

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

Ankit Goyal · Vivek Sharma · Neelam Upadhyay · Sandeep Gill · Manvesh Sihag

Revised: 11 December 2013 / Accepted: 26 December 2013
© Association of Food Scientists & Technologists (India) 2014

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

A. Goyal (✉) · V. Sharma · N. Upadhyay · M. Sihag
Dairy Chemistry Division, National Dairy Research Institute, Karnal,
Haryana, India 132001
e-mail: ankit_goyal@yahoo.co.in

V. Sharma
e-mail: Vishk12000@yahoo.com

N. Upadhyay
e-mail: neelam_2912@yahoo.co.in

M. Sihag
e-mail: manveshsihag@gmail.com

S. Gill
BITS Pilani, Hyderabad Campus Shameerpet Mandal Rangareddy
District, Hyderabad, Andhra Pradesh, India 500078
e-mail: sandeep77gill@gmail.com

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 4th 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; Kozłowska 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 physico-chemical 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

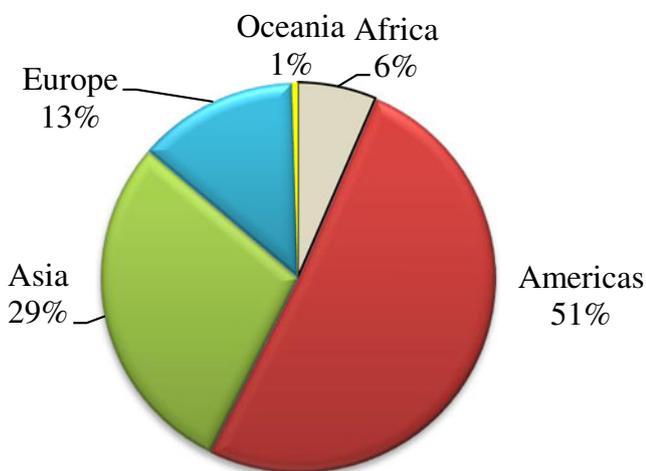


Fig. 1 Average production of linseed/flaxseed in the world (2000–2010)

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).

Proteins

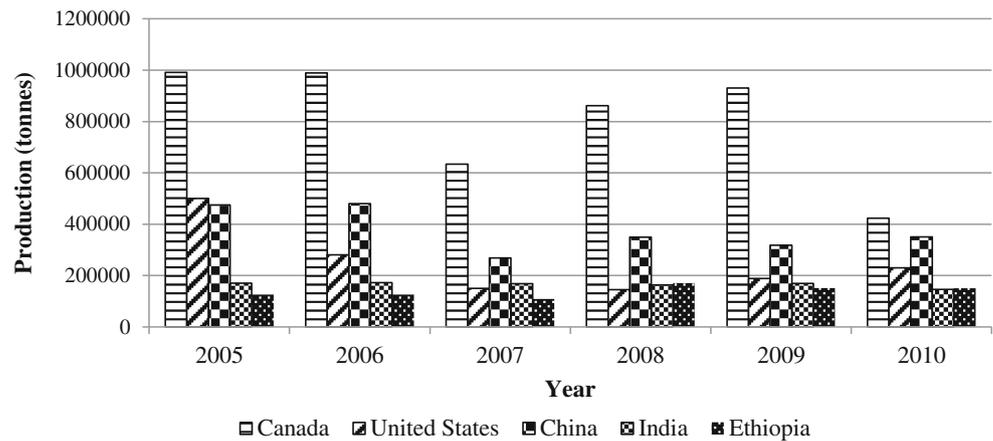
The protein content of flaxseed varies from 20 to 30 %, constituting approximately 80 % globulins (linin and conlinin) and 20 % glutelin (Hall et al. 2006). Flaxseed has an amino acid profile comparable to that of soybean and contains no gluten (Hongzhi et al. 2004; Oomah 2001). Although flax protein 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).

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 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

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 (gamma-glutamyl-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), *Tvagdosahrit* (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.	<ul style="list-style-type: none"> • 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 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

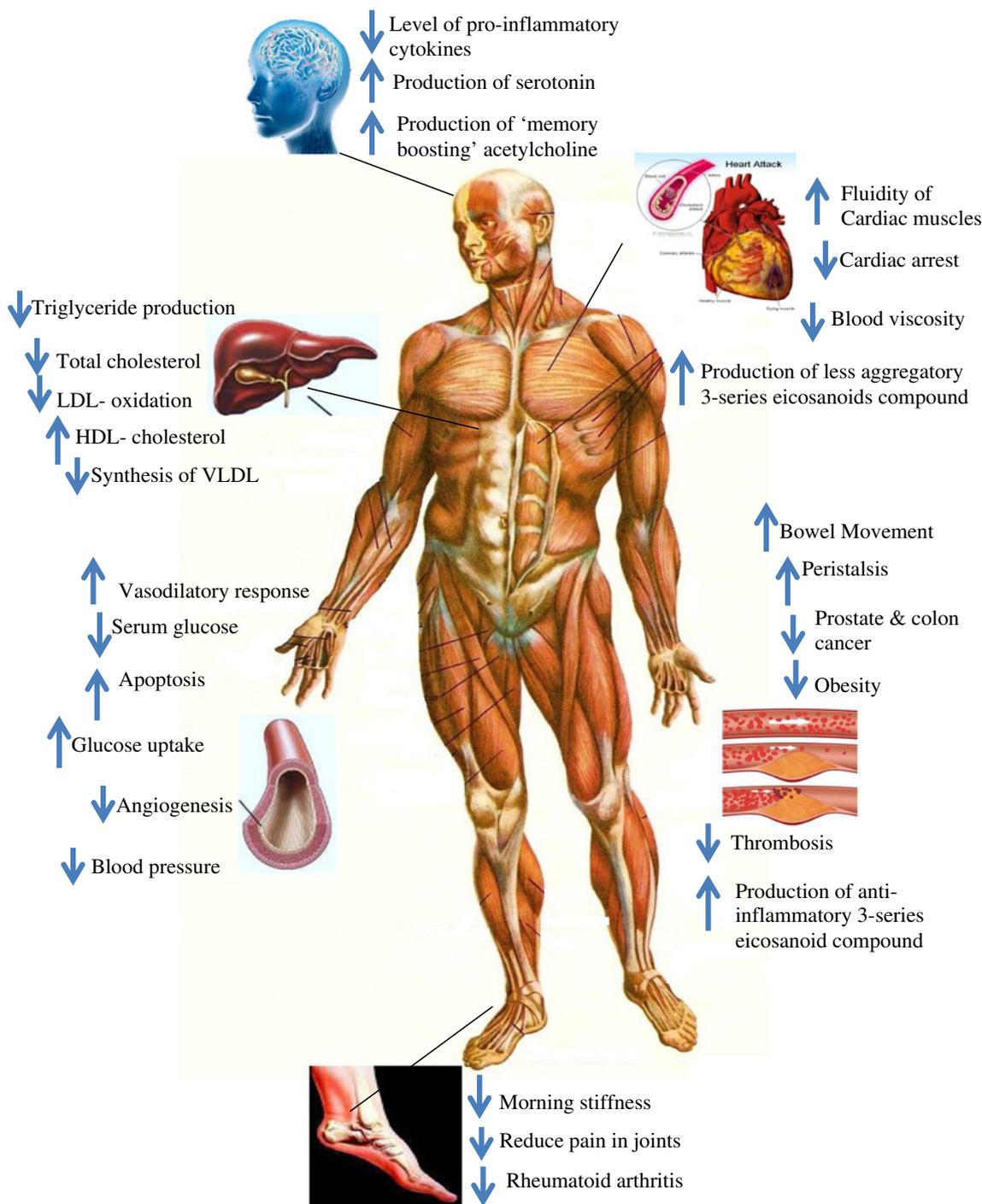


Fig. 3 Physiological effects imparted by functional elements of flaxseed (oil, fiber and lignans)

