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REVIEW

Flaxseed—a potential functional food source

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Abstract There is currently much interest in phytochemicals as bioactive molecules of food. Functional foods are an emerging field in food science due to their increasing popularity among health conscious consumers. Flaxseed is cultivated in many parts of world for fiber, oil as well as for medicinal purposes and also as nutritional product. In this review, nutrients, anti-nutrients, functional properties, processing, metabolism and health benefits of bioactive molecules viz., essential fatty acids, lignans and dietary fiber of flaxseed are discussed.

Keywords Flaxseed · Functional properties · Nutritional quality · Processing · Alpha-linolenic acid · Dietary fiber · Lignans · Health benefits

Introduction

Flax (*Linum usitassimum*) belonging to family Lineaceae, is a blue flowering annual herb that produces small flat seeds varying from golden yellow to reddish brown color. Flaxseed possesses crispy texture and nutty taste (Morris 2007; Rubilar et al. 2010). Flaxseed is also known as linseed and these terms are used interchangeably. Flaxseed is often used to describe flax when consumed by humans while linseed denotes when it is used specifically for industrial applications (Morris 2007). Almost all parts of linseed plant are utilized for various purposes. Seed contains oil which after refining is used for edible purpose (Singh et al. 2011a, b). The stem yields fiber of good quality possessing high strength and durability. Humans have been consuming flaxseed since ancient times. It has been cultivated for fiber as well as for medicinal purposes and as nutritional product (Tolkachev and Zhuchenko 2000). Currently, it is cultivated in more than 50 countries, predominantly in the Northern hemisphere. Canada is the world's largest producer and exporter of flaxseeds (Oomah 2001). The important flaxseed growing countries include India, China, United States, and Ethiopia (Oomah and Mazza 1998; Singh et al. 2011a, b). India ranks first among the leading flaxseed producing countries in terms of acreage accounting 23.8 % of the total and third in production contributing to 10.2 % of the world's production (Singh et al. 2011a, b). In India flaxseed is mainly cultivated in Madhya Pradesh, Maharashtra, Chattisgarh and Bihar. It is interesting to know that flaxseed was native of India and was a staple food crop. In India, flaxseed is still being consumed as food and as well as for medicinal purposes (Shakir and Madhusudan 2007). It enjoys a good status among oilseeds because of its versatile uses. It has emerged as an attractive nutritional food because of its exceptionally high content of alpha-linolenic acid (ALA), dietary fiber, high quality protein and phytoestrogens. Flaxseeds contain about 55 % ALA, 28–30 % protein and 35 % fiber (Carter 1993; Rubilar et al. 2010; Rabetafika et al. 2011). Flaxseed has been the focus of growing interest for the nutritionists and medical researchers due to its potential health benefits associated with its biologically active components—ALA, lignan-Secoisolariciresinol diglycoside (SDG) and dietary fiber (Toure and Xueming 2010).

Flaxseed is establishing importance in the world's food chain as a functional food. Functional food can be defined as the food or food ingredients that may provide physiological benefits and helps in preventing and/or curing of diseases (Al-Okbi 2005). Presently, flaxseed has new prospects as functional food because of consumer's growing interest for food with superb health benefits. Owing to its excellent nutritional profile and potential health benefits, it has become an

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attractive ingredient in the diets specially designed for specific health benefits (Oomah 2001). ALA is one of the essential polyunsaturated fatty acid and reported to exhibit anti-inflammatory, anti-thrombotic and anti-arrhythmic properties (Simopoulos 1999). Nutritionists all over the world suggest incorporation of omega 3 fatty acid sources in the diet. Flaxseed serves as the best omega 3 fatty acid source to the non-fish eaters. Edible flaxseed products include the whole flaxseed, ground meal and extracted oil or mucilage. These products have been proposed as nutritional additives in the preparation of a number of dietary items such as baked cereal products, ready to eat cereals, fiber bars, salad toppings, meat extenders, bread, muffins and spaghetti (Singh et al. 2011a, b). Inspite of the multiple clinical evidences of flaxseeds, people are still unaware about its nutritional as well as therapeutic benefits.

Nutritional composition

Among the functional foods, flaxseed has emerged as a potential functional food being good source of alpha-linolenic acid, lignans, high quality protein, soluble fiber and phenolic compounds (Oomah 2001). The composition of flaxseed is presented in Table 1 (Morris 2007; Gopalan et al. 2004; Payne 2000). Chemical composition of flaxseed depends upon growing environment, genetics and processing conditions (Morris 2007). The lipid content of flaxseed varies from 37 to 45 g/100 g of the seed as reported by various scientists (Carter 1993; Payne 2000; Morris 2007). Cotyledons are the major oil storage tissues, containing 75 % of the seed oil (Rubilar et al. 2010; Singh et al. 2011a, b). Flaxseed oil constitutes 98 % triacylglycerol, phospholipids and 0.1 % free fatty acids (Mueller et al. 2010). On an average it contains 21 % protein. Majority of the protein is concentrated in the cotyledons (Rabetafika et al. 2011). Major protein fractions are globulin (26–58 %) and albumin (20–42 %). Nutritional value and amino acid profile of flaxseeds are comparable to that of soya proteins (Madhusudan and Singh 1985; Oomah and Mazza 1993). Flaxseed protein is rich in arginine, aspartic acid and glutamic acid, while lysine is limiting (Singh et al. 2011a, b; Chung et al. 2005). High cysteine and methionine contents improve the antioxidant levels, thus helps in reducing risk of cancer (Oomah 2001). The processing conditions, dehusking and defatting affect the protein content. The defatted and dehusked meals have high protein content (Oomah and Mazza 1997, 1998) Flaxseed proteins exhibit antifungal properties against *Alternaria solani, Candida albicans and Aspergillus flavus* (Xu et al. 2008a, b).

Table 1 Nutritional composition of flaxseed

Nutrients	Amount per 100 g of edible flaxseed
Moisture (g)	6.5
Protein (*N*×6.25) (g)	20.3
Fat (g)	37.1
Minerals (g)	2.4
Crude fiber (g)	4.8
Total dietary fiber (g)	24.5
Carbohydrates (g)	28.9
Energy (kcal)	530.0
Potassium	750.0
Calcium (mg)	170.0
Phosphorous (mg)	370.0
Iron (mg)	2.7
Vitamin A (μg)	30.0
Vitamin E (mg)	0.6
Thiamine (B1) (mg)	0.23
Riboflavin (B2) (mg)	0.07
Niacin (mg)	1.0
Pyridoxine (mg)	0.61
Pantothenic acid	0.57
Biotin (μg)	0.6
Folic acid (μg)	112

Morris 2007; Gopalan et al. 2004; Payne 2000

Flaxseed is the richest source of phytoestrogens (lignans). The amount of secoisolariciresinol diglycoside (SDG) varies from 77 to 209 mg SDG/tbsp. of whole flaxseed (Morris 2007; Toure and Xueming 2010). Flaxseed contains very low level of carbohydrates (1 g/100 g) and thus contributing very little to total carbohydrates intake (Morris 2007).

