenic acid by various expert committees

Expert committee	RDA of ALA (per day)
North Atlantic Treaty Organization workshop in 1989	3 g ALA
International Society for the Study of Fatty Acids and Lipids (ISSFAL) in 1999	2.2 g ALA
Eurodiet Commission in 2000	2 g ALA
French Apports Nutritionnels Conseilles in 2001	1.8 g ALA

Source: Jheimbach and Port Royal (2009)

ranging from 12 to 34 g/d (Bingham et al. 2003), approximately 14.3 g/d in Japan and 21.9 g/d in USA, ranging from 12 to 36 g/d (Peters et al. 2003). It is commonly recommended dietary fiber intakes should be 30 g or more per day. This amount is expected to increase stool weight and frequency and normalize stool consistency (Devroede 1988).

Use of whole flaxseeds/flax flour and flaxseed oil in products for human consumption

Flaxseed is regaining its status as a functional food after centuries of use as natural medicine. Flaxseeds can be used as roasted and milled seeds, while flaxseed oil can be used in various food formulations in the form of neat oils, stable emulsions and micro- and nano-encapsulated powder. Bakery sector in the west has resorted to the method of adding ground flax seed into mixed grain bread for the purpose of meeting customer demands. Flax or flaxseed oil has been incorporated into baked foods (Payne 2000; Pohjanheimo et al. 2006), juices, milk and dairy products (Dodin et al. 2008; 2005; Ivanova et al. 2011), muffins (Ramcharitar et al. 2005; Aliani et al. 2011), dry pasta products (Sinha and Manthey 2008; Lee et al. 2004; Hall et al. 2005; Marconi and Carcea 2001), macaroni (Hall et al. 2005) and beef patties (Bilek and Turhan 2009).

In bakery and other food products

The wide consumption of bakery products makes them ideally suited for fortification as foods for the daily consumption as well as those used for clinical trials (Kadam and Prabhasankar 2010). With various positive reports regarding the health benefits of flax enriched food products, few reports showed neutral health impacts and lower sensory acceptability. Ramcharitar et al. (2005) found that the muffin containing 11.6 % milled flaxseed by weight was rated as significantly less acceptable than the control muffin. Pretzel type yeast bread containing 15 % flax was rated as significantly lower in flavor and overall acceptability compared to the control (Alpaslan and Hayta 2006).

The main advantage of milled flaxseed to be used in bakery products is its carbohydrate (gums) and protein fractions. Flaxseed gum has been reported to 1) enhance viscosity, best at pH 6–8; 2) stabilize foam and protein based emulsions (Wang et al. 2011), comparing favorably with ovalbumin; 3) increase absorption in bread while improving loaf volume, oven spring, and keeping quality; 4) significantly improve objective and subjective bread characteristics; 5) affect shear rate as gum arabic does; and 6) show promise as a “food thickener” and “improving agent” in baked goods (Carter 1993). Hall et al. (2005) recommended flaxseed particles could be used in breads to get the good quality baked products. Use of ground flaxseed at a 10 % level markedly increased loaf volume, specific loaf volume, Dallman degree, and retarded bread staling (Mentes et al. 2008). Incorporation of flaxseed hull into Chinese steamed bread (CSB) significantly enriched the phytochemical profile of the bread with a concomitant increase in the antioxidant activity (Hao and Beta 2012). Lipilina and Ganji (2009) prepared bread with 30 % flaxseed flour and observed a 15-fold increase in linolenic acid (28 g), a 100 % increase in linoleic acid (7 g) and a 70 % (16 g) increase in dietary fiber in enriched bread when compared with control.

The partial substitution of soy oil with flaxseed oil (25, 50 and 75 %) in bread formulations resulted in an increased ALA content and the gradual reduction of the ω-6 : ω-3 ratio without negative effects on bread technical quality or sensorial attributes (Aguiar et al. 2011). Minker et al. (1973) reported that linseed mucilage had emulsifying properties better than those of tween-80, gum arabic, and gum tragacanth, implying potential industrial use. Owing to the high mucilage content, the flaxseed hull has high-water absorption, moisture–binding capacity, as well as lubricity. This helps dough throughput and puffing during extrusion processing (cereals, snacks, or pet foods) or as a trans-fat free shortening alternative in cookies, muffins, breads, and other baked foods where the water absorption can impact the mixing time and dough-handling characteristics (Best 2004). Flaxseed contains no gluten, so useful for those with gluten allergy. Whole or ground flaxseed can replace some of the flour in bread, muffin, pancake, and cookie recipes. Cookies containing up to 20 % of full-fat flaxseed flour were acceptable in relation to their overall acceptability (Hussain et al. 2006). Ivanova et al. (2011) showed that butter with flaxseed additive has pure creamy flavor and odor without flavor and odor of additive, yellow color and good spreadability and plasticity.