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; Saggari 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-17 β -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 (Saggari 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 <i>Penicilliumchrysogenum</i> , <i>Fusariumgraminearum</i> & <i>Aspergillusflavus</i>	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); Udenigwe 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&linusititn	Tolkachev and Zhuchenko (2000)
Anti-tumor	Due to presence of low lysine/arginine ratio	Oomah (2001)

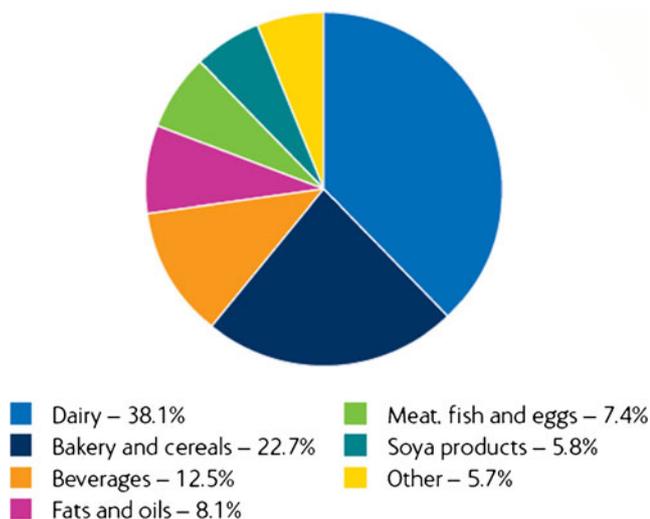


Fig. 4 Global functional foods market by sector, 2010 (% value)

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.

References

- Adlercreutz H (2007) Lignans and human health. *Crit Rev Clin Lab Sci* 44(5–6):483–525
- Aguiar ACD, Boroski M, Monteiro ARG, Souza NED, Visentainer JV (2011) Enrichment of whole wheat flaxseed bread with flaxseed oil. *J Food Process Preserv* 35:605–609
- Aguirre DB, Canovas GVB (2012) Fortification of queso fresco, cheddar and mozzarella cheese using selected sources of omega-3 and some nonthermal approaches. *Food Chem* 133(3):787–797
- Ahn DU, Sunwoo HH, Wolfe FH, Sim JS (1995) Effects of dietary alpha-Linolenic acid and strain of hen on the fatty acid composition, storage stability and flavor characteristics of chicken eggs. *Poult Sci* 74:1540–1547
- Alhassane T, Xu XM (2010) Flaxseed lignans: source, biosynthesis, metabolism, antioxidant activity, bio-active components and health benefits. *Compr Rev Food Sci Food Saf* 9:261–269
- Aliani M, Ryland D, Pierce GN (2011) Effect of flax addition on the flavor profile of muffins and snack bars. *Food Res Int* 44:2489–2496
- Aliani M, Ryland D, Pierce GN (2012) Effect of flax addition on the flavor profile and acceptability of bagels. *J Food Sci* 71(1):S62–S70. doi:10.1111/j.1750-3841.2011.02509.x
- Alpaslan M, Hayta M (2006) The effects of flaxseed, soy and corn flours on the textural and sensory properties of a bakery product. *J Food Quality* 29:617–627
- Andar BP, Weber AR, Rampersad PP, Gilchrist JS, Pierce GN, Lukas A (2004) Dietary flaxseed protects against ventricular fibrillation induced by ischemiare perfusion in normal and hypercholesterolemic rabbits. *J Nutr* 134:3250–3256
- Anwar F, Zreen Z, Sultana B, Jamil A (2013) Enzyme-aided cold pressing of flaxseed (*Linum usitatissimum* L.): enhancement in yield, quality and phenolics of the oil. *Grasas y Aceites* 64(5):463–471
- Austria JA, Richard MN, Chahine MN (2008) Bioavailability of alpha-linolenic acid in subjects after ingestion of three different forms of flaxseed. *J Am Coll Nutr* 27:214–221
- Avenell A (2006) Glutamine in critical care: current evidence from systematic reviews. *Proc Nutr Soc* 65(3):236–241
- Baggio B, Musacchio E, Priante G (2005) Polyunsaturated fatty acids and renal fibrosis: pathophysiologic link and potential clinical implications. *J Nephrol* 18:362–367
- Barakat LAA, Mehmoud RH (2011) The antiatherogenic, renal protective and immunomodulatory effects of purslane, pumpkin and flax seeds on Hypercholesterolemic rats. *N Am J Med Sci* 3(9):351–357
- Barre DE, Mizier-Barre KA, Griscti O, Hafez K (2008) High dose flaxseed oil supplementation may affect fasting blood serum glucose management in human type 2 diabetics. *J Oleo Sci* 57(5):269–273
- Bell A, McSteen PM, Cebat M, Picur B, Siemion IZ (2000) Antimalarial activity of cyclolinopeptide A and its analogues. *Acta Pol Pharm* 57: 134–136
- Best D (2004) Low-carb revolution fuels innovation with flaxseed. Functional ingredient <http://newhope360.com/conditions/low-carb-revolution-fuels-innovation-flaxseed> Last accessed 21/05/2012