Flaxseeds contain a good amount of phenolic compounds. These phenolic compounds are well known for anticancer and anti-oxidative properties. Basically, flaxseeds have three different types of phenolic compounds–phenolic acids, flavonoids and lignans. Major phenolic acids present in defatted flaxseed are ferulic acid (10.9 mg/g), chlorogenic acid (7.5 mg/g), gallic acid (2.8 mg/g). Other phenolic acids include p-coumaric acid glucosides, hydroxycinnamic acid glucosides and 4-hydroxybenzoic acid that are present in low quantities (Beejmohun et al. 2007; Mazza 2008). Flavone C- and Flavone O-glycosides are the major flavonoids found in flaxseeds (Mazza 2008).

It serves as a good source of minerals especially, phosphorous (650 mg/100 g), magnesium (350–431 mg/100 g), calcium (236–250 mg/100 g) and has very low amount of sodium (27 mg/100 g) (Morris 2007). It contains highest amount of potassium 5600–9200 mg/kg among various foods and high potassium intake is inversely related to blood platelet aggregation, free radicals in blood and stroke incidence (Carter 1993). Flaxseed contains small amounts of water-soluble and fat-soluble vitamins. Vitamin E is present as γ-tocopherol, amounting to 39.5 mg/100 g. γ-tocopherol is an antioxidant providing protection to cell proteins and fat from oxidation; promotes sodium excretion in urine, which may help in lowering of blood pressure and heart disease risks and Alzheimer disease (Morris et al. 2005; Morris 2007).

Anti-nutrients

Flaxseeds contain anti-nutrients that may have adverse influence on the health and well-being of human population. Cyanogenic glycosides are the major anti-nutrients and are fractionated into linustatin (213–352 mg/100 g), neolinustatin (91–203 mg/100 g), linmarin (32 mg/100 g). The content of these three glycosides depend upon cultivar, location etc. (Oomah et al. 1992). Fiber type linseed has a higher percentage of glycosides than the seed type, and ripe seed contains less glycoside than the immature seed. Whole flaxseed contains 250–550 mg/100 g cyanogenic glycoside (Singh et al. 2011a, b). In the intestine, cyanogenic glycosides release hydrogen cyanide, a potent respiratory inhibitor, by intestinal β-glycosidase that produces thiocyanates. Thiocyanates interfere with iodine uptake by thyroid gland and long term exposure aggravates iodine-deficiency disorders, goiter and cretinism. Cyanogenic glycosides are heat labile and easily destroyed by processing methods namely autoclaving, microwave roasting, pelleting and by certain detoxifying enzymes such as β-glycosidases, releasing hydrogen cyanide which can be evaporated by using steam (Cunnane et al. 1993; Feng et al. 2003; Yamashita et al. 2007).

Phytic acid, another anti-nutrient present in flaxseed, ranges from 23 to 33 g/kg of the flaxseed meal (Oomah et al. 1996a, b). Phytic acid interferes with the absorption of calcium, zinc, magnesium, copper and iron. It is a strong chelator, forming protein and mineral-phytic acid complexes and thus reducing their bioavailability (Erdman 1979; Akande et al. 2010). Clinical studies reveal that flaxseed fed rats had no effect on their Zn status (Ratnayake et al. 1992). Ganorkar and Jain (2013) have also reviewed that flaxseed antinutrients have lesser impact on human health as compared to that of soyabean and canola. Linatine (antipyrodoxidine factor) has been identified as a vitamin B6 antagonist in case of chicks. While in humans, flaxseeds are not found to be associated with vitamin B6 deficiency (Dieken 1992; Ratnayake et al. 1992). Trypsin inhibitors are also reported in flaxseed, though activity is insignificant as compared to soybean and canola seeds (Bhatty 1993).

Flaxseed as functional food

Flaxseed is considered as functional food owing to the presence of three main bioactive components—alpha-linolenic acid, lignans and dietary fiber.

Alpha-linolenic acid

Alpha-linolenic acid is the main functional component of flaxseed. It serves as an exclusive source of omega-3 fatty acid in the vegetarian diets (Riediger et al. 2009). Flaxseed oil is rich in polyunsaturated fatty acid (73 % of total fatty acid), moderate in monounsaturated fat (18 %) and low amount of saturated fat (9 %) (Cunnane et al. 1993; Dubois et al. 2007). It is rich in both the essential fatty acids—alpha-linolenic acid (ALA), and linolenic acid (LA). Fatty acids are termed as essential because both they are required by the body but body cannot synthesize them, therefore need to be supplied in the diet. Human body lacks the enzymes which are required for the synthesis of these essential fatty acids (de Lorgeril et al. 2001).

Metabolism

Omega-3 fatty acid is known as essential fatty acid because humans cannot introduce a double bond beyond the ninth carbon from carboxyl end of fatty acid. The metabolism of essential fatty acids is depicted in Fig. 1. ALA serves as the precursor for the synthesis of polyunsaturated fatty acids—EPA (Eicosapentaenoic acid) and DHA (Docosahexanoic

