Australian Journal of basic and Applied Sciences, 4(9): 4304-4312, 2010
ISSN 1991-8178

Flax (*Linum usitatissimum* L.): Current Uses and Future Applications

Amit J. Jhala and Linda M. Hall

Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, T6G 2P5, AB, Canada.

Abstract: The archaeological evidence of flax cultivation dates back to >6000 BC and it is considered as one of the oldest and most useful crops. Components of flax have diverse uses. Cultivar development of flax is currently focused on enhancing the oil content and nutritional value to meet the demand of nutraceutical market supply, as an alternate source of fish oil, a rich source of eicosapentaenoic acid (EPA, C20:5) and docosahexaenoic acid (DHA, C22:6). Flax seed is also rich in soluble and insoluble fibers and lignans, makes it useful as a dietary supplement. Intake of flaxseed in daily diet may reduce the risk of cardiovascular diseases such as coronary heart disease and stroke. There is also evidence that flax has anticancer effects in breast, prostate and colon cancers. Flax fiber is used in the textile industry for linen cloth and also in paper industry. The residues remaining after the oil extraction from linseed contains about 35-40% protein and 3-4% oil, a rich source of feed to livestock like cattle and buffalo. Flax is naturally high in polyunsaturated fatty acids (PUFA), more specifically in ω-3 fatty acids; and hence flax seed as a component of poultry meal, can provide ω-3 enriched eggs. Rapid drying linseed oil is used for several purposes in industry, including paint and flooring (linoleum) industries. Because of its novel oil profile, flax may also be a suitable platform crop for synthesis of specialized industrial and nutraceutical products.

Key words: ALA, biocomposites, cardiovascular, functional food, industrial, linen, linoleum, nutraceutical, omega-3

INTRODUCTION

Flax or linseed is among the oldest crop plants cultivated for the purpose of oil and fiber. It belongs to the genus *Linum* and family Linaceae. The botanical name, *Linum usitatissimum* was given by Linnaeus in his book "Species Plantarum" (Linnaeus, C., 1857). It is an annual herbaceous plant with shallow root system. The common names flax and linseed are used in North America and Asia, respectively, for *L. usitatissimum*. Oilseed varieties and fiber varieties are specialized development of this species (Millam, S., *et al.,* 2005). The cultivars grown primarily for seed/oil purpose are relatively short in height and possess more secondary branches and seed bolls (seed capsule). The cultivars grown for fiber purpose are tall growing with straight culms and have fewer secondary branches.

The Mediterranean and Southwest Asia have both been proposed as the center of origin ((Millam, S., *et al.,* 2005.); however the exact location is uncertain (Lay, C.L., and C.D. Dybing, 1989). The initial use of flax has also been debated. Based on archeological evidence, it was proposed that flax was used first for fiber. However, a more recent comparative study of genetic diversity of the stearoyl-ACP desaturase II (*sad2*) locus from flax and pale flax (*L. angustifolium*) showed reduced diversity in the cultivated species. This suggests that flax may have been initially selected as an oilseed crop (Allaby, R. G., *et al.,* 2005).

Flax, while a minor crop, is grown in a wide range of countries, climates and for many different products (Fig.1). Because of its adaptability and product diversity, it is being considered as a platform for the development of novel bioproducts. Research on use of flax for bioproduct production is being conducted in Australia, North America, Europe and Asia. The objective of this paper is to discuss the various applications, demands and developments of an under utilized oilseed crop, flax (*L. usitatissimum*).

Area and Production of Flax:

Flax was grown in 47 countries in 2004 with the seed production of 1.903 million metric tonnes (Smith,H. V. and J. Jimmerson. 2005). Canada has the highest area and production of flax in the world followed by China, USA, India and EU. In 2006, Canada produced 1.014 million tonnes of flax seed from an area of about 800 thousand hectares (Statistics Canada 2006).

Corresponding Author: Amit J. Jhala, Department of Plant Sciences, University of California, Davis, 95616, USA.
E-mail: ajjhala@ucdavis.edu OR linda.hall@ualberta.ca
Phone: 530-554-8228 Fax: 780-492-4265