- Bhatty RS (1995) Nutritional composition of whole flaxseed and flaxseed meal. In: Cunnane SC, Thompson LH (eds) *Flaxseed in human nutrition*. AOCS Press, Champaign, pp 22–45
- Bilek AE, Turhan S (2009) Enhancement of the nutritional status of beef patties by adding flaxseed flour. *Meat Sci* 82:472–477
- Bingham SH, Day NE, Luben R, Ferrari P, Slimani N, Norat T, Clavel-Chapelon F, Kesse E, Nieters A, Boeing H, Tjoenneland A, Overvad K, Martinez C, Dorronsoro M, Gonzalez CA, Key TJ, Trichopoulou A, Naska A, Vineis P, Tumino R, Krogh V, Bueno-de-Mesquita HB, Peeters PHM, Berglund G, Hallmans G, Lund E, Skeie J, Kaaks R, Riboli E (2003) Dietary fibre in food and protection against colorectal cancer in the European Prospective Investigation into Cancer and Nutrition (EPIC): an observational study. *Lancet* 361:1496–1501
- Bjrok S, Kapur A, King H, Nair J, Ramachandran A (2003) Global policy: aspects of diabetes in India. *Health Policy* 66:61–72
- Bloedon LT, Balikai S, Chittams J, Cunnane SC, Berlin JA, Rader DJ, Szapary PO (2008) Flaxseed and cardiovascular risk factors: results from a double blind, randomized, controlled clinical trial. *J Am Coll Nutr* 27(1):65–74
- Boden-Albala B, Cammack S, Chong J, Wang C, Wright C, Rundek T, Elkind MS, Paik MC, Sacco RL (2008) Diabetes, fasting glucose levels, and risk of ischemic stroke and vascular events: findings from the Northern Manhattan Study (NOMAS). *Diabetes Care* 31: 1132–1137
- Bozan B, Temelli F (2008) Chemical composition and oxidative stability of flax, safflower and poppy seed and seed oils. *Bioresour Technol* 99(14):6354–6359
- Cardozo LFMDF, Chagas MA, Soares LL, Troina AA, Bonaventura GT (2010) Exposure to flaxseed during lactation does not alter prostate area or epithelium height but changes lipid profile in rats. *Nutr Hosp* 25(2):250–255
- Carter JF (1993) Potential of flaxseed and flaxseed oil in baked goods and other products in human nutrition. *Cereal Food World* 38(10):753–759
- Caston LJ, Squires EJ, Leeson S (1994) Hen performance, egg quality, and the sensory evaluation of eggs from SCWL hens fed dietary flax. *Can J Anim Sci* 74:347–353
- Chen J, Power KA, Mann J, Cheng A, Thompson LU (2007) Flaxseed alone or in combination with tamoxifen inhibits MCF-7 breast tumor growth in ovariectomized athymic mice with high circulating levels of estrogen. *Exp Biol Med* 232:1071–1080
- Chen J, Sagggar JK, Corey P, Thompson LU (2009) Flaxseed and pure secoisolariciresinol diglucoside, but not flaxseed hull, reduce human breast tumor growth (MCF-7) in athymic mice. *J Nutr* 139:2061–2066
- Chen J, Sagggar JK, Corey P, Thompson LU (2011a) Flaxseed cotyledon fraction reduces tumour growth and sensitises tamoxifen treatment of human breast cancer xenograft (MCF-7) in athymic mice. *Br J Nutr* 105:339–347
- Chen J, Sagggar JK, Ward WE, Thompson LU (2011b) Effects of flaxseed lignan and oil on bone health of breast-tumor-bearing mice treated with or without tamoxifen. *J Toxicol Environ Health* 74(12): 757–768
- Choo WS, Birch J, Dufour JP (2007) Physicochemical and quality characteristics of cold-pressed flaxseed oils. *J Food Compos Anal* 20(3):202–211
- Chung MWY, Lei B, Li-Chan ECY (2005) Isolation and structural characterization of the major protein fraction from NorMan flaxseed (*Linum usitatissimum* L.). *Food Chem* 90:271–279
- Cicero AF, Derosa G, Di G, Bove M, Gaddi AV, Borghi C (2010) Omega-3 polyunsaturated fatty acids supplementation and blood pressure levels in hypertriglyceridemic patients with untreated normal-high blood pressure and with or without metabolic syndrome: a retrospective study. *Clin Exp Hypertens* 32(2): 137–144