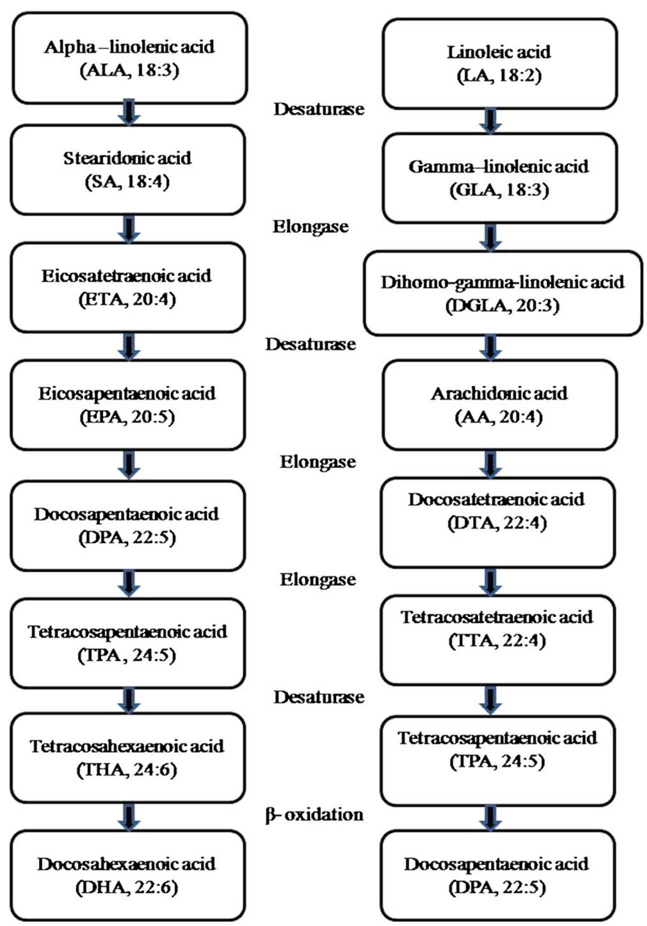


Fig. 1 Flowchart for metabolism of essential fatty acids

acid). During the transformation of ALA into EPA and DHA, a series of fatty acids belonging to n-3 PUFA family are also synthesized via desaturation and elongation reactions in the presence of specific desaturases and elongases. Similarly, linolenic acid is also synthesized using similar enzymatic reactions. It has been reported that the conversion of ALA to EPA and DHA is not very efficient in humans and animals and there exist competition between both the fatty acids for the same enzymes. Lower order animals are known to have such enzymatic activities which are capable of converting n-6 fatty acid to n-3 fatty acids, while mammals lack such activities. But recent research findings indicated that mice are the only mammals possessing the enzymes capable of converting n-6 fatty acid to n-3 fatty acid (Spychalla et al. 1997; Lunn and Theobald 2006; Kang 2007).

Long chain PUFAs, EPA and DHA are further metabolized by the enzymes cyclooxygenase and lipoxygenase to eicosanoids, prostaglandins, leukotrienes. Among these eicosanoids, E_2 series prostaglandins, leukotrienes B_4 derived from linoleic acid are the key metabolites which are responsible for many inflammatory diseases like cardiovascular diseases and arthritis, while eicosanoids and E3 series prostaglandins derived from linolenic acid have anti-inflammatory responses (James et al. 2000; Funk 2001; Barcelo-Coblijn and Murphy 2009; Kaur et al. 2012). Therefore, it is advised that human beings should consume a diet that contains a balanced ratio of omega-3 and omega-6 essential fatty acids. The two groups of essential fatty acids compete with each other for placement within cell membranes. If the intercellular environment has a higher proportion of one type of fatty acid as compared to the other, it is likely that the predominant fatty acid will be incorporated into cell membrane, resulting in adverse effects in the fluidity of the cell membrane affecting cellular functions and overall health of the cell. If there is an equal proportion of both the essential fatty acid in the intercellular environment, there is selective preference for omega-3 fatty acid. Both these fatty acids have opposing, yet necessary, influences over physiological functions (Lunn and Theobald 2006; Kaur et al. 2012).

EPA and DHA can be converted endogenously into different metabolites known as resolvins, neuroprotectins and protectins. The resolvins act as potent anti-inflammatory mediator. In particular, they function to limit the extent of inflammation by blocking the actions of prostanoids, and also by helping to clear site of inflammation from breakdown products of inflammatory process. Resolvins and protectins promote resolution in oral, lung, kidney, skin, gastrointestinal and various other inflammations to maintain homeostasis by activating specific mechanisms. DHA is converted into neuroprotectins which exhibit neuroprotective effects (Simpolous 2011; Macmohan and Godson 2004). In order to maintain good health, it is therefore important that both fatty acids should be present in a balanced ratio.

Ratio of omega-6 to omega-3 fatty acid

Fatty acid profiles of various oilseeds are reported in Table 2. It is evident from the data that flaxseed contains highest amount of linolenic acid followed by soybeans and mustard oil, while sunflower and safflower oils contain large amount of linoleic acid which may leads to various diseases. Over the past 100 to 150 years, the consumption of vegetable oils from corn, sunflower seeds, safflower seeds, cottonseeds and soybeans has greatly increased, which resulted in drastic imbalance of the essential fatty acids. Today, the ratio of omega-6 to omega-3 fatty acid is shifted to 20–30:1 in western diets and the situation is even worse in case of Indian diets where this ratio attains a high value of 38–50:1 which reveals that more of omega-6 fatty acids are incorporated into the cell membrane (Simpolous 2004; Pella et al. 2003). Therefore, the cellular functions support more of the pro-inflammatory processes than anti-inflammatory processes. Simple dietary choices, which favour foods containing omega-3 fatty acids, can ameliorate this imbalance. The recommended ratio of omega-6 to omega-3 fatty acids may be in the range of 4:1 to 10:1, and omega-6 and omega-3 fatty acid intakes should account for at least 3 and 0.5 % of total energy intake, respectively (de Lorgeril et al. 2001; Tolkachev and Zhuchenko 2000; WHO 2003). These variations in the ratio of fatty acids may be considered as a deciding factor for the development of therapeutic doses for prevention of colorectal cancer, asthma and rheumatoid arthritis (Arend and Dayer 1995).

Health benefits

A large number of clinical studies have recognized the tremendous potential of n-3 polyunsaturated fatty acids against inflammatory mediators like prostaglandins E_2, leukotriene B_4, TNF-α, interleukin, and cytokines. These clinical studies revealed that n-3 polyunsaturated fatty acids are helpful in prevention of coronary heart diseases, atherosclerosis, rheumatoid arthritis and asthma (Arend and Dayer 1995; Kremer 2000). Daily intake of 3 g EPA and DHA for more than 12 weeks was found to be effective in reducing the inflammation of rheumatoid arthritis (Kremer 2000). It has also been reported that the consumption of omega-3 dietary supplements lead to significant reduction of nonsteroidal anti-inflammatory drugs (Arend and Dayer 1995). Flaxseed oil supplementation for about 4 weeks resulted in protecting the mice against *Streptococcus pneumonia* infection (Saini et al. 2010). Flaxseed and its oil reduces the growth of tumors at the later stage of carcinogenesis; whereas, mammalian lignan precursor exert the greatest inhibitory effect on the growth of new tumors (Thompson et al. 1996). The role of flaxseed oil in tumors prevention is attributed to its high alpha-linolenic acid. The fatty acid composition of the tumors revealed higher

Table 2 Fatty acid profile of various oilseeds

Fatty acid	Flaxseed	Mustard	Soyabean	Rice bran	Corn	Sesame	Safflower	Olive	Sunflower
Saturated	10	8	15.7	21.3	14.8	15.7	9.1	15.3	12.8
Monounsaturated	18.5	62.4	24.2	42.4	28.1	40.1	13.9	73.8	22.4
Polyunsaturated	71.8	31.5	59.8	35.9	57.1	45.7	77.3	10	66
Linoleic acid (n6)	16.8	21.6	52.1	34.6	56.1	45.3	76.5	9.4	65.6
Linolenic acid (n3)	55	9.9	7.8	1.2	1	0.4	0.8	0.6	0.5
n6/n3	0.3	2.2	6.7	2	56	113	7.4	16	131

Dubois et al. 2007

incorporation of alpha-linolenic acid which in turn resulted in suppression of the growth of the tumor cells (Gonzalez et al. 1991; Thompson 1996; Gabor and Abraham 1986).