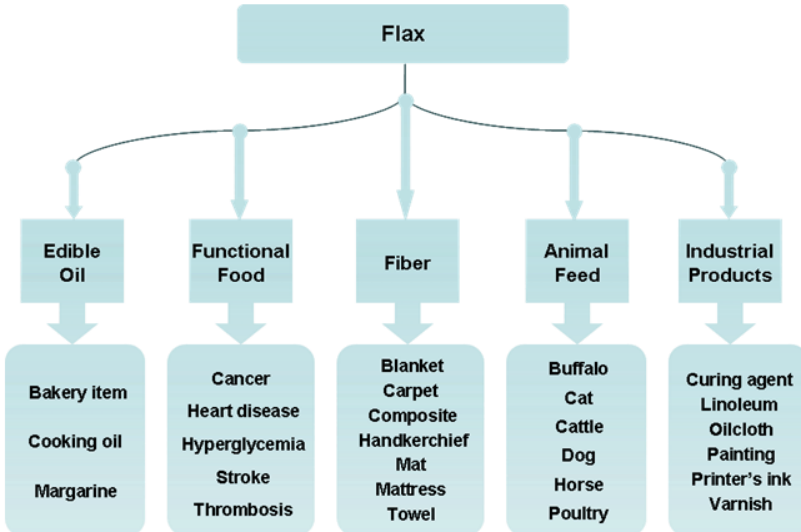

Fig. 1: Schematic diagram of flax use

The Canadian prairie (Manitoba, Saskatchewan and Alberta) is the major flax growing area in Canada. In the USA, flax has been grown primarily in North Dakota, South Dakota, Minnesota and Montana (Berglund, D.R., 2002). In India, flax is grown mainly in Uttar Pradesh, Madhya Pradesh and Maharashtra, with three states accounting for about 74% of the linseed output in India (Gill, K.S., 1987). In India, flax is grown primarily for oil, although in temperate hill regions like Himachal Pradesh, it is grown for fiber on a small scale (Richharia, R.H., 1962). Flax for fiber purpose is grown primarily in China, Russia, Egypt, and near the northwestern European coast for the production of high quality linen and several other products (Vromans, J., 2006).

Flax for Human Consumption:

Flax was being used as a food source and natural laxative dating back as far as the ancient Greeks and Egyptians. It was also being used as a food in Asia and Africa (Berglund, D.R., 2002). The unique and diverse properties of flax are reviving interest in this crop. In 2005, approximately 200 new food and personal care products were introduced in the US market containing flax or flax ingredients (Morris, H.M., 2007), which suggests that flax based products have the highest growth potentials in functional food industry.

Conventional flax seed, containing a mixture of the fatty acids, is rich in two essential fatty acids, alpha-linolenic acid (ALA; C18:3) (Canadian Egg Marketing Agency, 2007; de Lorgeril, M. *et al,* 1999; Foulk, J.A., *et al.,* 2002)) (ω-3) and linoleic acid (LA; C18:2) (Bloedon, L. T. and P. O. Szapary, 2004; Canadian Egg Marketing Agency, 2007; de Lorgeril, M., *et al.,* 1999)) (ω-6) (Table 1). In an average Canadian flax cultivar, ALA comprises about 57% of the total fatty acids in flaxseed, whereas ω-6 comprises about 16%, giving ω-6/ω-3 ratio of 0.3:1.0. The typical Western diet is high in ω-6 and low in ω-3. Current dietary ω-6/ω-3 ratio ranges from 10:1 to 25:1 while Health Canada recommends a ratio of 4:1 to 10:1, especially for pregnant women and infants (Scientific Review Committee, 1990). Consuming flax or other food rich in alpha linolenic acid like fish oil, ω-3 enriched eggs, increases ω-3 family intake, which improve ω-6/ ω-3 ratio.

Flax is the richest source of ALA, a precursor for the synthesis of very long chain polyunsaturated fatty acids (VLCPUFA), eicosapentaenoic acid (EPA, C20:50 (Bhathena, S. J., *et al.,* 2002; Cahoon E. B., 2003; Clavel T., *et al.,* 1991; Fitzpatrick, K., 2007; Green floors linoleum flooring. Linoleum flooring. Accessed: April 23, 2008)) and docosahexaenoic acid (DHA, C22:6) (Berglund, D.R., 2002; Blumenthal, M., *et al.,* 2000; Chan, J., *et al.,* 1991; Dev, D. K. and E. Quensel, 1988; Gill, K.S., 1987; Heart and Stroke Foundation of Canada. 2003)). Metabolism of ALA in animals by a series of alternating desaturations and elongations, converts it into very long chain polyunsaturated fatty acids (VLCPUFA), EPA, and DHA. Conversion of ALA to VLCPUFA in humans is affected by various hormonal changes and dietary factors (Yamazaki, K., *et al.,* 1992). High level of ω-6 fatty acids in food supply interfere with the conversion of ALA to EPA and DHA because ω-3 and ω-6 family compete for the same desaturase enzymes.

The ω-3 fatty acids, particularly DHA, are required for the optimal development of nervous system and maturation of visual acuity (retina) in preterm and term infants (Neuringer, M. and W.E. Connor, 1986; Uauy, R., *et al.,* 1996). EPA and AA (arachidonic acid; C20: 4) (Bhathena, S.J., *et al.,* 2002; Cahoon E. B., 2003; Clavel T., *et al.,* 1991; Fitzpatrick, K., 2007)) are the precursors of eicosanoids and also components of mammalian cell membranes, including the prostaglandins, blood clotting, cell signaling and blood pressure regulation (Kinsella, J.E., *et al.,* 1990). Deficiency in ω-3 increases the chances of diabetes, cancer, arthritis, inflammatory diseases, depression, heart disease, hypertension, memory problems, weight gain and some allergies (Morris, H.M., 2007).