Omega-3 enriched foods offer more food choices to consumers seeking to increase the ω-3 content of their diet. Giroux et al. (2010) prepared dairy beverages enriched with linseed oil. Matumoto- Pintroa et al. (2011) added commercially available flax lignan -SDG extract to the formulation of dairy beverages enriched with flaxseed oil to increase its oxidative stability. Some other food uses of flaxseed are ready-to-eat breakfast cereals, breakfast drinks, salad dressings made with cold-pressed flaxseed oil, salad toppings, biscuits, meat extenders, crackers, soups, bagels, fiber bars, and cakes. Recent research work on enrichment of flax in various food products is shown in Table 10.

Omega-3 enriched eggs from laying hens fed a special flax diet are gaining in popularity amongst consumers on the North American continent and abroad. The organoleptic quality of ω-3 enriched eggs was acceptable without off-flavors when hens were fed 5 % (or less) flaxseed oil in diet (Cloughley et al. 1997). Generally, sensory quality of ω-3 enriched eggs tends to be similar to regular table eggs although in some cases panelists were able to detect off-flavors (Caston et al. 1994; Ahn et al. 1995). A 'fishy' or fish-product related flavor was detected in eggs from hens on diet containing 15–20 % flaxseed. Data from a study conducted by Leeson et al. (1998) also suggested that high (>10 %) levels of flaxseed would result in some decrease in overall egg acceptability as assessed by aroma and flavor. This remains a problem associated with the commercial production of this type of product. It has been suggested that the use of combinations of anti-oxidants in the hen's diet could help to suppress these off-flavors. Other food products, such as ω-3 enriched pork, are produced by including flax in animal rations.

Table 10 Recent reports of various food products enriched with whole flaxseed, flax flour and flax oil

Consumed flax form	Amount supplemented	Flax enriched food product	Main results	References
Flax flour	15 %	Bread	Musty aroma was significantly reduced in flax bread during 4 weeks of storage with addition of Vitamin C, BHA & BHT	Conforti and Cachaper (2009)
Flax flour	Not available	Muffins & Snack bar	Flax muffins & snack bar showed lower acceptability than non-flax products. However, flavouring enhanced the overall acceptability significantly	Aliani et al. (2011)
Flaxseed oil	1 %	Cheese	High retention of flax oil (5.2 mg/g) was observed in cheese without affecting the shelf life of the product	Aguirre and Canovas (2012)
Flaxseed oil	25, 50, 75 & 100 %	Shortening & biscuits	Biscuits made with 100 % substituted shortening were acceptable as control	Hassan et al. (2012)
Flax flour	16 %	Corn snacks	7 fold increase in dietary fibres, almost 100 % increase in protein content, with similar acceptability score when compared to control	Trevisan and Areas (2012)
Flaxseed oil (powder)	1, 2.5, 5.0 & 10 %	Bread	Water absorption capacity increased from 62 (control) to 70 % (10 % flax-bread). No effects on sensorial properties were observed	Gokmen et al. (2011)
Milled flaxseed (Flour)	15 & 25 %	Yeast bread	Highest taste & aroma acceptance scores were found for yeast bread with 15 % flax bread. No significant increase in peroxide value was observed with 25 % flax bread till bread staling	Mentes et al. (2008)
Milled flaxseed	23 %	Bagels	Flax aroma & flavours were detected in fortified bagels as compared to non-fortified bagels, but still were acceptable	Aliani et al. (2012)
Full fat and partially defatted flaxseed flour	4–20 %	Unleavened flat bread	12 % full fat and 16 % defatted flaxseed flour enriched bread showed maximum acceptability. The level of soluble, insoluble and total dietary fibres and essential amino acids were higher in flax flour enriched bread than control	Hussain et al. (2012)
Flaxseed oil	0–12 %	Ice cream	Flax-ice cream showed minimal fat flocculation, less stabilisation of air cells resulting in a soft ice cream that had a high meltdown rate. Incorporation of 2 % flaxseed oil in a 12 % (w/w) ice cream was possible affecting the ice cream functionality	Goh et al. (2006)
Flaxseed cake	10 & 15 %	Brown bread	Bread samples with inclusion levels of 10 and 15 % flaxseed oil cake were acceptable to the consumer sensory panel.	Ogunronbi et al. (2011)
Ground flaxseed	7.3, 11.6 & 15.5 %	Muffins	Control muffin had higher score than the flax muffin for appearance, colour, flavour, texture, overall acceptability & food acceptance. Flaxseed muffin (11.6 %) was "neither liked nor disliked" to "liked slightly" in overall acceptability	Ramcharitar et al. (2005)
Flaxseed flour	0–18 %	Cookies	Cookie dough stickiness significantly decreased with flaxseed flour. The 18 % flaxseed cookies had the firmest texture & darkest colour, unacceptable by consumers. While 6 & 12 % flaxseed cookies were acceptable without negatively affecting the physical and sensory properties	Khouryieh and Aramouni (2012)