Flaxseed possesses antioxidant and hepatoprotective properties. Several studies advocated the cholesterol lowering benefits of flaxseed meal (Cunnane et al. 1993; Ridges et al. 2001; Bhathena et al. 2003). A study on hypercholesterolemic rats fed on flaxseed chutney supplemented diet (15 %) revealed significant reduction in LDL cholesterol and total serum cholesterol and no change in HDL cholesterol. In CCl_4 intoxicated rats, lipid peroxidation products were neutralized by flaxseed lignans (Shakir and Madhusudan 2007). Several clinical studies showed that EPA and DHA play a major role in reducing depression symptoms. During depression or stress proinflammatory cytokines such as TNF-α, interferon gamma etc. are produced. Increased of n-6 fatty acid to n-3 fatty acid ratio may lead to the production of proinflammatory cytokines which causes depression and mood swings in elderly persons (Maes et al. 1996; Tiemeier et al. 2003; Locke and Stoll 2001).

Lignans

Lignans are phytoestrogens, which are abundantly available in fiber rich plants, cereals (wheat, barley, and oats), legumes (bean, lentil, soybean), vegetables (broccoli, garlic, asparagus, carrots) fruits, berries, tea and alcoholic beverages. Flaxseed contains about 75–800 times more lignans than cereal grains, legumes, fruits and vegetables (Mazur et al. 2000; Meagher and Beecher 2000; Murphy and Hendrich 2002; Hosseinian and Beta 2009). Secoisolariciresinol diglycoside (SDG) is the major lignan of flaxseed, alongwith minor contents of matairesinol, pinoresinol, lariciresinol and isolariciresinol (Meagher et al. 1999; Sicilia et al. 2003; Krajcova et al. 2009). SDG ranges from 11.7 to 24.1 mg/g in defatted flour and 6.1 to 13.3 mg/g in whole flaxseed flour (Johnsson et al. 2000).

Lignans are the diphenolic compounds synthesised by the coupling of two coniferyl alcohol residues existing in cell wall of higher plants (Toure and Xueming 2010; Westcott and Muir 2003). Secoisolariciresinol (SECO) is produced by acid hydrolysis of secoisolariciresinol diglycoside. Secoisolariciresinol diglycoside existing bound form as a complex of five secoisolariciresinol diglycoside residues held together by four HMGA (3-hydroxy-3-methylglutaric acid) residues in the outer layers of the seed (Kamal-Eldin et al. 2001; Raffaelli et al. 2002; Muir 2006). Structures of the flaxseed lignans complied from different sources (Toure and Xueming 2010; Meagher et al. 1999) are presented in Fig. 2.

Metabolism

SDG is metabolized by bacteria in the colon of humans to synthesize mammalian lignans known as enterodiol (END) and enterolactone (ENL) (Chen et al. 2007). In human body, the lignans are acted upon by the gastrointestinal microflora to release SECO, non-sugar moiety of SDG. Further hydroxylation and demethylation by the microflora, lead to the production of mammalian lignan-enterodiol (END), which is then oxidized to give enterolactone (ENL) (Morris 2007; Hu et al. 2007; Toure and Xueming 2010). The metabolism of flaxseed lignans is presented in Fig. 3. *Bacteroides* as well as *Clostridia* have been identified to release the glucosyl moieties from SDG to yield SECO (Clavel et al. 2006; Struijs et al. 2009). *Peptostreptococcus productus*, *Eubacterium callanderi*, *Eubacterium limosum* and *Bacteroides methylotrophicum* are found to be responsible for carrying out demethylation reactions, while dehydroxylation reaction are carried out by *Eubacterium lentum* (Wang et al. 2000; Clavel et al. 2007). The dehydrogenation of END into ENL has been carried out by several *Clostridia* and *Ruminococcus* sp. (Clavel et al. 2007; Jin et al. 2007). The END and ENL, so formed can be excreted in faeces or are absorbed by the human colon and enter the circulation.

Health benefits

Epidemiological studies indicate that phytoestrogens rich diets reduce the risk of various hormone dependent cancers, heart diseases and osteoporosis (Krajcova et al. 2009; Toure