Table 1: Comparison of fat profile of ω-3 enriched eggs and conventional eggs (Canadian Egg Marketing Agency, 2007)

content	ω-3 enriched egg[a,b]	conventional egg[a]
Total fatty acids	4.9 g	5.0 g
ω-6	0.7 g	0.7 g
ω-3	0.4 g	0.04 g
Monosaturated	1.6 g	2.0 g
Saturated	1.2 g	1.5 g
Cholesterol	185 mg	190 mg

[a]based on one whole large egg
[b]values are based on 10% flax in the diet

Table 2: Fatty acids composition in conventional and Solin flax (Morris, H.M., 2007)

Fatty acid	No. of double bonds	Omega family	Formula	Average % fatty acid
Conventional flax	0	-	18:0	9
Saturated				
Stearic acid				
Monounsaturated				
Oleic acid	1	ω-9	18:1 Δ^{9}	18
Palmitoleic acid	1	ω-7	16:1 Δ^{9}	
Polyunsaturated				
Linoleic acid (LA)				
Alpha-linolenic acid (ALA)	2	ω-6	18:2 $\Delta^{9,12}$	16
	3	ω-3	18:3 $\Delta^{9,12,15}$	57
Solin flax				
Saturated				
Stearic acid	0	-	18:0	9
Monounsaturated				
Oleic acid				
Palmitoleic acid	1	ω-9	18:1 Δ^{9}	18
	1	ω-7	16:1 Δ^{9}	
Polyunsaturated				
Linoleic acid (LA)	2	ω-6	18:2 $\Delta^{9,12}$	71
Alpha-linolenic acid (ALA)	3	ω-3	18:3 $\Delta^{9,12,15}$	2 to 3

In leafy green plants, fatty acids are usually in the form of ALA alone; however, their over all lipid content is very low, so they can not meet the total requirement of ALA alone. Most fish contain only trace amount of ALA, although a few species of fish such as salmon are rich in EPA and DHA (Nelson, G.J., and J.G. Chamberlain, 1995). However, the consumption of fish oil is predicted to continue to decrease because of diminished global fish stocks and heavy metals contamination of oils derived from fish which may affect neuropsychological function in adults (Yokoo, E.M., *et al.,* 2003). For vegetarian diets, flax is the richest plant source of ALA.

Flax for Edible Oil:

The direct use of unprocessed conventional flax oil in the human diet is limited by product stability. Linseed oil with high ALA is highly susceptible to oxidation and polymerization. While these properties make it suitable for other industrial applications (discussed below), it limits the direct substitution of flax oil in place of canola (*Brassica napus*) or corn (*Zea mays*) oil. The oil properties of flax are so unique that considerable effort is being expended to emulate the fatty acid profile. Modification of soybean oil (*Glycin max*) and canola oil using conventional and molecular approaches to enhance the ALA content and therefore the health benefits and to replace fish oils in the diet are an extremely active area of research (Cahoon E.B., 2003; Scarth R. and Tang J., 2006).

To use flax oil in food applications where stability is essential Green and Marshall (Green, A. G. and D. R. Marshall, 1984) isolated mutants with as low as 1-3% α-linolenic acid, a level which is considered suitable with self stability for traditional edible oil applications (Rowland, G. G., 1991). Solin is the name given by the Flax Council of Canada to describe the flax cultivars with less than 5 % ALA for use in the food industry. A domestic source of a vegetable oil high in palmitic acid also has potential in Canada for the manufacture of high quality margarines. Edible oil of linseed also provides an opportunity to produce cocoa-butter replacement oil (Rowland, G. G., *et al.,* 1995). However, this oil has reduced health benefits due to the reduction in (<5%) ALA content.

Flax For Functional Food:

Functional or nutraceuticals are foods that claimed to have health-promoting or disease-prevention properties in addition to basic nutritional properties in the food. Many health-claims have been made for whole flax seed, flax meal and milled flax. While a complete assessment of the research on flax as a functional food is beyond the scope of this article, readers are directed to (Bloedon, L.T. and P. O. Szapary, 2004; Fitzpatrick, K., 2007).

A recent study in Europe indicate that the consumption of flax oil for 12 weeks (one tablespoon, providing 8 g ALA/day) in daily diet lowered blood pressure significantly in middle aged men with high blood cholesterol levels (Paschos, G. K., *et al.,* 2007). A role of the flax oil in preventing thrombosis has been reported in a study by 40% increase in the activated protein ratio in a population who consumed flax oil diet for six weeks (Allman-Farinelli, M.A., *et al.,* 1999; Richard, S. and L. U. Thompson, 1997). In a study of 50 men with high blood cholesterol levels who consumed one table spoon of flax oil daily for 12 weeks reduced 48% C-reactive protein (CRP) and 32% serum amyloid A (SAA) levels (Paschos, G.K., *et al.,* 2005).

Clinical studies on rats and other animals reported that flax has antioxidant effects and decreases blood lipids and inflammation (Bhathena, S.J., *et al.,* 2002; Prasad, K., 1997). Many studies revealed that consuming traditional milled flax or partially defatted flax decreased total cholesterol, low-density lipoprotein (LDL) cholesterol without a significant decrease in high-density lipoprotein (HDL) cholesterol (Chan, J., *et al.,* 1991; Jenkins, D.J.A., 1999). Cardiovascular disease which includes several diseases (like coronary heart disease, stroke) is one of the leading causes of death in North America (Heart and Stroke Foundation of Canada 2003).