- Cloughley J, Noble R, Speake B, Sparks N (1997) Manipulation of docosahexaenoic (22: 6 n-3) acid in chicken's egg. *Prostaglandins Leukot Essent Fat Acids* 57:222
- Condori SQ, Saldana MDA, Temelli F (2011) Microencapsulation of flax oil with zein using spray and freeze drying. *Food Sci Technol* 44: 1880–1887
- Conforti FD, Cachaper KF (2009) Effects of selected antioxidants on physical and sensory characteristics of yeast bread containing flaxseed meal. *Int J Consum Stud* 33:89–93
- Coresh J, Selvin E, Stevens LA, Manzi J, Kusek JW, Eggers P, Van-Lente F, Levey AS (2007) Prevalence of chronic kidney disease in the United States. *JAMA* 298(17):2038–2047
- Cunnane SC, Ganguli S, Menard C, Liede AC, Hamadeh MJ, Chen ZY, Wolever TMS, Jenkins DJA (1993) High α -linolenic acid flaxseed (*Linum usitatissimum*): some nutritional properties in human. *Br J Nutr* 69(2):443–453
- Cunnane SC, Hamadeh MJ, Liede AC, Thompson LU, Wolever TMS (1995) Nutritional attributes of traditional flaxseed in healthy young adults. *Am J Clin Nutr* 61(1):62–68
- Danaei G, Finucane MM, Lu Y, Singh GM, Cowan MJ, Paciorek CJ, Lin JK, Farzadfar F, Khang YH, Stevens GA, Rao M, Ali MK, Riley LM, Robinson CA, Ezzati M (2011) National, regional, and global trends in fasting plasma glucose and diabetes prevalence since 1980: systematic analysis of health examination surveys and epidemiological studies with 370 country-years and 2.7 million participants. *Lancet* 378:31–40
- Dash B, Sharama BK (2001) *Charak Samhita*, 7th edn. Chaukhamba Sanskrit Series Office, Varanasi
- Dev DK, Quensel E (1988) Preparation and functional properties of linseed protein products containing differing levels of mucilage. *J Food Sci* 53:1834–1837
- Dev DK, Quensel E (1989) Functional properties of linseed protein products containing deferent levels of mucilage in selected food systems. *J Food Sci* 54:183–186
- Devroede G (1988) Constipation. In: Kumar D, Gustavsson S (eds) *Gastrointestinal motility*. Wiley, London, pp 411–445
- Dieken HA (1992) Use of flaxseed as a source of omega-3 fatty acids in human nutrition. In the 54th proceeding of Flax Inst. of United States. p 1–4
- Dodin S, Lemay A, Jacques H, Legare F, Forest JC, Masse B (2005) The effects of flaxseed dietary supplement on lipid profile, bone mineral density, and symptoms in menopausal women: a randomized, double-blind, wheat germ placebo-controlled clinical trial. *J Clin Endocrinol Metab* 90(3):1390–1397
- Dodin S, Cunnane SC, Masse B, Lemay A, Jacques H, Asselin G, Tremblay-Mercier J, Marc I, Lamarche B, Legare F, Forest JC (2008) Flaxseed on cardiovascular disease markers in healthy menopausal women: a randomized, double-blind, placebo-controlled trial. *Nutr* 24(1):23–30
- Dribnenki JCP, McEachern SF, Chen Y, Green AG, Rashid KY (2007) 2149 Solin (low linolenic flax). *Can J Plant Sci* 87(2):297–299
- Drouillard JS, Farran TB, Blasi DA, LaBrune HJ, Montgomery SP, Sindt JJ, Coetzer CM, Hunter RD, Spire MF, Elsassar TH, Higgins JJ (2000) Modulation of immune response in feeder cattle with flaxseed. *Proceedings of the 58th Flax Institute of the United States*, pp. 53–62
- Dubey H, Das SK, Panda T (2006) Numerical simulation of a fully baffled biological reactor: the differential circumferential averaging mixing plane approach. *Biotechnol Bioeng* 95:754–766
- Dupasquier CMC, Weber AM, Ander BP, Rampersad PP, Steigerwald S, Wigle JT, Mitchell RW, Kroeger EA, Gilchrist JS, Moghadasian MM, Lukas A, Pierce GN (2006) The effects of dietary flaxseed on vascular contractile function and atherosclerosis in rabbits during prolonged hypercholesterolemia. *Am J Physiol Heart Circ Physiol* 291:H2987–H2996
- Dupasquier CMC, Dibrov E, Kostenuk AL, Yeganeh B, Moghadasian MH, Pierce GN (2007) The beneficial effects of dietary flaxseed on atherosclerosis in the LDL receptor deficient mouse occur in part through anti-proliferative and anti-inflammatory actions. *Am J Physiol Heart Circ Physiol* 293:H2394–H2402
- Ernesto M, Cardoso AP, Nicala D, Mirione E, Massaza F, Cliff J, Haque MR, Bradbury JH (2002) Persistent konzo and cyanogen toxicity from cassava in northern Mozambique. *Acta Trop* 82:357–362
- Faintuch J, Bortolotto LA, Marques PC, Faintuch JJ, Franca JJ, Ceconello I (2011) Systemic inflammation and carotid diameter in obese patients: pilot comparative study with flaxseed powder and cassava powder. *Nutr Hosp* 26:208–213
- FAO (2012) FAOSTAT. Food and Agricultural Organization of the United Nations http://faostat3.fao.org/home/index.html#VISUALIZE_BY_DOMAIN Last accessed 25/05/2012
- FAO/WHO (1996) Preparation and use of food-based dietary guidelines Nutrition Programme. WHO, Geneva
- Flax council of Canada (2007) http://www.flaxcouncil.ca/spanish/pdf/FlxPmr-R11-Ch1_Span.pdf Last accessed 25/05/2012
- Flax council of Canada (2012) <http://www.flaxcouncil.ca/english/index.jsp?p=what&mp=what> Last accessed 25/05/2012
- Flores HEM, Barrera ES, Garnica-Romo MG, Penagos CJC, Saavedra JP, Macazaga-Alvarez R (2006) Functional characteristics of protein flaxseed concentrate obtained applying a response surface methodology. *J Food Sci* 71(8):C495–C498
- Gebauer SK, Psota TL, Harris WS, Kris-Etherton PM (2006) n-3 fatty acid dietary recommendations and food sources to achieve essentiality and cardiovascular benefits. *Am J Clin Nutr* 83:1526S–1535S
- Gillingham LG, Gustafson JA, Han SY, Jassal DS, Jones PJH (2011) High-oleic rapeseed (canola) and flaxseed oils modulate serum lipids and inflammatory biomarkers in hypercholesterolaemic subjects. *Br J Nutr* 105:417–427
- Giroux HJ, Houde J, Britten M (2010) Use of heated milk protein-sugar blends as antioxidants in dairy beverages enriched with linseed oil. *LWT Food Sci Technol* 43:1373–1376
- Global Industry Analysts (2010) <http://www.prweb.com/pdfdownload/4688424.pdf> Last accessed 25/05/2012
- Gogus U, Smith C (2010) n-3 Omega fatty acids: a review of current knowledge. *Int J Food Sci Technol* 45:417–436
- Goh KKT, Pinder DN, Hall CE, Hemar Y (2006) Rheological and light scattering properties of flaxseed polysaccharide aqueous solutions. *Biomacromolecules* 7:3098–3103
- Gokmen V, Magol BA, Lumaga RB, Fogliano-Vincezo F, Kaplun Z (2011) Development of functional bread containing nanoencapsulated omega-3 fatty acids. *J Food Eng* 105:585–591
- Gopalan C, Ramasastri BV, Subramanian SC (2007) Nutritive value of Indian foods. National Institute of Nutrition, Hyderabad
- Gopinath B, Harris DC, Flood VM, Burlutsky G, Mitchell P (2011) Consumption of long-chain n-3 PUFA, α -linolenic acid and fish is associated with the prevalence of chronic kidney disease. *Br J Nutr* 105:1361–1368
- Gornik HL, Creager MA (2004) Arginine and endothelial and vascular health. *J Nutr* 134(10):2880S–2887S
- Green BE, Martens R, Tergesen J, Milanova R (2005) Flax protein isolates and production. US patent 2005/0107593 A1
- Greenwald P, Clifford CK, Milner JA (2001) Diet and cancer prevention. *Eur J Cancer* 37:948–965
- Guimaraes RDCA, Macedo MLR, Munhoz CL, Filiu W, Viana LH, Nozaki VT, Hiane PA (2013) Sesame and flaxseed oil: nutritional quality and effects on serum lipids and glucose in rats. *Food Sci Technol (Campinas)* 33(1):209–217
- Hall AA, Manthey FA, Lee RE, Niehaus M (2005) Stability of α -linolenic acid and secoisolaricresinol diglucoside in flaxseed fortified macaroni. *J Food Sci* 70:C483–C489
- Hall C, Tulbek MC, Xu Y (2006) Flaxseed. *Adv Food Nutr Res* 51:1–97
- Hallund J, Tetens I, Bugel S, Tholstrup T, Bruun JM (2008) The effect of a lignan complex isolated from flaxseed on inflammation markers in healthy postmenopausal women. *Nutr Metab Cardiovasc* 18:497–502