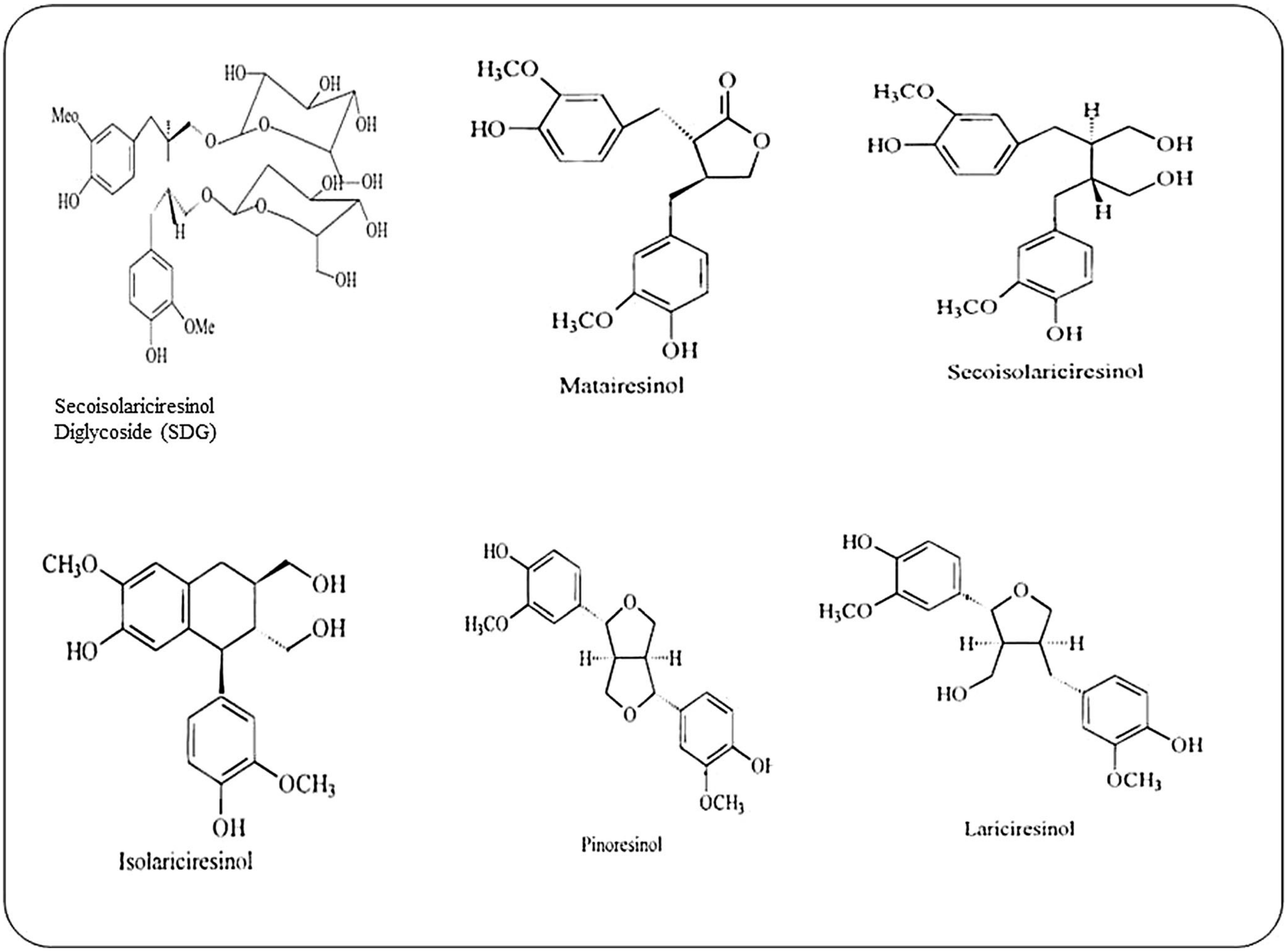
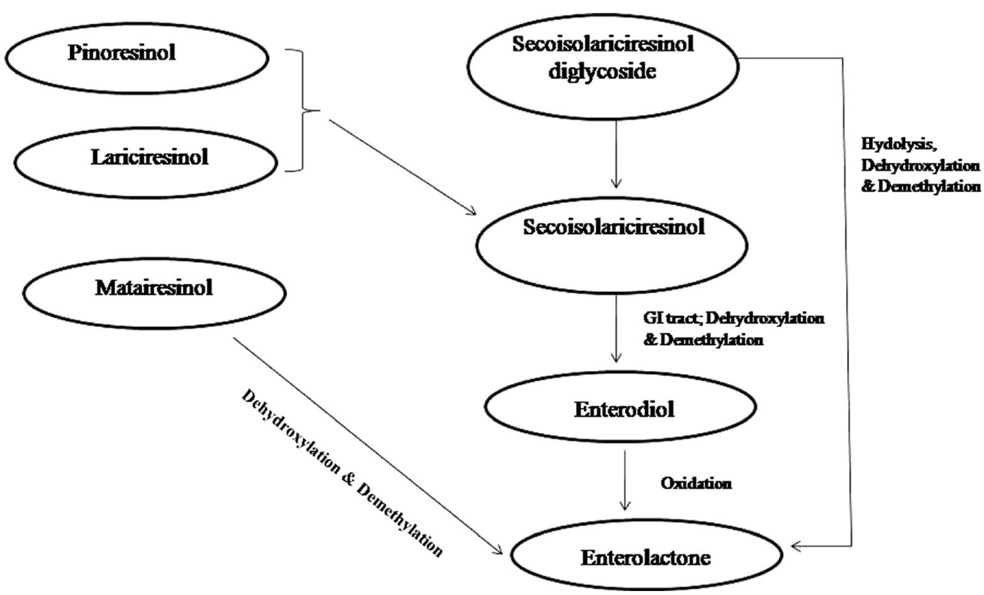


Fig. 2 Structure of various lignans present in flaxseed

and Xueming 2010). Research studies also demonstrate the ability of SDG to scavenge hydroxyl free radicals and shown that it is a potent antioxidant Human body produces free radicals during the oxidation of fats, proteins and

Fig. 3 Flowchart depicting the metabolism of flaxseed lignans



carbohydrates. Free radicals damages tissues, membrane lipids, nucleic acids, proteins which may cause cancer, lung diseases, neurological diseases, premature aging and diabetes (Prasad 1997; Toure and Xueming 2010; Singh et al. 2011a, b). Anticancer activity of lignans is attributed to its ability to scavenge hydroxyl free radicals (Prasad 1997; Hu et al. 2007; Sok et al. 2009). SECO, SDG also play an important role in reduction of hypercholesterolemia, atherosclerosis, hypertension and diabetes (Prasad 2000, 2004). Daily administration of 100 mg SDG was found to be effective in reducing blood cholesterol and hepatic diseases risk in moderately hypercholesterolemic men (Fukumitsu et al. 2010). Flaxseed lignans behaviour depends on biological levels of estrogen hormone. At normal levels of estrogen, it exhibit antagonistic activity, but in postmenopausal phase when estrogen level is low, flaxseed lignans acts as weak estrogen (Sok et al. 2009; Toure and Xueming 2010; Saini et al. 2010). The mammalian lignans stimulate the synthesis of sex hormone binding globulin, which binds sex hormones and reduce their circulation in blood stream, and decrease their biological activity and thus reducing the risk of developing cancer (Thompson et al. 1996). These mammalian lignans are believed to act by binding to estrogen receptors on cell membranes in the same manner as body's own steroids do but not as powerful as endogenous estrogens (Sok et al. 2009; Morris 2007; Toure and Xueming 2010). Lignans, enterodiol and enterolactone are believed to be partly responsible for growth inhibition of human prostate cancer (Westcott and Muir 2003).

Flaxseed lignans play an important role in preventing various types of cancer specially the hormone sensitive ones. Flax lignans are reported to have antioxidant property which presumably is the main reason of the anticancer activity (Schweigerer et al. 1992; Prasad 1997). The lower incidences of prostate and breast cancers in Asian men and women compared to European men and women has been speculated to be due to the higher consumption of diets rich in fruits and vegetables. (Adlercreutz 1990; Morton et al. 1997). Various clinical studies imply that lignans prevent breast cancer by balancing the hormonal mechanisms. The lignans inhibit the aromatase activity in adipose tissue resulting in the circulation of estrogen (Sturgeon et al. 2008; Adlercreutz et al. 1993).

In postmenopausal women, lignans act as weak estrogens, while at normal estrogen levels, lignans act as estrogen antagonists (Wang et al. 1994; Hutchins and Slavin 2003). Dietary flaxseed moderately lowers the serum levels of steroid sex hormones which are implicated in development of breast cancer in obese postmenopausal women (Sturgeon et al. 2008).

Dietary fiber

Flaxseeds serve as a good source of both soluble and insoluble dietary fiber. Flaxseed holds a unique place among the oilseeds due to presence of mucilage located in outer layers of the seed (Singh et al. 2011a, b). Flaxseed mucilage has gained momentum due to its superb health benefits and potential functional properties (Susheelamma 1987; Mazza and Biliaderis 1989). It contains 35–45 % of fibre and two-third is insoluble and one third is soluble fiber. Insoluble fiber consists of cellulose, hemicellulose and lignin (Morris 2007; Oomah and Mazza 1993). Most of the soluble fiber of flaxseed appears to be the mucilage of seed coat. It makes up 7–10 % of seed weight (Mazza and Biliaderis 1989). Soluble fiber in the form of mucilaginous material consists mainly of water soluble polysaccharides; its recovery and purity vary with the extraction conditions. The water binding capacity of flaxseed mucilage is reported to be about 1600–3000 g of water/ 100 g of solids. High water binding capacity of flaxseed is attributed due to the presence of polysaccharides in the seed coat (Fedenuik and Biliaderis 1994; Wanasundara and Shahidi 1997).