Experiments revealed no effect of linseed oil on blood total cholesterol and LDL-cholesterol levels (Layne, K. S., *et al.,* 1996; Sanders T.B.A. and Roshanai F., 1983). However, studies conducted on rats suggest that the diets rich in ALA from flax seed have been shown to decrease blood cholesterol and triacylglycerol levels (Kim, H. and H. Choi, 2005; Vijaimohan, K., *et al.,* 2006) and also in some human population (Chan, J., *et al.,* 1991). The high mucilaginous soluble fiber content of flaxseed has been utilized in the cure of hyperglycemia and hypercholesterolemia in humans (Richard, S. and L. U. Thompson, 1997).

Flax helps reduce cardiovascular diseases by altering the ω-3 fatty acid content of cell membranes by improving blood lipids and endothelial function and also by exerting antioxidant effects (Bloedon, L.T. and P. O. Szapary, 2004). The advantageous effects of flax in human health cited in previous studies were achieved with intakes of 2-5 tablespoon of milled flax which provides 4-11 g of ALA or 1-3 tablespoon of flax oil which provides 3-20 g of ALA in daily diet.

Data derived from animal trials on the effects of flax on breast cancer suggest that the main nutritional components of flax interfere with tumor initiation and promotion. By altering estrogen metabolism and decreasing cell proliferation, flax favorably affected breast cancer risk (Hutchins, A.M., *et al.,* 2000; Thompson, L. U., *et al.,* 2005). Some studies have also suggested that flax may reduce prostate cancer risk by dampening inflammatory reactions (Zhao, G., *et al.,* 2004; Zhao G., *et al.,* 2007). However, there is no any direct evidence of flax contributes to prostate cancer and the data are mainly from animal studies. Indeed, more studies are required in humans.

Lignan act as antioxidants in humans. Flax seed provides 800 times more lignans than any other plant seed (except sesame seeds which has 47 times less lignan than flax seed), thus it is considered as one of the richest sources of plant lignans. On consumption of flax, lignans are converted into phytoestrogenic compounds. Studies have revealed that the chemical release of phytoestrogenic compounds is believed to block the action of hormone sensitive cancers (Morris, H.M., 2007). However, it is reported that the activity of flax lignans depends on the presence of specific bacteria (Clavel T., *et al.,* 1991). It is recommended that eating 2-4 table spoon of flaxseed in daily diet help in preventing the formation of the cancerous tumors.

Flaxseed is also an important source of both soluble and insoluble fibers, which is important for the efficient digestive system. Most of the soluble fiber in flax is mucilage, which serve as an effective cholesterol-lowering agent. It is being utilized by backing of the flaxseed into muffins, bread or can also be added with juice. Studies have reported that insoluble fiber is also helpful in preventing constipation and regulating bowel movements. In Germany, the government has authorized use of linseed for constipation, irritable bowel syndrome and general stomach discomfort (Blumenthal, M., *et al.,* 2000).

Investigation of the functionality of flax is an exciting field of research that holds promise for additional flax products and health benefits (Fitzpatrick, K., 2007).

Flax Fiber and its Uses:

For centuries, flax fiber has occupied a prominent place in textile industry. Flax fiber was used by the pre-historic Lake Dwellers of Switzerland for the production of linen > 5000 years BP. The art of weaving flax fiber to linen may have originated in Egypt because winding-clothes for the bodies of the Pharaohs of Egypt were composed of flax fiber. It was then introduced in India, where, before the use of cotton, linen was worn by many tribes (Richharia, R.H., 1962). The early colonists brought flax for fiber to the United States. With the increased area and production of cotton and invention of cotton gin in USA, the use of flax linen for textile declined.

Flax bast fibers are primarily phloem cells, in which cell wall thickness can reach 10 µm and more (10 to 100 times thicker than other cell types). One of the limitations of flax is the separation of bast fiber from other stem fibers. This was traditionally done by retting; two traditional methods were used commercially to ret flax for industrial grade fibers, water- and dew-retting (Sharma, H.S.S. and C.F. Van Sumere, 1992). Water retting method was discontinued because of the high cost of drying and the pollution from the anaerobic decomposition of flax stem in lakes and rivers. Dew-retting has also limitations including poor quality fiber and is restricted to regions which have appropriate moisture and temperature ranges suitable for retting (Foulk, J.A., *et al.,* 2002).

In the 1980s, several efforts were made to overcome these limitations and to develop a new method known as enzyme-retting, replacing the anaerobic bacteria with enzymes (Van Sumere, C., 1992). Attempts were also being made by United States Department of Agriculture (USDA) to develop an enzyme-retting pilot plant method to replace traditional methods of retting, thus producing flax fibers with specific properties for industrial uses (Foulk, J.A., *et al.,* 2002). Advantages of this new method include reduced retting time, increased yield and fiber consistency and consistency of supply (Foulk, J.A., *et al.,* 2002).

Flax fiber is soft, lustrous and flexible. It is stronger than cotton fiber but less elastic. Fiber obtained from flax is known for its length, strength and fineness; however chemical composition and diameter are also important (Smeder, B. and S. Liljedahl, 1996). In comparison to industrial wood particles, flax particles were characterized by higher length to thickness and length to width ratios and lower bulk density (Papadopoulos, A. N. and J. R. B. Hague, 2003). The best grades are used for linen fabrics such as damasks, lace and sheeting. Coarser grades are used for the manufacturing of twine and rope.