- Hao M, Beta T (2012) Development of Chinese steamed bread enriched in bioactive compounds from barley hull and flaxseed hull extracts. *Food Chem* 133:1320–1325
- Haque RM, Bradbury HJ (2002) Total cyanide determination of plants and foods using the picrate and acid hydrolysis methods. *Food Chem* 77:107–114
- Hasler CM, Kundrat S, Wool D (2000) Functional foods and cardiovascular disease. *Curr Atheroscler Rep* 2(6):467–475
- Hassan AA, Rasmay NM, Foda MI, Bahgaat WK (2012) Production of functional biscuits for lowering blood lipids. *World J Dairy Food Sci* 7(1):01–20
- Health Canada (1998) Final policy paper on nutraceuticals/functional foods and health claims on foods. http://www.hc-sc.gc.ca/fn-an/label-etiquet/claims-reclam/nutra-funct_foods-nutra-fonct_aliment-eng.php Last accessed 30/12/12
- Health Canada (2009) Do Canadian adults meet their nutrient requirements through food intake alone? http://www.hc-sc.gc.ca/fn-an/alt_formats/pdf/surveill/nutrition/commun/art-nutr-adult-eng.pdf Last accessed 26/05/2012
- Holstun J, Zetocha D (1994) An analysis of flaxseed utilization in the health food industry. Institute for Business and Industry Development, North Dakota State University, Fargo
- Hongzhi Y, Zhihuai, Hequn T (2004) Determination and removal methods of cyanogenic glucoside in flaxseed ASAE/CSAE meeting presentation: 04066
- Hussain S, Anjum FM, Butt MS, Khan MI, Asghar A (2006) Physical and sensoric attributes of flaxseed flour supplemented cookies. *Turk J Biol* 30:87–92
- Hussain S, Anjum FM, Butt MS, Sheikh MA (2008) Chemical composition and functional properties of flaxseed (*Linum usitatissimum*) flour. *Sarhad J Agric* 24(4):649–653
- Hussain S, Anjum FM, Butt MS, Alamri MS, Khan MR (2012) Biochemical and nutritional evaluation of unleavened flat breads fortified with healthy flaxseed. *Int J Agric Biol* 14:190–196
- Ibrugger S, Kristensen M, Mikkelsen MS, Astrup A (2012) Flaxseed dietary fiber supplements for suppression of appetite and food intake. *Appetite* 58:490–495
- Ivanova S, Rashevskaya T, Makhonina M (2011) Flaxseed additive application in dairy products production. *Procedia Food Sci* 1: 275–280
- Jennifer LA, Susan JW, Bernhard HJ, Lilian UT, Jane A (2010) Health effects with consumption of the flax lignan secoisolariciresinol diglucoside. *Br J Nutr* 103(7):929–939
- Jheimbach LLC, Port Royal VA (2009) Determination of the GRAS status of the addition of whole and milled flaxseed to conventional foods and meat and poultry products http://www.accessdata.fda.gov/scripts/fcn/gras_notices/grn000280.pdf Last accessed 26/05/2012
- Johnsson P, Kamal-Eldin A, Lundgren LN, Aaman P (2000) HPLC method for analysis of secoisolariciresinol diglucoside in flaxseeds. *J Agric Food Chem* 48(11):5216–5219
- Kadam SU, Prabhasankar P (2010) Marine foods as functional ingredients in bakery and pasta products. *Food Res Int* 43:1975–1980
- Kapoor S, Sachdeva R, Kochhar A (2011) Efficacy of flaxseed supplementation on nutrient intake and other lifestyle pattern in menopausal diabetic females. *Ethnomedicine* 5(3):153–160
- Karaca AC, Low N, Nickerson M (2011) Emulsifying properties of canola and flaxseed protein isolates produced by isoelectric precipitation and salt extraction. *Food Res Int* 44(9):2991–2998
- Kelley DS, Vemuri M, Adkins Y, Gill SHS, Fedor D, Mackey BE (2009) Flaxseed oil prevents trans-10, cis-12-conjugated linoleic acid-induced insulin resistance in mice. *Br J Nutr* 101:701–708
- Khalesi S, Jamaluddina R, Ismailab A (2011) Effect of raw and heated flaxseed (*Linum usitatissimum* L.) on blood lipid profiles in rats. *Int J Appl Sci Technol* 1(4):84–89
- Khatab RY, Zeitoun MA (2013) Quality evaluation of flaxseed oil obtained by different extraction techniques. *LWT-Food Sci Technol* 53(1):338–345
- Khouryieh H, Aramouni F (2012) Physical and sensory characteristics of cookies prepared with flaxseed flour. *J Sci Food Agric* 92(11):2366–2372
- King H, Aubert RE, Herman WH (1998) Global burden of diabetes, 1995e2025: prevalence, numerical estimates, and projections. *Diabetes Care* 21(9):1414–1431
- Kozłowska J, Munoz GA, Kolodziejczyk PP (2008) Food and feed applications for flaxseed components. In: International conference on flax and other bast plants. Saskatoon, Canada, pp. 299–307
- Kristensen M, Savorani F, Christensena S, Engelsen SB, Bugelb S, Toubroc S, Tetens I, Astrupa A (2011) Flaxseed dietary fibers suppress postprandial lipemia and appetite sensation in young men. *Nutr Metab Cardiovasc In press*. doi:10.1016/j.numecd.2011.03.004
- Kristensen M, Jensen MG, Aarestrup J, Petersen KEN, Sondergaard L, Mikkelsen MS, Astrup A (2012) Flaxseed dietary fibers lower cholesterol and increase fecal fat excretion, but magnitude of effect depend on food type. *Nutr Metabol* 9:1–8
- Lakka HM, Laaksonen DE, Lakka TA, Niskanen LK, Kumpusalo E, Tuomilehto J, Salonen JT (2002) The metabolic syndrome and total and cardiovascular disease mortality in middle-aged men. *J Am Med Assoc* 288:2709–2716
- Lauretani F, Maggio M, Pizzarelli F, Michelassi S, Ruggiero C, Ceda GP, Bandinelli S, Ferrucci L (2009) Omega-3 and renal function in older adults. *Curr Pharm Des* 15(36):4149–4156
- Laux M (2011) http://www.agmrc.org/commodities_products/grains_oilseeds/flax_profile.cfm Last accessed 13–03–2012
- Lay CL, Dybing DD (1989) Linseed. In: Robbelen G, Downey RK, Ashri A (eds) Oil crops of the world. McGraw Hill, New York, pp 416–430
- Leatherhead Food Research (2011) Future directions for the global functional foods market: market report. www.leatherheadfood.com/market Last accessed 22/05/2012
- Lee RE, Manthey FA, Hall CA (2004) Content and stability of hexane extractable lipid at various steps of producing macaroni containing ground flaxseed. *J Food Process Preserv* 28:133–144
- Leeson S, Caston L, MacLaurin T (1998) Organoleptic evaluation of eggs produced by laying hens fed diets containing graded levels of flaxseed and vitamin E. *Poult Sci* 77:1436–1440
- Lemay A, Dodin S, Kadri N, Jacques H, Forest JC (2002) Flaxseed dietary supplement versus hormone replacement therapy in hypercholesterolemic menopausal women. *Obstet Gynaecol* 100(3):495–504
- Leyva DR, Zahradkab P, Ramjiawanc B, Guzmanc R, Alianid M, Piercea GN (2011) The effect of dietary flaxseed on improving symptoms of cardiovascular disease in patients with peripheral artery disease: rationale and design of the FLAX-PAD randomized controlled trial. *Contemp Clin Trials* 32(5):724–730
- Lipilina E, Ganji V (2009) Incorporation of ground flaxseed into bakery products and its effect on sensory and nutritional characteristics—a pilot study. *J Foodservice* 20(1):52–59
- Long JJ, Fu YJ, Zu YG, Li J, Wang W, Gu CB, Luo M (2011) Ultrasound-assisted extraction of flaxseed oil using immobilized enzymes. *Bioresour Technol* 102(21):9991–9996
- Mani UV, Mani I, Biswas M, Kumar SN (2011) An open-label study on the effect of flax seed powder (*Linum usitatissimum*) supplementation in the management of diabetes mellitus. *J Diet Suppl* 8(3):257–265
- Marambe PWMLHK, Shand PJ, Wanasundara JPD (2008) An in vitro investigation of selected biological activities of hydrolyzed flaxseed (*Linum usitatissimum* L.) proteins. *J Am Oil Chem Soc* 85:1155–1164
- Marconi E, Carcea M (2001) Pasta from non-traditional raw materials. *Cereal Foods World* 46:522–530