Mucilage of flaxseed consists of acidic and neutral polysaccharides. The neutral fraction constitutes L-arabinose, D-xylose and D-galactose and arabinoxylan and acidic fraction contains L-rhamnose, L-fucose, L-galactose and D-galactouronic acid (Wanasundara and Shahidi 1997). Functionally, these polysaccharides possess similar properties to guar gum (Wanasundara and Shahidi 1994; Tarpila et al. 2005). The mucilage can be extracted by water and exhibit good foam-stability properties (Susheelamma 1987).

Metabolism

Dietary fiber of flaxseed reaches the large intestine and is fermented by colonic microflora with production of short chain fatty acids (SCFA), hydrogen, carbon dioxide, methane and biomass and exhibit laxative effects (Kritchevsky 1979). In the large intestine, both soluble and insoluble fibers have their bulking effect resulting in increasing both dry and wet weight of the colon contents and faeces. Soluble fiber increases water binding, initially by the binding capacity of its macromolecules, later by increasing the mass of microbial cells. The contribution of soluble fiber to faecal weight was insignificant compared to insoluble fiber. Recent studies, however, have shown that it is of the same magnitude (Malkki 2004).

Health benefits

Water-binding capacity of flaxseed insoluble fiber increases the intestinal bulk which is useful in the treatment of constipation, irritable bowel syndrome and diverticular disease. Soluble fiber from flaxseed mucilage increases the viscosity of intestinal contents and delays gastric emptying and nutrient absorption Inclusion of flaxseed mucilage in the diet of broiler chicks resulted in decreased faecal digestibility of fat and fatty acids while protein digestion was unaffected. Intestinal viscosity of the broiler chicks increased on addition of flaxseed mucilage in the diet (Rebole et al. 2002). Traditionally, dietary fiber is used for the treatment of constipation, irritable bowel syndrome (Cann et al. 1984; Tarpila et al. 2005). Dietary fiber delays gastric emptying, regulate post prandial blood glucose levels and helpful in prevention of constipation (Spiller 1994). Flaxseed fiber plays an important role in lowering the blood glucose levels. Studies demonstrated that insoluble fiber slows down the release of sugar in the blood and thus help in reducing blood glucose levels to great extent (Thakur et al. 2009; Kapoor et al. 2011). Soluble gum of the flaxseed may be helpful in the prevention of cardiovascular diseases by exhibiting hypocholesterolemic effect (Jenkins et al. 1987; Cunnane et al. 1994). Kristensen et al. 2012 studied the effect of differently processed flax fibers on the fat excretion and energy balance. It was observed that flax fiber enriched drink lowered the cholesterol to a large extent as compared to fiber enriched bread. However, the consumption of fiber bread increased the fecal fat excretion and maintained proper energy balance. Studies have shown that the high intake of dietary fibers is beneficial for the prevention of obesity in both men and women (Du et al. 2010).

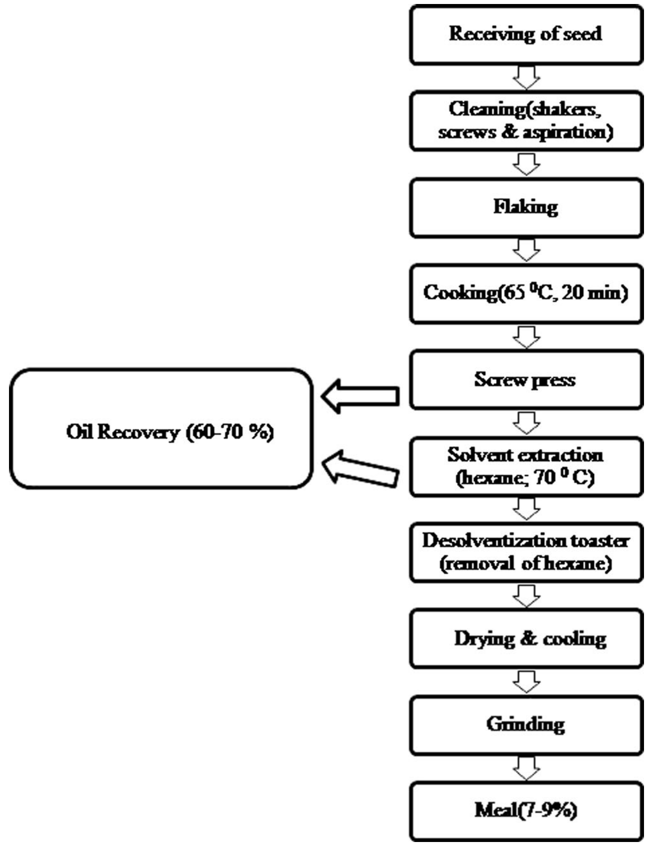


Fig. 4 Processing of flaxseed

Processing

Commercial processing of flaxseeds is carried out to obtain oil and various by-products. Compositional changes during processing are of prime importance to food, feed and nutraceuticals industry. Processing of flaxseeds at commercial level involves multiple steps as shown in Fig. 4 (Oomah and Mazza 1998). The amount of heat as well as extraction time influence the quality of oilseed meal as excessive heating reduce the nitrogen digestibility and net protein utilization (Young 1982). During the processing of flaxseed to meal, protein, carbohydrates and mineral levels increased significantly which contribute to decrease in lipid content. Protein solubility of seeds declined while processing to meal but substantial increase in solubility of protein were observed in flaxseed flakes which may be credited to the increased surface exposure of protein during conditioning treatment. Heat treatment affects the quality of protein and therefore decreases the protein solubility. (Madhusudan and Singh 1984; Oomah and Mazza 1998). However, the total cyanogenic contents of the meal remained unaltered by processing. Several attempts are being made from time to time to reduce the cyanogenic compounds of the flaxseeds. One of the simple and convenient methods to eliminate the cyanogenic glycosides by use of exogenous enzymes to produce hydrogen cyanide from the flaxseed meal and then subjected to steam for evaporation of hydrogen cyanide (Yamashita et al. 2007). Similarly, autoclaving, microwave roasting, pelleting of flaxseeds resulted in significant reduction in cyanogenic glycoside content of the meal without lowering nutritional quality of the seed (Feng et al. 2003).

