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FOOD AND FEED RESEARCH

Journal of the Institute of Food Technology – FINS
University of Novi Sad

ISSN:
2217-5369 (print),
2217-5660 (online)

UDK 636.085:633.521:665.12

DOI: 10.5937/ffr49-35420

Review article

A COMPREHENSIVE REVIEW ON RECENT NOVEL FOOD AND INDUSTRIAL APPLICATIONS OF FLAXSEED: 2014 ONWARDS

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Abstract: Flaxseed or linseed is an oilseed obtained from a plant, known as the flax (*Linum usitatissimum*). It is a valuable source of various bioactive components such as omega-3 polyunsaturated fatty acids, proteins, lignans, dietary fibres and phytochemicals. The *in-vivo*, *in-vitro* studies and research on human subjects and in animal models, conducted throughout the globe, on health benefits associated with the consumption of various forms of flaxseed are discussed in this review. It provides an insight into recent developments and potential applications of flaxseeds in the form of whole seeds, meals, flour or oil in an array of food and feed products and non-food industrial applications. The details about novel health benefits associated with flaxseeds and information related to commercially available flaxseed-based i.e. enriched products are also the salient feature of the review. Here, we have provided the state of the art of most recent comprehensive information post the first detailed review on flaxseed as a modern food released in 2014.

Key words: *Omega-3 fatty acids; in-vivo studies; food applications; feed applications; commercial products*

INTRODUCTION

Linum usitatiissimum is the botanical name of flaxseed and it belongs to Linaceae family (Shim, Gui, Wang & Reaney, 2015). Worldwide, flaxseed is acknowledged for being a well-known richest plant source of omega-3 fatty acids (ω-3 FA) having alpha-linolenic acid (ALA, 18:3) which contributes 39.00 to 60.42% of total fatty acids (comprising of polyunsaturated fatty acid (PUFA) 73%, monounsaturated fatty acids (MUFA) 18% and saturated fatty acids (SFA) 9%) followed by oleic (18:1n-9) 13.44-19.39%, linoleic (18:2n-6) 12.25-17.44%, palmitic (16:0) 4.90-8.00% and stearic acids (18:0) 2.24-4.59%. Higher intake of omega-6 fatty acids (ω-6 FA) rich vegetable oils like sun-flower, soybean and groundnut oil in a diet results in disruption of ω-6/ω-3 FA metabolic homeostasis. Also, it increases the risk of inflammatory disorders and cardiovascular diseases (CVDs). According to World Health Organization (WHO) 2021 report, 17.9 million people died due to cardiovascular diseases in 2019, representing 32% of all global deaths.

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Therefore, it is important to have an adequate ratio of ω-6/ω-3 FAs to get the maximum benefits to the health. The Institute of Medicine (IOM) 2002 and Food and Agriculture Organization (FAO)/WHO 2008 preferred ω-6/ω-3 FAs ratio to 5:1. The dietary recommendations for ALA have been set to attain nutrient adequacy that helps to prevent deficiency associated with ω-3 FA. The adequate intake (an intake related to a low prevalence of inadequacy) of ALA by different organizations/authorities is given in Table 1 (Gebauer, Psota, Harris & Kris-Etherton, 2006; Sioen et al., 2017; ICMR-NIN, 2020). However, other than ALA, flaxseed also contains lignans, proteins and dietary fibres and is being considered an abundant source of bioactive components. Secoisolariciresinol diglucoside is the main lignan present in flaxseeds, while secoisolariciresinol and matairesinol are also present in small amounts (Herchi et al., 2014). Flaxseed contains 20-30% protein, consisting of about 80% globulins (linin and conlinin) and 20% glutelin (Hall, Tulbek & Xu, 2006). The protein present in flaxseed is not considered a complete protein due to the presence of low levels of lysine which is considered the limiting amino acid (Chung, Lei & Li-Chan, 2005). Although flaxseed is rich in glutamic acid/ glutamine, arginine, branched-chain amino acids like valine and leucine and aromatic amino acid such as tyrosine and phenylalanine (Oomah & Mazza, 1993).