- Matumoto- Pintroa PT, Petita HV, Giroux HJ, Cortes C, Agnona NG, Britten M (2011) Effect of flaxseed lignans added to milk or fed to cows on oxidative degradation of dairy beverages enriched with polyunsaturated fatty acids. *J Dairy Res* 78(1):111–117
- Mazur W, Fotsis T, Wahala K, Ojala S, Salakka A, Adlercreutz H (1996) Isotope dilution gas chromatographic-mass spectrometric method for the determination of isoflavonoids, coumestrol, and lignans in food samples. *Anal Biochem* 233:169–180
- Mazza G (2008) Production, processing and uses of Canadian flax. First CGNA International Workshop, Temuco, Chile, August 3–6
- Mazza G, Biliaderis CG (1989) Functional properties of flax seed mucilage. *J Food Sci* 54(5):1302–1305
- Mazza G, Oomah BD (1995) Flaxseed: dietary fiber and cyanogens. In: Cunnane SC, Thompson LU (eds) *Flaxseed in human nutrition*. AOCS Press, Champaign, pp 56–81
- McCann SE, Wactawski-Wende J, Kufel K, Olson J, Ovando B, Kadlubar SN, Davis W, Carter L, Muti P, Shields PG, Freudenheim JL (2007) Changes in 2-hydroxysterone and alpha-hydroxysterone metabolism with flaxseed consumption, modification by COMT and CYP1B1 genotype. *Cancer Epidemiol Biomarkers Prev* 16(2):256–262
- McCullough RS, Edel AL, Bassett CMC, LaVallee RK, Dibrov E, Blackwood DP, Ander BP, Pierce GN (2011) The alpha linolenic acid content of flaxseed is associated with an induction of adipose leptin expression. *Lipids* 46:1043–1052
- Mentes O, Bakkalbassi E, Ercan R (2008) Effect of the use of ground flaxseed on quality and chemical composition of bread. *Food Sci Technol Int* 14(4):299–306
- Milder IE, Arts IC, Van de Putte B, Venema DP, Hollman PC (2005) Lignan contents of Dutch plant foods: a database including lariciresinol, pinoresinol, secoisolariciresinol and matairesinol. *Br J Nutr* 93(3):393–402
- Minker E, Bogdanova SV, Penovak I (1973) Linseed mucilage as a water-in-oil type emulsifier. *Farmatsiya (Sofya)* 23:13
- Misra B (1963) “Tailavarga” in Bhavaprakashanighantu. Part I. In: Misra B, Vaisya R (eds) *The Kashi Sanskrit series*. Chaukhumba Bharati Academy, Varanasi, p 779
- Moghaddasi MS (2011) Linseed and usages in Humanlife. *Adv Environ Biol* 5(6):1380–1392
- Mohamed DA, Al-Okbi SY, El-Hariri DM, Mousa II (2012) Potential health benefits of bread supplemented with defatted flaxseeds under dietary regimen in normal and type 2 diabetic subjects. *Pol J Food Nutr Sci* 62(2):103–108
- Morisset AS, Lemieux S, Veilleux A, Bergeron J, Weisnagel SJ, Tchermof A (2009) Impact of a lignan-rich diet on adiposity and insulin sensitivity in post-menopausal women. *Br J Nutr* 102:195–200
- Morris DH (2003) *Flax—a health and nutrition primer* Flax Council of Canada Winnipeg, MB
- Morris DH (2008) Linseed in the ruminant diet— adding linseed to feed enhances the fat profile of milk Winnipeg, MB, Flax Council of Canada. http://www.flaxcouncil.ca/files/web/Beef_R3_final.pdf Last accessed 25/05/2012
- Mueller K, Eisner P, Kirchhoff E (2010a) Simplified fractionation process for linseed meal by alkaline extraction- functional properties of protein and fiber fractions. *J Food Eng* 99:49–54
- Mueller K, Eisner P, Yoshie-Stark Y, Nakada R, Kirchhoff E (2010b) Functional properties and chemical composition of fractionated brown and yellow linseed meal (*Linum usitatissimum* L.). *J Food Eng* 98:453–460
- Naqshbandi A, Khan W, Rizwan S, Khan F (2012) Studies on the protective effect of flaxseed oil on cisplatin-induced hepatotoxicity. *Hum Exp Toxicol*. doi:10.1177/0960327111432502
- Nazni P, Amrithaveni M, Poongodi VT (2006) Impact of flaxseed based therapeutic food on selected type II diabetic patients. *Indian J Nutr Diet* 43:141–145
- Ogborn MR, Nitschmann E, Bankovic-Calic N, Weiler HA, Aukema H (2002) Dietary flax oil reduces renal injury, oxidized LDL content, and tissue n-6/n-3 FA ratio in experimental polycystic kidney disease. *Lipids* 37(11):1059–1065
- Ogunronbi O, Jooste PJ, Abu JO, Vander-Merwe B (2011) Chemical composition, storage stability and effect of cold-pressed flaxseed oil cake inclusion on Bread quality. *J Food Process Preserv* 35:64–79
- Oikarinen SI, Pajari AM, Salminen I, Heinonen SM, Adlercreutz H, Mutanen M (2005) Effects of a flaxseed mixture and plant oils rich in a-linolenic acid on the adenoma formation in multiple intestinal neoplasia (Min) mice. *Br J Nutr* 94:510–518
- Omoni AO, Aluko RE (2006) Effect of cationic flaxseed protein hydrolysate fractions on the in vitro structure and activity of calmodulin-dependent endothelial nitric oxide synthase. *Mol Nutr Food Res* 50:958–966
- Oomah BD (2001) Flaxseed as a functional food source. *J Sci Food Agric* 81(9):889–894
- Oomah BD, Mazza G (1993) Flaxseed proteins—a review. *Food Chem* 48:109–114
- Oomah BD, Mazza G (1998) Flaxseed products for disease prevention. In: Mazza G (ed) *Functional foods, biochemical and processing aspects*. Technomic Publishing Co, Inc, Lancaster, pp 91–138
- Oomah BD, Mazza G (2000) Bioactive components of flaxseed: occurrence and health benefits. In: Shahidi F, Ho CT (eds) *Phytochemicals and phytopharmaceuticals*. AOCS Press, Champaign, pp 105–120
- Park JB, Velasquez MT (2012) Potential effects of lignan-enriched flaxseed powder on bodyweight, visceral fat, lipid profile, and blood pressure in rats. *Fitoterapia*. doi:10.1016/j.fitote.2012.04.010
- Park ER, Hong JH, Lee DH, Han SB, Lee KB, Park JS, Chung HW, Hong KH, Kim MC (2005) Analysis and decrease of cyanogenic glucosides in flaxseed. *J Korean Soc Food Sci Nutr* 34:875–879
- Patade A, Devareddy L, Lucas EA, Korlagunta, Daggy BP, Arjmandi BH (2008) Flaxseed reduces total and LDL cholesterol concentrations in Native American postmenopausal women. *J Womens Health (Larchmt)* 17:355–366
- Patwardhan B, Vaidya ADB, Chorghade M (2004) Ayurveda and natural products drug discovery. *Curr Sci* 86(6):789–799
- Patwardhan B, Warude D, Pushpangadan P, Bhatt N (2005) Ayurveda and traditional Chinese medicine: a comparative overview. *J Evid Based Complement Altern Med* 2(4):465–473
- Payne TJ (2000) Promoting better health with flaxseed in bread. *Cereal Foods World* 45(3):102–104
- Pellizzon MA, Billheimer JT, Bloedon LT, Szapary PO, Rader DJ (2007) Flaxseed reduces plasma cholesterol levels in Hypercholesterolemic mouse models. *J Am Coll Nutr* 26(1):66–75
- Penttinen P, Jaehrling J, Damdimopoulos AE, Inzunza J, Lemmen JG, Van-der Saag P, Pettersson K, Gauglitz G, Makela S, Pongratz I (2007) Dirt derived polyphenol metabolite enterolactone is a tissue-specific estrogen receptor activator. *Endocrinol* 148(10):4875–4886
- Peters U, Sinha R, Chatterjee N, Subar AF, Ziegler RG, Kullendorff M, Bresalier R, Weissfeld JL, Flood A, Schatzkin A, Hayes RB (2003) Dietary fibre and colorectal adenoma in a colorectal cancer early detection programme. *Lancet* 361:1491–1495
- Pisani P (2008) Hyper-insulinaemia and cancer: meta-analyses of epidemiological studies. *Arch Physiol Biochem* 114:63–70
- Pohjanheimo TA, Hakala MA, Tahvonen RL, Salminen SJ, Kallio HP (2006) Flaxseed in bread making, effects on sensory quality, aging, and composition of bakery products. *J Food Sci* 71:5343–5348
- Pradhan RC, Meda V, Rout PK, Naik S, Dalai AK (2010) Supercritical CO₂ extraction of fatty oil from flaxseed and comparison with screw press expression and solvent extraction processes. *J Food Eng* 98(4):393–397
- Prasad K (2001) Secoisolariciresinol diglucoside from flaxseed delays the development of type 2 diabetes in Zucker rat. *J Lab Clin Med* 138:32–39