Flax is a source of industrial fibers and, as currently processed, results in long-line and short fibers (Van Sumere, C., 1992). Long line fiber is used in manufacturing high value linen products, while short staple fiber has historically been the waste from long line fiber and used for lower value products like blankets, mats, mattresses and carpets. Flax fiber threads are strong enough for preparation of sewing threads, button threads and shoe threads. Linen is also used in making the highest quality handkerchiefs, bedding, curtains, drapery, cushion covers, wall coverings, towels, other decorative materials and materials for suits and traditional dresses in Asia (Gill, K.S., 1987). It can also be used for manufacturing composites such as particleboard (Papadopoulos, A. N. and J. R. B. Hague, 2003). Flax fibers are also becoming an integral part of new composite materials utilized in automobile and constructive industry. Biocomposites made up from the flax fiber based on polyhydroxybutyrate (PHB) polymer could be an eco-friendly and biodegradable alternative to conventional plastics (Wrobel, M., *et al.,* 2004).

After extraction of bast fiber from flax stem, 80% of the remains fiber can be separated mechanically. This material can be converted into pulp and can be used for manufacturing papers. Flax fiber is also a raw material for the paper industry for the use of printed banknotes and paper for cigarettes. There are several advantages of using flax fibers for industrial applications. It is a biodegradable, renewable raw material, nonabrasive. However, for technical uses, the mechanical properties like tensile strength, elastic modules it may not be suitable (Smeder, B. and S. Liljedahl, 1996; Wedler, M., and R. Kohler, 1994). The relation between the cost of production and the comparative advantages of the fiber may limit the use of flax in large scale applications.

Flax as an Animal Feed:

Flax is integrated into animal rations in several forms; whole seed, oil supplements, hulls, or as meal. Meal, known as LSOM or linseed cake in Europe and Asia, respectively, is the residue after the extraction of oil from seeds. This valuable feed product can be used to supplement the diets of both ruminants and non-ruminants.

The quantity of hull in flax seed meal is about 38%, twice the level in canola or soybean meals ()Agriculture and Agri-Food Canada, 1997. The fine fraction obtained as a byproduct of dehulling (a process of preparing flaxseed for value added industrial products) could be a potential ingredient in pet food; whereas the medium and mix fractions can be blended into poultry feed formulations (Oomah, D. B. and G. Mazza, 1998). Flax seed oil is also used in mixed pet diets, including dogs, cats and horses. The essential fatty acids (ALA and LA) present in flax seed contribute to a lustrous coat, help prevent dry skin and dandruff, and also help in reducing digestive and skin problems in animals.

The ω-3 enriched eggs are produced by increasing ground flax seed to 10-20% of the diet of laying hens. Eggs produced from this diet formula would be ten times higher in ω-3 fatty acids than conventional eggs (Canadian Egg Marketing Agency, 2007) (Table 1). A single ω-3 enriched egg provides half of the optimal daily intake of ALA and about one quarter of EPA and DHA (de Lorgeril, M., *et al.,* 1999).

Flax for Industrial Use:

Industrial applications are possible because an average Canadian flax cultivar contains 57% α-linolenic acid (18:3 C Δ (Canadian Egg Marketing Agency, 2007; de Lorgeril, M., *et al.,* 1999; Foulk, J.A., *et al.,* 2002)). When this flax oil is exposed to air, the double bonds of ALA react with oxygen and result in relatively soft, durable film. This property is known as "drying" quality of linseed oil, is responsible for extensive use in manufacturing varnishes, oilcloth, printer's ink, imitation leather and also as an anti-spalling and curing agent for concrete surfaces on highways (Rowland, G. G., *et al.,* 1995). The drying quality of oil can be improved by addition of metal catalyst to promote oxidation and also by partially pre-oxidizing oil through exposure to the air. Along with the use of flax oil as an oil paint carrier, it is also being used as a painting medium, making oil paints more fluid, transparent and glossy. Linseed oil can also be used as "finishing oil" for wooden furniture to prevent it from denting. It does not cover the surface of wood but soaks into the pores, leaving a shiny but not glossy surface. It is used by billiards/pool cue manufacturers on the shaft portion of the cue.

Linseed oil is the most important raw material used to make the flooring from linoleum. In the process of linoleum manufacturing, oxidized linseed oil is mixed with rosin and other raw material to form linoleum granules, which are pressed onto a jute backing, making linoleum sheets (Green floors linoleum flooring. Linoleum flooring. Accessed: April 23, 2008). This natural material made from a sustainable resource is long lasting and attractive.

Flax seed mucilage has emulsifying properties better than Tween 80 and gum Arabic and has potential industrial uses (Minker, E., *et al.,* 1973). Dehulling of flax seed is also an important process for preparing value added industrial products. To obtain low and high protein products, the attempts have been made to remove flax seed hydrocolloidal gum with dry dehulling of seeds (Dev, D. K. and E. Quensel, 1988). The hull fraction obtained through this process can be used as a raw material for the extraction of phytochemicals (Oomah, D. B. and G. Mazza, 1998).