Use of flaxseed by-product as a protein source

Flaxseed is one of the oilseeds grown primarily for their oil content and fatty acid composition, leaving protein-rich meals as an underutilized by-product. To date flaxseed has not yet been widely exploited as a source of protein for human consumption. Within the food protein ingredient market, industry is pushing toward finding plant-based alternatives to animal-derived ingredients based on consumer perceived fears (e.g., prion disease), religious inhibitions, and dietary and moral preferences associated with consuming animal by-products (Karaca et al. 2011). The main product obtained from flaxseed is oil, and the residual paste is used as an ingredient for making animal feed. However, flaxseed grain and flaxseed paste contain about 21 % and 34 % protein, respectively. One way of adding flaxseed paste to conventional foods is to convert the paste into protein concentrate. In this way, it is possible to obtain a product with both high protein content and certain desirable functional characteristics. Flaxseed proteins have been investigated for their emulsifying properties with mixed results (Wang et al. 2010b, c).

It is shown that crude flaxseed protein (containing flaxseed mucilage) has better water absorption, oil absorption, emulsifying activity and emulsion stability compared to soybean protein (Dev and Quensel 1988, 1989). Karaca et al. (2011) reported that creaming stability of emulsions (96.6 %) stabilized by flaxseed proteins was comparable to whey protein isolates (WPI)-stabilized emulsions (90.8 %). Flax protein concentrate showed high oil and water absorption capacities of 150.25 and 253.5 %, respectively, better foam stability (83.33 %), emulsifying capacity (84.76 mL/g), and emulsifying activity (88.37 %) at a pH 6 (Flores et al. 2006). This property is very important if the protein concentrate is to be used in products such as salad dressings, mayonnaise, hamburgers and bread products.

Similarly, partial defatting of flax flour improved foam capacity, foam stability and water absorption capacity (Hussain et al. 2008). Same author reported that the replacement of roasted and partially defatted flaxseed flours upto a level of 16 % supplementation in whole wheat flour was found acceptable for sensory attributes of chapattis (Indian bread) (Hussain et al. 2008).

Flaxseeds for a new millennium

To achieve optimal nutrition through the intake of healthy foods, Food Science and Technology experts are creating a new framework for food-based dietary recommendations, principally in the areas of food physics, methods of food storage and preservation, nutrient restoration and fortification of foods, as well as the development of health-focused designer foods and functional foods (FAO/WHO 1996; USDA 2010). Initiatives have been undertaken by the food industry to increase the level of ω-3 fatty acids, dietary fibers and antioxidants, etc. Flaxseed has drawn the attention of scientists, researchers and industry due to its ω-3 fatty acids and lignans and various health benefits. In the functional arena of 21st century, flaxseed's use is not just limited to its fibers but has been extended to its various nutraceuticals and therapeutic attributes which make it a potent value added food ingredient. Although flaxseed oil unlike fish oil, does not contain EPA and DHA, but still it is gaining popularity in India and Western countries due to its high ALA content. A major hurdle with ω-3 rich fish oil is consumers' increased awareness of environmental contaminants [e.g., heavy metals and polychloro biphenyls (PCBs)] and bioaccumulation of these contaminants in fish. If FDA approves the flax to be labeled as a whole grain, the fortified food products variety will see enormous growth in future. Flax is a rich source of ALA (ω-3 fatty acid), dietary fibers, high quality proteins, antioxidants, and lignans, some of which offer synergistic health benefits. Flax contains almost no digestible or glycemic carbohydrates. In all respects, flax offers a model for whole grains or seeds and underscores the recognition given to the nutritional value of "whole grains", "whole seeds" and "whole foods".

Conclusions

Based on the information, it is evident that flaxseeds are the richest source of α-linolenic acid and lignans. It is also a considerable potential source of soluble fiber, antioxidants and high quality protein. Its long journey from being a medicine in ancient times to the health food source in 21st century has opened the doors for a large population. The role of flaxseed lignans and ω-3 fatty acid in reducing the risks associated with cardiac and coronary disease, cancer (breast, colon, ovary and prostate) and other human health risk factors has been well known. When healthy heart is one of the most desired and highly demanded health benefits from functional foods; and where food industry's goal is to develop innovative solutions to address nutritional challenges, flaxseed is going to play a vital role for the same. Flaxseed can contribute in improving the availability of healthy food choices, specifically by improving the nutrient profile of foods through reductions in the salt, sugar and saturated fat content; and by increasing the content of ω-3 fatty acids and other bioactive compounds. With contribution from such factors, worldwide market for healthy heart foods is estimated to grow rapidly in the coming years. As a result, flax and flaxseed oil may be preferred ingredients of functional foods and nutraceuticals in future. There is no doubt that a change to an omega-3 rich and high fiber diet would be beneficial. Therefore the use of flaxseed in whole seed or ground form can be recommended as a dietary supplement. Modern techniques like high power ultrasound, micro-fluidization, spray granulation and nanoencapsulation will pave way for new approaches to the processing, stabilization and utilization of flaxseed oil. Further, enrichment of diets of the animals with flax/flaxseed oil for production of ω-3 enriched eggs, milk, meat and other animal origin products could be another approach in utilizing flaxseeds.

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