- Prasad K (2002) Suppression of phosphoenolpyruvate carboxykinase gene expression by secoisolariciresinol diglucoside (SDG), a new antidiabetic agent. *Int J Angiol* 11:107–109
- Prasad K, Mantha SV, Muir AD, Westcott ND (2000) Protective effect of secoisolariciresinol diglucoside against streptozotocin-induced diabetes and its mechanism. *Mol Cell Biochem* 206:141–149
- Prim CR, Baroncini LA, Precoma LB, Caron PH, Winter G, Poletti MO, Precoma DB (2012) Effects of linseed consumption for a short period of time on lipid profile and atherosclerotic lesions in rabbits fed a hypercholesterolaemic diet. *Br J Nutr* 107(5):660–664
- Pu J, Bechtel PJ, Sathivel S (2010) Extraction of shrimp astaxanthin with flaxseed oil: effects on lipid oxidation and astaxanthin degradation rates. *Biosyst Eng* 107(4):364–371
- Rabetafika HN, Remoortel VV, Danthine S, Paquot M, Blecker C (2011) Flaxseed proteins: food uses and health benefits. *Int J Food Sci Technol* 46:221–228
- Ramcharitar N, Badrie M, Mattfeldt-Beman M, Matsuo H, Ridley C (2005) Consumer acceptability of muffins with flaxseed (*Linum usitatissimum*). *J Food Sci* 70(7):504–507
- Ratnayake WMN, Behrens WA, Fischer PWF, Labbe MR, Mongeau R, Beare-Rogers JL (1992) Flaxseed, Chemical stability and nutritional properties. *Proc Flax Inst US* 54:37
- Saggar JK, Chen J, Corey P, Thompson LU (2010a) Dietary flaxseed lignan or oil combined with tamoxifen treatment affects MCF-7 tumor growth through estrogen receptor- and growth factor-signaling pathways. *Mol Nutr Food Res* 54:415–425
- Saggar JK, Chen J, Corey P, Thompson LU (2010b) The effect of secoisolariciresinol diglucoside and flaxseed oil, alone and in combination, on MCF-7 tumor growth, cell proliferation, apoptosis and estrogen receptor and growth factor signaling. *Nutr Cancer* 62:533–542
- Santos AP, Rogero MM, Bastos DH (2010) Edible plants, their secondary metabolites and antiobesogenic potential. *Recent Pat Food Nutr Agric* 2:195–212
- Simmons RK, Alberti KG, Gale EA, Colagiuri S, Tuomilehto J, Qiao Q, Ramachandran A, Tajima N, Brajkovich Mirchov I, Ben-Nakhi A, Reaven G, Hama Sambo B, Mendis S, Roglic G (2010) The metabolic syndrome: useful concept or clinical tool? Report of a WHO expert consultation. *Diabetologia* 53(4):600–605
- Simmons CA, Turk P, Beamer S, Jaczynski J, Semmens K, Matak KE (2011) The effect of a flaxseed oil-enhanced diet on the product quality of farmed brook trout (*Salvelinus fontinalis*) filets. *J Food Sci* 76(3):S192–S197
- Simopoulos AP (2000) Human requirement for omega-3 polyunsaturated fatty acids. *Poul Sci* 79:961–970
- Singh KK, Mridula D, Rehal J, Barnwal P (2011) Flaxseed- a potential source of food, feed and fiber. *Crit Rev Food Sci Nutr* 51:210–222
- Sinha S, Manthey FA (2008) Semolina and hydration level during extrusion affect quality of fresh pasta containing flaxseed flour. *J Food Process Preserv* 32:546–559
- Smithers GW (2008) Whey and whey proteins—from ‘gutter-to-gold’. *Dairy J* 18:695–704
- Strandas C, Kamal-Eldin A, Andersson R, Aman P (2008) Phenolic glucosides in bread containing flaxseed. *Food Chem* 110:997–999
- Sturgeon SR, Volpe SL, Puleo E, Bertone-Johnson ER, Heersink J, Sabelawski S, Wahala K, Bigelow C, Kurzer MS (2011) Dietary intervention of flaxseed: effect on serum levels of IGF-1, IGF-BP3, and C-peptide. *Nutr Cancer* 63(3):376–380
- Tarpila A, Wennberg T, Tarpila S (2005) Flaxseed as a functional food. *Curr Top Nutraceuticals Res* 3(3):167–188
- Thakur G, Mitra A, Pal K, Rousseau D (2009) Effect of flaxseed gum on reduction of blood glucose and cholesterol in type 2 diabetic patients. *Int J Food Sci Nutr* 60:126–136
- Tham DM, Gardner CD, Haskell WL (1998) Potential health benefits of dietary phytoestrogens, a review of the clinical, epidemiological, and mechanistic evidence. *J Clin Endocrinol Metab* 83(7):2223–2235
- Tolkachev ON, Zhuchenko AA (2000) Biologically active substances of flax: medicinal and nutritional properties (a review). *Pharm Chem J* 34(7):360–367
- Tonon RV, Grosso CRF, Hubinger MD (2011) Influence of emulsion composition and inlet air temperature on the microencapsulation of flaxseed oil by spray drying. *Food Res Int* 44:282–289
- Tourel A, Xueming X (2010) Flaxseed lignans: source, biosynthesis, metabolism, antioxidant activity, bio-active components, and health benefits. *Comp Rev Food Sci Food Saf* 9:261–269
- Trevisan AJB, Areas JAG (2012) Development of corn and flaxseed snacks with high-fibre content using response surface methodology (RSM). *Int J Food Sci Nutr* 63(3):362–367
- Truan JS, Chen JM, Thompson LU (2010) Flaxseed oil reduces the growth of human breast tumors (MCF-7) at high levels of circulating estrogen. *Mol Nutr Food Res* 54(10):1414–1421
- Truan JS, Chen JM, Thompson LU (2012) Comparative effects of sesame seed lignan and flaxseed lignan in reducing the growth of human breast tumors (mcf-7) at high levels of circulating estrogen in athymic mice. *Nutr Cancer* 64(1):65–71
- U. S. Department of Agriculture, Agricultural Research Service, Nutrient Data Laboratory (2010) USDA national nutrient database for standard reference, release 23 Available from: <http://www.nal.usda.gov/fnic/foodcomp/search/> Last accessed 25/05/2012
- Udenigwe CC, Aluko RE (2010) Antioxidant and angiotensin converting enzyme-inhibitory properties of a flaxseed protein-derived high Fischer ratio peptide mixture. *J Agric Food Chem* 58(8):4762–4768
- Udenigwe CC, Lub YL, Hanb CH, Houc WC, Aluko RE (2009) Flaxseed protein-derived peptide fractions: antioxidant properties and inhibition of lipopolysaccharide-induced nitric oxide production in murine macrophages. *Food Chem* 116(1):277–284
- USDA (2010) Dietary guidelines for Americans. U.S. Department of Agriculture. U.S. Dept. of Health and Human Services <http://www.cnpp.usda.gov/Publications/DietaryGuidelines/2010/PolicyDoc/PolicyDoc.pdf> Last accessed 26/05/2012
- Vaisey-Genser M, Morris DH (2003) Introduction, history of the cultivation and uses of flaxseed. In: Muir AD, Westcott ND (eds) *Flax, the Genus Linum*. Taylor and Francis, London, pp 1–21
- Valiathan MS (2003) *The legacy of caraka*. Orient Longman, Chennai
- Vedtofte MS, Jakobsen MU, Lauritzen L, Heitmann BL (2011) Dietary α -linolenic acid, linoleic acid, and n-3 long-chain PUFA and risk of ischemic heart disease. *Am J Clin Nutr* 94(4):1097–1103
- Wanders AJ, Van-den Borne JJ, De GC, Hulshof T, Jonathan MC, Kristensen M, Mars M, Schols HA, Feskens EJ (2011) Effects of dietary fibre on subjective appetite, energy intake and body weight: a systematic review of randomized controlled trials. *Obes Rev* 12(9):724–739
- Wang L, Chen JM, Thompson LU (2005) The inhibitory effect of flaxseed on the growth and metastasis of estrogen receptor negative human breast cancer xenografts is attributed to both its lignan and oil components. *Int J Cancer* 116:793–798
- Wang C, Harris WS, Chung M, Lichtenstein AH, Balk EM, Kupelnick B, Jordan HS, Lau J (2006) n-3 fatty acids from fish or fish-oil supplements, but not α -linolenic acid, benefit cardiovascular disease outcomes in primary-and secondary-prevention studies: a systematic review. *Am J Clin Nutr* 84:5–17
- Wang B, Li D, Wang LJ, Huang ZG, Zhang L, Chen XD, Mao ZH (2007) Effect of moisture content on the physical properties of fibered flaxseed. *Int J Food Eng* 3:1–11
- Wang B, Wang LJ, Li D, Bhandari B, Wu WF, Shi J, Chen XD, Mao ZH (2009) Effects of potato starch addition and cooling rate on rheological characteristics of flaxseed protein concentrate. *J Food Eng* 3:392–401