Conclusion:

An oil seed cum fiber crop, flax (*Linum usitatissimum* L.) has been used by humans from more than 6000 years and it is among the first plants domesticated. The utilization of flax for various purposes including industry, nutraceutical, bio- pharmaceutical, fiber, animal feed and human food is continuing to develop. Increasing cost of artificial fibers and the advantages of natural flax fiber, new technology and equipments for growing, harvesting of flax is useful to make flax a model plant species. New improved methods of retting flax, more efficient processes at each stage of linen manufacture point towards a possible upturn of the utilization of flax fiber than its current limited use, especially in North America. There is a demand for alternative sources of VLCPUFA and the possibility of obtaining them from higher plants in commercial quantity is particularly attractive. As no oil-seed species produces such products naturally, genetically engineering would be required to synthesize these fatty acids. Because flax already contains the precursor to VLCPUFA and the highest value of ALA, it may be a choice platform species. Linoleum and other flax based materials such as linen will become increasingly popular as governments and consumers turn to products with smaller environmental footprints. There are also opportunities for production of sustainable bio-products and green building materials. The molecular and gene expression experiments are not widely studied in flax, which may also expand the applications and uses of flax in future.

Several constrains must be overcome to facilitate the further development of flax and flax bioproducts. Because flax is a minor crop, it has not received significant research resources compared to other North American oilseeds such as canola and soybean. While flax can be easily transformed, (McHughen, A., 2002; McHughen, A. and F. A. Holm, 1995; McHughen, A. and F. A. Holm, 1995) and herbicide resistant traits have been developed to increase the agronomic yield of flax, constraints in the European market for transgenic LSO meal effectively block this pathway of crop improvement and economic enhancement (McHughen, A., 1995). The public sector remains the primary contributor to flax breeding and research because the lack of commercial prospects limits the interest of the private sector. Currently, a lack of basic knowledge of flax genomics, and a concerted effort in flax breeding limits rapid development of flax for bioproducts.

ACKNOWLEDGMENTS

This study was financially supported by Alberta Ingenuity Scholarship Fund, Alberta Innovation and Science and Alberta Agriculture and Rural Development, Canada. We wish to express our thanks to Debby Topinka for her excellent technical assistance to prepare this manuscript.

REFERENCES

Agriculture and Agri-Food Canada, 1997. Flaxseed: Situation and outlook, bi-weekly bulletin, Market Analysis Division, Policy Branch, Agriculture and Agri-Food Canada, 10: 22, Winnipeg, MB.

Allaby, R.G., G.W. Peterson, D.A. Merriwether and Y.B. Fu, 2005. Evidence of the domestication history of flax (*Linum usitatissimum* L.) from genetic diversity of the *sad2* locus. Theor. Appl. Genet., 112(1): 58-65.

Allman-Farinelli, M.A., D. Hall, K. Kingham, D. Pang, P. Petocz and E.J. Favaloro, 1999. Comparison of the effects of two low fat diets with different α-linolenic:linoleic acid ratios on coagulation and fibrinolysis. Atherosclerosis, 142(1): 159-168.

Berglund, D.R., 2002. Flax: New uses and demands. In: Janick,J. and A. Whipkey (eds.), Trends in New Crops and New Uses. ASHS Press, Alexandria, VA, USA, pp: 358-360.

Bhathena, S.J., A.A. Ali, A.I. Mohamed, C.T. Hansen and M.T. Velasquez, 2002. Differential effects of dietary flaxseed protein and soy protein on plasma triglyceride and uric acid levels in animal models. J. Nutr. Biochem., 13(11): 684-689.

Bloedon, L.T. and P.O. Szapary, 2004. Flaxseed and cardiovascular risk. Nutr. Rev., 62: 18-27.

Blumenthal, M., A. Goldberg and J. Brinckmann (eds), 2000, Herbal Medicine: Expanded Commission E Monographs, American Botanical Council, Austin, TX, USA, pp: 85.

Cahoon, E.B., 2003. Genetic enhancement of soybean oil for industrial uses: Prospects and challenges. AgBioForum, 6: 11-13.

Canadian Egg Marketing Agency, 2007. Omega-3 enriched eggs. Canadian Egg Marketing Agency, Accessed: April 28, 2008. http://www.eggs.ca/pdf/omega-3_e.pdf.

Chan, J., V. Bruce and B. McDonald, 1991. Dietary alpha-linolenic acid is as effective as oleic acid and linoleic acid in lowering blood cholesterol in normolipidemic men. Am. J. Clin. Nutr., 53(5): 1230-1234.

Clavel, T., D. Borrmann, A. Braune, J. Dore and M. Blaut, 1991. Occurrence and activity of human intestinal bacteria involved in the conversion of dietary lignans. Am. J. Clin. Nutr., 53: 1230-1234.

de Lorgeril, M., P. Salen, J.L. Martin, I. Monjaud, J. Delaye and N. Mamelle, 1999. Mediterranean diet, traditional risk factors, and the rate of cardiovascular complications after myocardial infarction: Final report of the Lyon Diet Heart Study. Circulation, 99: 779-785.

Dev, D.K. and E. Quensel, 1988. Preparation and functional properties of linseed protein products containing differing levels of mucilage. J. Food Sci., 53: 1834-1837.