Extraction of oil

Commercially majority of the flaxseed is processed for extraction of oil which is then used for paints, coatings, linoleum, inks, floor coverings, etc. (Tolkachev and Zhuchenko 2000). Industrial oil is not suitable for food or feed, but the residual meal can be used as feed for cattle. The very high content of alpha-linolenic acid content of flaxseed make it susceptible to autoxidation, leading to deterioration of quality, therefore flaxseed oil extraction has been done by cold pressing and solvent extraction methods. Even after cold extraction of flax oils, it is strongly recommended that oil should be stored in dark glass bottles, supplemented with antioxidants to avoid quality deterioration (Lukaszewicz et al. 2004) In India, various techniques are used for the extraction of flaxseed oil, namely bullock driven ghanis (Kohlu), power driven rotary ghanis hydraulic press and screw-press oil expellers (Singh et al. 2011a, b). Flaxseed oil is generally screw pressed without heat treatment as well no refining is done except for sedimentation and filtration (Wiesenborn et al. 2005). Fresh unrefined oil has a pleasant nutty flavor and attractive golden color. The oil recovery using double stage compression screw press ranges from 86 to 92 %. However, various pretreatments viz., the adjustment of moisture content, (Singh and Bargale 2000) use of enzymes (Shankar et al. 1997) steam treatment, cooking (Singh et al. 2011a, b) prior to pressing results in significant improvement in oil recovery. Decreasing the moisture content of the flaxseeds from 13.8 and 6.5 % resulted in significant increase in oil recovery varying from 44.4 and 81 % (Singh et al. 2011a, b).

Solvent extraction of oilseeds using hexane is usually carried out for recovery of high quality oil and retention of polar lipids (Nash and Frankel 1986). Cold pressing results in only partial recovery of the oil; therefore, pressing of the seeds is followed by solvent extraction at high temperatures to achieve maximum oil recovery. But the alpha-linolenic acid is degraded by exposure to high temperature; therefore, supercritical fluid extraction technique can be a boon to such oils. Supercritical carbon dioxide (SC-CO_2) is the most often used supercritical fluid for purpose of oil extraction as the low critical temperature of CO_2 (31 °C) allows extraction of heat sensitive compounds without quality deterioration. Lipid composition of the flaxseed oils obtained by both SC-CO_2 and petroleum ether extraction were studied and it was found that the alpha-linolenic acid content was higher in case of the oil extracted using SC-CO_2 as compared to oil extracted using petroleum ether (Bozan and Temelli 2002). Ultrasonic power is also employed for the extraction of flaxseed oil. A study revealed that ultrasonic assisted extraction of oil resulted in enhanced recovery of oil with increased ultrasonic power. Ultrasonic assisted extraction saves time and lesser solvent consumption (Zhang et al. 2008).

Dehulling

Dehulling leads to removal of outer layer of the seed coat and hence increasing the availability of nutrients. As it is well known that flaxseeds passes through the gut as such and useful nutrients are not absorbed by the body, therefore efforts are being made to remove the hard outer layers of the seeds by using different methods viz., crushing, dehulling, grinding etc. Dehulling removes the hull which results in the elimination most of the mucilage and crude fiber (Dev and Quensel 1988). Dehulled seed contain high level of protein and low carbohydrate content, which makes the flaxseed as potential ingredient for food and feed products (Oomah and Mazza 1997). The hull of flaxseed contain an outer layer which is tough and fibrous containing negligible amounts of oil and protein and inner layer of the hull is soft and has small amount of oil as well as protein. Both these layers of hull are intact; therefore they are considered as single component (Mandokhot and Singh 1979). Several attempts have been made to remove the outer mucilaginous layers of the flaxseed. Traditionally, mucilage has been removed by aqueous extraction methods. The aqueous extraction method involves soaking of seeds in water at temperature preferably between 50 and 80 °C with occasional stirring followed by filtration. The extract is treated with acetone, washed, dialyzed against water and then lyophilized. Hot water extraction result in high yields of mucilage as compared to cold water extraction (Fedenuik and Biliaderis 1994; Cui and Mazza 1996). The mucilage obtained using aqueous extraction is known to be free of specially cotyledon fractions, but this extraction is not economical as it involves various steps including filtration, centrifugation, drying etc. Dry dehulling is also practiced using mechanical methods. Simple process of dry dehulling involves fractionation of ground flaxseeds using graded sieves and air separation method (Dev and Quensel 1988; Smith et al. 1946). Method adopted by Smith et al. 1946 revealed that adjusting the moisture content of the seed before grinding results in significant improved separation of hull with less contamination of cotyledon fractions. The dehulled meal is rich in crude fiber and crude protein. Dehulling also leads to quality deterioration of the dehulled meal because abrasive force used for dehulling may results in removal of some growth promoting factors as well as some protein fraction (Mandokhot and Singh 1979). Most common method used for dry dehulling of flaxseed is TADD (Tangential Abrasive Dehulling Device). This is a simple method for assessing dehulling quality; it requires small sample size and is useful for routine testing in breeding programmes. Dehulling done by TADD method revealed that reduction in moisture content of the seed resulted in exponential increase in hull recovery. However, the amount of hull recovered was independent of speed of rotating disk and dehulling time (Oomah and Mazza 1997). Dehulling of flaxseeds by TADD resulted in significant increase in oil and protein contents and decrease in carbohydrates. Water hydration capacity and viscosity are reduced upon dehulling as the hull contains good percentage of fiber and mucilage which accounts for these properties. The hull fraction contains highest palmitic acid and low amounts of stearic and oleic acid as compared to whole and dehulled flaxseeds. The very high content of dehulled meal makes it an attractive unusual source of protein, whereas, high amount of carbohydrates in hull fraction makes it a good source of dietary fiber to human nutrition (Oomah and Mazza 1997).

Flaxseed as food

As ingredient

In functional foods arena, flaxseed has resurged as a new potential functional ingredient with a vast array of medical benefits. Flaxseed supplemented food products are gaining popularity because of its high content of polyunsaturated fatty acids, protein, soluble fiber and phytochemicals. It is utilized