- Wang B, Dong L, Wang LJ, Ozkan N (2010a) Effect of concentrated flaxseed protein on the solubility and rheological properties of soybean oil-in-water emulsions. *J Food Eng* 96:555–561
- Wang B, Li D, Wang LJ, Ozkan N (2010b) Effect of concentrated flaxseed protein on the stability and rheological properties of soybean oil-in-water emulsions. *J Food Eng* 96:555–561
- Wang B, Li D, Wang LJ, Adhikari B, Shi J (2010c) Ability of flaxseed and soybean protein concentrates to stabilize oil-in-water emulsions. *J Food Eng* 100:417–426
- Wang Y, Li D, Wang LJ, Adhikari B (2011) The effect of addition of flaxseed gum on the emulsion properties of soybean protein isolate (SPI). *J Food Eng* 104:56–62
- Watkins BA, Devitt AA, Feng S (2001) Designed eggs containing conjugated linoleic acids and omega-3 polyunsaturated fatty acids. *World Rev Nutr Diet* 90:162–182
- Health and Welfare Canada (1990) Nutrition recommendations the report of the scientific review committee. Department of Supply and Services. Cat.No.H49–42/1990E. Ottawa, Ontario
- Westcott ND, Muir AD (1996) Variation in the concentration of the flax seed lignan concentration with variety, location and year. In: Proceedings of the 56th Flax Institute of the United States Conference, Flax Institute of the United States, Fargo, ND, pp. 77–80
- WHO (2009) Diabetes. Fact sheet no. 312. World Health Organization, Geneva
- WHO (2010) Global status report on noncommunicable diseases. World Health Organization, Geneva
- WHO (2011) Noncommunicable diseases country profiles 2011. World Health Organization, Geneva
- WHO (2012) The world health statistics 2012 report. World Health, Geneva
- Wilkes AP (2007) Flax heart health. Prepared foods- development trends & technologies for formulators & marketers. Flax council of Canada. www.PreparedFoods.com
- Woodside JV, Campbell MJ, Denholm EE, Newton L, Honour JW, Morton MS, Young IS, Leatham AJ (2006) Short-term phytoestrogen supplementation alters insulin-like growth factor profile but not lipid or antioxidant status. *J Nutr Biochem* 17(3):211–215
- Wu H, Pan A, Yu Z, Qi Q, Lu L, Zhang G, Yu D, Zong G, Zhou Y, Chen X, Tang L, Feng Y, Zhou H, Chen X, Li H, Demark-Wahnefried W, Hu FB, Lin X (2010) Lifestyle counseling and supplementation with flaxseed or walnuts influence the management of metabolic syndrome. *J Nutr* 140(11):1937–1942
- Xu Y, Hall C, Wolf-Hall C, Manthey F (2006) Antifungal activity of flaxseed flours. In: Carter JF (ed) Proceedings of the 61st Flax Institute of the U.S. North Dakota State University, Fargo, pp 177–185
- Xu Y, Hall IIC, Wolf-Hall C (2008) Antifungal activity stability of flaxseed protein extracts using response surface methodology. *J Food Sci* 73:M9–M14
- Zhang ZS, Wang LJ, Li D, Li SJ, Ozkan N (2011) Characteristics of flaxseed oil from two different flax plants. *Int J Food Prop* 14(6): 1286–1296
- Zimmerman DC (1988) Flax, linseed oil, and human nutrition. *Proc Flax Inst US* 52:30