Fitzpatrick, K., 2007. Innovation in western Canadian functional food. Cereal Foods World, 52: 289-290.

Foulk, J.A., D.E. Akin and R.B. Dodd, 2002. Flax fiber: Potential for a new crop in the southeast. In: Janick,J. and A. Whipkey (eds.), Trends in New Crops and New Uses. ASHS Press, Alexandria, VA, USA, pp: 361-370.

Gill, K.S., 1987. Linseed. Indian Council of Agricultural Research, New Delhi, India, pp. 386.

Green floors linoleum flooring. Linoleum flooring. Accessed: April 23, 2008. http://www.greenfloors.com/HP_Linoleum_Table_Insert.htm.

Green, A.G. and D.R. Marshall, 1984. Isolation of induced mutants in linseed (*Linum usitatissimum* L.) having reduced linolenic acid content. Euphytica, 33: 321-328.

Heart and Stroke Foundation of Canada, 2003. The growing burden of heart disease and stroke in Canada 2003. Accessed: May 14, 2008. http://ww2.heartandstroke.ca/Page.asp?PageID=1613&ContentID=10564&ContentTypeID=1.

Hutchins, A.M., M.C. Martini, B.A. Olson, W. Thomas and J.L. Slavin, 2000. Flaxseed influences urinary lignan excretion in a dose-dependent manner in post menopausal women. Cancer Epidemiol. Biomarkers Prev., 9: 1113-1118.

Jenkins, D.J.A., C.W.C. Kendall, E. Vidgen, S. Agarwal, A.V. Rao and R.S. Rosenberg, 1999. Health aspects of partially defatted flaxseed, including effects on serum lipids, oxidative measures, and ex vivo androgen and progestin activity: a controlled crossover trial. Am. J. Clin. Nutr., 69(3): 395-402.

Kim, H. and H. Choi, 2005. Stimulation of acyl-coA oxidase by α-linolenic acid rich parilla oil lowers plasma tricylglycerol level in rats. Life Sci., 77: 1293-1306.

Kinsella, J.E., B. Lokesh, S. Broughton and J. Whelan, 1990. Dietary polyunsaturated fatty acids and eicosanoids: Potential effects on the modulation of inflammatory and immune cells: An overview. Nutrition, 6: 24-44.

Lay, C.L. and C.D. Dybing, 1989. Linseed. In: Robbelen,G., R. K. Downey and A. Ashri (eds.), Oil Crops of the World. McGraw-Hill, New York, USA, pp: 416-430.

Layne, K.S., Y.K. Goh, J.A. Jumpsen, E.A. Ryan, P. Chow and M.T. Clandinin, 1996. Normal subjects consuming physiological levels of 18:3(n-3) and 20:5(n-3) from flaxseed or fish oils have characteristic differences in plasma lipid and lipoprotein fatty acid levels. J. Nutr., 126(9): 2130-2140.

Linnaeus, C., 1857. Species Plantarum. The Royal Society of London, London, UK, pp: 300.

McHughen, A., 2002. Transgenic linseed flax. Marcel Dekker, Inc., New York, USA, pp: 899.

McHughen, A., 1995. Just the flax. Bio-Technology, 13(9): 926-926.

McHughen, A. and F.A. Holm, 1995. Development and preliminary field testing of a glufosinate-ammonium tolerant transgenic flax. Can. J. Plant Sci., 75(1): 117-120.

McHughen, A. and F.A. Holm, 1995. Transgenic flax with environmentally and agronomically sustainable attributes. Transgenic Res., 4(1): 3-11.

Millam, S., O. Bohus and P. Anna, 2005. Plant cell and biotechnology studies in *Linum usitatissimum* - A review. Plant Cell Tissue Organ Cult., 82: 93-103.

Minker, E., S.V. Bogdanova and I. Penovak, 1973. Linseed mucilage as a water in oil-type emulsifier. Farmatsiva (Sofya), 23: 13.

Morris, H.M., 2007. Flax: A health and nutrition primer. Flax Council of Canada, Winnipeg, Canada, pp: 140.

Nelson, G.J. and J.G. Chamberlain, 1995. The effect of α-linolenic acid on blood lipids and lipoproteins in humans. In: Cunnane,S. C. and L. U. Thompson (eds.), Flaxseed in Human Nutrition. AOCS Press, Champaign, IL, USA, pp: 187-206.

Neuringer, M. and W.E. Connor, 1986. n-3 fatty acids in the brain and retina: evidence for their essentiality. Nutr. Rev., 44: 285-294.

Oomah, D.B. and G. Mazza, 1998. Fractionation of flaxseed with a batch dehuller. Ind. Crop Prod., 9: 19-27.

Papadopoulos, A.N. and J.R.B. Hague, 2003. The potential for using flax (*Linum usitatissimum* L.) shiv as a lignocellulosic raw material for particleboard. Ind. Crop Prod., 17: 143-147.

Paschos, G.K., F. Magkos, D.B. Panagiotakos, V. Votteas and A. Zampelas, 2007. Dietary supplementation with flaxseed oil lowers blood pressure in dyslipidaemic patients. Eur. J. Clin. Nutr., 61: 1201-1206.