Table 3 Flaxseed as functional ingredient in various food products

Flaxseed as ingredient	Processing methods	Products	Characteristics	References
Flaxseed flour + wheat flour	Baking	Bread	Acceptable in terms of sensory and nutritional characteristics, specific volume of bread decreased with increase in flaxseed concentration	Lipilina and Ganji 2009
Flaxseed flour	Baking	Cookies	15 % supplementation improved alpha-linolenic acid content, acceptable sensory and rheological characteristics	Rajiv et al. 2011
			20 % supplementation acceptable, however, with increase in supplementation level, spread factor decreased	Hussain et al. 2006
			12 % supplementation acceptable without affecting sensory and physical characteristics	Khouryieh and Aramouni 2012
Flaxseed (raw & roasted) flour (along with wheat flour)	Baking	Muffins	Softer products with better nutritional quality and overall acceptability at 20 % level of supplementation	Chetana et al. 2010
Flaxseed flour (full fat and partial defatted)	Baking	Chapatti	Total, soluble and insoluble dietary fibers, essential amino acid contents and alpha-linolenic acid content of chapattis and breads increased	Hussain 2009
Ground flaxseed	Baking	Beef patties	Cooking losses improved, good nutritional characteristics at 3–6 % supplementation	Bliek and Turhan 2009
Ground whole flaxseed and ground flaxseed hull	Extrusion	Macaroni	Lipids remained stable during processing, free fatty levels reduced	Lee et al. 2004
			ALA and SDG remained stable over 32 week storage period	Hall et al. 2005
Flaxseed flour	Extrusion	Pasta	Retardation of microbial activity	Manthey et al. 2008
Flaxseed with corn meal	Extrusion	Puffs	15 % incorporation produced good puffed product, however, lignan content decreased by 25–52 %	Wu et al. 2007
Flaxseed with corn & soy flour	Extrusion	Puffs	Good puffing characteristics at 10 % supplementation, low color scores and poor textural characteristics	Alpaslan and Hayta 2006
SDG (lignan content) isolated from flaxseed	Pasteurization, fermentation, milk renneting	Dairy products	SDG remained stable during processing as well as storage	Hyvarinen et al. 2006a
	Baking	Baked products		Hyvarinen et al. 2006b
Linseed polysaccharide	Steaming	Idli	Good soft texture and overall acceptability	Susheelamma 1989
Defatted crushed flaxseed	Fermentation	Spoonable/drinkable snack	Acceptable oat and buckwheat supplemented flaxseed product with probiotic property	Salimnen et al. 2010
Ground flaxseed	Roasting	Energy rich bar	15 % flaxseed + 45 % sweeteners along with other ingredients had acceptable quality, nutritionally as well as organoleptically	Mridula et al. 2011
Flaxseed oil	Homogenization	Ice cream	Oil act as foam stabilizer, improved meltdown time and soft creamy texture	Goh et al. 2006

as a versatile ingredient in various types of food products (Table 3). It is convenient to use flax seeds as whole or milled in batters, dough and various baked products. Flaxseed-water mixture serve as egg substitute in the diet of vegetarians especially in baked products pancakes, muffins and cookies. These baked goods are slightly gummier and chewier, and have low loaf volume than normal. One tablespoon of milled flaxseed (approx. 15 g) along with three tablespoon of water (approx. 45 mL) substitute for one egg. Flaxseed gum (0.45 % w/w) can be utilized for stabilization of emulsion in case of salad dressings (Stewart and Mazza 2000). Functional properties of flaxseed constituents are presented in Table 4. Flaxseed products are quiet stable for a longer period at ambient temperature despite of generous amount of alpha-linolenic acid. Several studies justify the above statement that storing the milled flaxseed for about 4 months did not result in deterioration of quality (Singh et al. 2011a, b). Similarly, bread prepared with the flaxseed oil cake at the rate of 10 and 15 % had peroxide levels well below the threshold limits after the 6 months of storage (Ogunronbi et al. 2011). Flaxseed is also being incorporated in the feed of animals to improve the nutritional quality of the meat and fat obtained from them. Omega-3 enriched eggs, pork products are now-a-days available commercially (Kassis et al. 2011).

Edible oil

As already discussed, flaxseed oil is rich in polyunsaturated fatty acids specifically the alpha-linolenic acid. Decades back, flaxseed was used mainly in the manufacturing of drying oil, paints, coating, and printing inks etc. But recently there has been resurgence in the use of flaxseed oil for edible purposes because of its nutraceuticals values. Fresh flaxseed is golden yellow in colour, has neutral taste and is very sensitive to heat, light, oxygen; therefore it is usually extracted by cold pressing when it is meant for edible purposes (Choo et al. 2007a, b). Since, flaxseed oil has very high amount of alpha-linolenic acid, it is highly susceptible to oxidation, rancidity and poor sensory quality (Hosseinian et al. 2004; Wiesenborn et al. 2005). The oxidation products serve as a causative agent for chronic diseases.

Flaxseed oil is not recommended for high temperature processing. Studies reported that the high temperature treatment of the oil result in the alteration of its nutritional composition. It has been reported that elevated temperature deteriorate the alpha-linolenic acid (heat labile) which is not desirable in terms of its associated health benefits (Choo et al. 2007a, b). In China, stir frying of flaxseed oil at 150 °C is very common for cooking purposes (Pan 1990). Some studies state that stir frying of flaxseed oil upto177°C did not cause any loss to the quality of the oil (Hadley 1996). Tocopherols, plastochromanol-8, phenolic acids, flavonoids, lignans and chlorophyll pigments act as natural antioxidants in various vegetable oils and these are also present in fair amounts in flaxseed oil (Choo et al. 2007a, b). Storage as well as heat treatment resulted in destruction of these natural antioxidants, thus deterioration of the oil quality and shelf-stability (Tautorus and McCurdy 1990; Li et al. 1996). Attempts are being made in terms of encapsulation of the oil with gelatin-arabic gum capsules, which provide protection against oxidative products formed during processing or storage (Liu et al. 2010).

Due to its high alpha-linolenic acid content, it has multiple industrial applications. Based on the scientific research on the stupendous health benefits of linolenic acid it has attracted the intellectuals from various fields are doing sincere efforts to widen its food applications. Plant breeders, food technologists and nutritionists are using conventional and molecular approaches for altering the fatty acid profile of flaxseed and create its competitive food market. In this respect, initiative was taken by Green 1995 reduced the alpha-linolenic acid of flaxseed oil, to less than 5 %. Flax council has given the name solin for such cultivars containing less than 5 % alpha-linolenic acid. The high levels of palmitic acid, oleic acid,

Table 4 Functional properties of flaxseed constituents

Functional ingredient	Applications	References
Mucilage	Emulsifier & stabilizer in sauces, sausages, meat emulsions, salad dressings	Stewart and Mazza 2000
	Anti-staling agent in baked products	Lipilina and Ganji 2009
	Improves cooking quality of noodles	Kishk et al. 2011
	Functional food ingredient (interaction of mucilage and protein regulate blood glucose level)	Singer et al. 2011
Protein	Stabilizer & emulsifier in ice cream, sauces and meat emulsions	Martinez-Flores et al. 2006
	Antifungal property	Xu et al. 2008a, b
	Viscoelastic texture to extruded pastes for breakfast cereals and snacks	Wu et al. 2010
	Enhances nutrition in gluten free meal	Gambus et al. 2009
	Egg and gelatin substitute in baked goods and ice cream	Shearer and Davies 2005
	Functional food ingredient	Moller et al. 2008

linoleic acid in the solin cultivars make them suitable for manufacturing of margarines and shortenings (Hosseinian et al. 2004).

Conclusion

Various clinical trials revealed that the flaxseed constituents provide disease preventive and therapeutic benefits. This encourages development of new branded healthy and functional foods using flaxseeds, oil and cakes. More in vivo studies are required to ascertain the health benefits of flaxseed constituents and to know the minimum amount of flaxseed required to explore its therapeutic potential for all population groups including pregnant and lactating women and to know possible problems posed by its overdose. There is need for the development of rapid, reproducible and economic techniques for the analysis of nutraceuticals from flaxseed.

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