Paschos, G.K., N. Yiannakouris, L.S. Rallidis, I. Davies and B.A. Griffin, 2005. Apolipoprotein E genotype in dyslipidemic patients and response of blood lipids and inflammatory markers to alpha-linolenic acid. Angiology, 56: 49-60.

Prasad, K., 1997. Dietary flax seed in prevention of hypercholesterolemic atherosclerosis. Atherosclerosis, 132: 69-76.

Richard, S. and L.U. Thompson, 1997. Health effects of flaxseed mucilage, lignans. International News on Fats, Oils and Related Materials (INF), 8: 860-865.

Richharia, R.H., 1962. Linseed. The Indian Central Oiseeds Committee, Hyderabad, India, pp. 155.

Rowland, G.G., 1991. An EMS-induced low-linolenic acid mutant in McGregor flax (*Linum usitatissimum* L.). Can J. Plant Sci., 71: 393-396.

Rowland, G.G., A. McHughen, R.S. Bhatty, S.L. Mackenzie and D.C. Taylor, 1995. The application of chemical mutagenesis and biotechnology to the modification of linseed (*Linum usitatissimum* L.). Euphytica, 85(1-3): 317-321.

Sanders, T.B.A. and F. Roshanai, 1983. The influence of different types of ω-3 polyunsaturated fatty acids on blood lipids and platelet function in healthy volunteers. Clin. Sci., 64: 91-99.

Scarth R. and J. Tang, 2006. Modification of *Brassica* oil using conventional and transgenic approaches. Crop Sci., 46: 1225-1236.

Scientific Review Committee, 1990. Nutrition recommendations. Minister of National Health and Welfare, Ottawa, ON, Canada.

Sharma, H.S.S. and C.F. Van Sumere, 1992. Enzyme treatment of flax. Genetic Eng. Biotechnol., 12: 19-23.

Smeder, B. and S. Liljedahl, 1996. Market oriented identification of important properties in developing flax fibers for technical uses. Ind. Crop Prod., 5: 149-162.

Smith, H.V. and J. Jimmerson, 2005. Briefing. Agricultural Marketing Policy Center, Montana State University, MO, USA. Accessed: June 18, 2006. http://www.ampc.montana.edu/briefings/briefing56.pdf.

Statistics Canada, 2006. Production data of field and specialty crops. Accessed: February 17, 2007. http://www40.statcan.ca/l01/cst01/prim11b.htm.

Thompson, L.U., J.M. Chen, T. Li, W.K. Straaser and P.E. Goss, 2005. Dietary flaxseed alters tumor biological markers in post menopausal breast cancer. Clin. Cancer Res., 11: 3828-3835.

Uauy, R., P. Perano, D. Hoffman, P. Mena, D. Birch and E. Birch, 1996. Role of essential fatty acids in the function of the developing nervous system. Lipids, Suppl.: S167-S176.

Van Sumere, C., 1992. Retting of flax with special reference to enzyme-retting. In: Sharma,H. and C. Van Sumere (eds.), The Biology and Processing of Flax. M Publications, Belfast, Northern Ireland, pp: 157-198.

Vijaimohan, K., M. Jainu, K.E. Sabitha, S. Subramaniyam, C. Anandhan and C.S. Shyamala Devi, 2006. Beneficial effects of alpha linolenic acid rich flaxseed oil on growth performance and hepatic cholesterol metabolism in high fat diet fed rats. Life Sci., 79(5): 448-454.

Vromans, J., 2006. Molecular genetic studies in flax (*Linum usitatissimum* L.). Wageningen University, Wageningen, The Netherlands, pp: 22-39.

Wedler, M. and R. Kohler, 1994. Non-textile use of flax, In: Flax in the world, FAO, Bonn, Germany, pp: 53-56 .

Wrobel, M., J. Zebrowski and J. Szopa, 2004. Polyhydroxybutyrate synthesis in transgenic flax. J. Biotech., 107: 41-54.

Yamazaki, K., M. Fujikava, T. Hamazaki, S. Yano and T. Shono, 1992. Comparison of the conversion rate of α-linolenic acid (18:3n-3) and stearidonic acid (18:4n-3) to longer polyunsaturated fatty acids in rats. Biochem. Biophys. Acta, 1123: 18-26.

Yokoo, E.M., J.G. Valente, L. Grattan, S.L. Schmidt, I. Platt and E.K. Silbergeld, 2003. Low level methylmercury exposure affects neuropsychological function in adults. Environmental Health: A global access science source. Accessed: April 25, 2008. http://www.ehjournal.net/content/pdf/1476-069X-2-8.pdf.

Zhao, G., T.D. Etherton, K.R. Martin, S.G. West, P.J. Gillies and K.M. Etherton, 2004. Dietary α-linolenic acid reduces inflammatory and lipid cardiovascular risk factors in hypercholesterolemic men and women. J. Nutr., 134: 2991-2997.

Zhao, G., T.D. Etherton, K.R. Martin, P.J. Gillies, S.G. West and P.M. Kris-Etherton, 2007. Dietary α-linolenic acid inhibits proinflammatory cytokine production by peripheral blood mononuclear cells in hypercholesterolemic subjects. Am. J. Clin. Nutr., 85(2): 385-391.