A daily intake of 10 g of flaxseed in diet accounts for the consumption of 1 g and 3 g of soluble and insoluble fibres, respectively. About 30 g of flaxseed portion is required to meet 7 to 30% of the recommended dietary allowances (RDA) for minerals such as

Table 1.
Recommendations for ALA intake according to national and international organizations/ authorities

Organization/Authority (Year)	**Recommended daily alpha-linolenic (ALA) intake values for different targeted age groups (years)**							
	Infants	**Children**	**Girls**	**Boys**	**Men**	**Women**	**Pregnant women**	**Lactating women**
NATO (1989)	3 g/d							
Eurodiet, Bulgaria (2000)	1.6 g/d							
APC, France (2001)	1.8 g/d							
US National Academics of Science, IOM, USA (2002)	0.5 g/d (0-1)	0.7 -0.9 g/d (1-8)	1-1.1 g/d (9-18)	1.2-1.6 g/d (9-18)	1.6 g/d (19 +)	1.1 g/d (19 +)	1.4 g/d	1.3 g/d
ISSFAL (2004)	1.6 g/d							
FAO/WHO (2008)	0.2-0.3 E% (0-0.5)	0.4-0.6 E% < 3 E% Upper-ADMR (0.5-2)	> 0.5 E% Lower –ADMR (2-4, 4-6, 6-10, 10-18, 19+)					
EFSA, Europe (2010)	0.5 E%							
ANSES, France (2011)	0.5 E% (0-0.5)	1 E%						
AECOSAN, Spain (2014)	2 g/d (> 2 and 19+)							
ICMR-NIN, India (2020)	0.5-1 E%							

Note: Figures in brackets indicate year for each of the age groups
NATO- North Atlantic Treaty Organization, APC- Apports Nutritionnels Conseilles, IOM, USA-Institute of Medicine, United States of America, ISSFAL- International Society for the study of Fatty Acids and Lipids, E%-Energy percentage as acceptable macronutrient distribution range (ADMR), *EFSA- European Food Safety Authority, ANSES- French Agency for Food, Environmental and Occupational Health and Safety, AECOSAN- Spanish Agency for Food Safety and Nutrition, ICAR-NIN- Indian Council of Medical Research, National Institute of Nutrition*

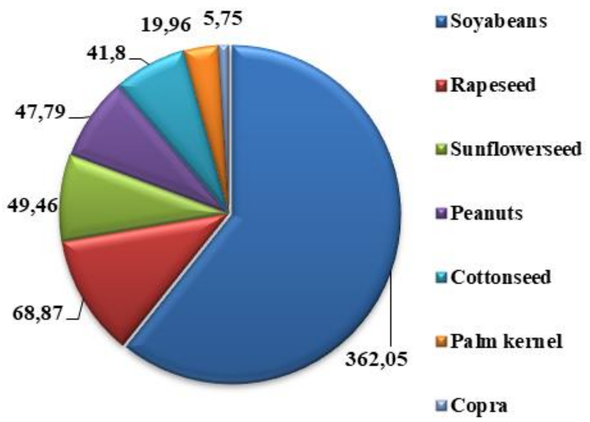
calcium, phosphorus and magnesium (Bozan & Temelli, 2008). The RDA values for calcium, phosphorus and magnesium for Indians as proposed by ICMR-NIN (2020) are 1000 mg/d, 1000 mg/d and 370 mg/d for adults, respectively.

The whole and milled flaxseed hold “Generally Recognized as Safe (GRAS)” status, therefore food manufacturers use flaxseed in the formulation of various food products (Flax Focus, 2015). One tablespoon of milled flaxseed provides 1.8 g ALA which is good enough to fulfil adequate intake of ALA for adults, whereas one tablespoon of flaxseed oil provides 8 g ALA and half a teaspoon of flaxseed oil provides 1.3 g ALA which is more sufficient to meet adequate intake of ALA (IOM, 2002). According to the Food Safety and Standards Authority of India, the permitted range for the usage of flaxseed and its oil for adults is 10-20 g/day and 10-20 ml/day, respectively. However, for 5-16 years old children and between 1-5 years aged children, the permitted range of usage is ½ and ¼ of the permitted range of usage for adults, respectively (FSSR, 2016). As per the Labelling Standards for Food (Korean Food system) labels of products containing flaxseed (excluding flaxseed oil) are required to include the statement *“Be cautious in taking flaxseed as the total daily intake amount shall not exceed 16 g and 1 serving size shall not exceed 4 g”* (Chung & Olson, 2022). Owing to these benefits flaxseed or its components are utilized as an ingredient in many dairies, bakeries, meat, extruded snacks, etc. i.e. food products with a vast array of reported nutritional and health benefits which are reviewed in subsequent sections.

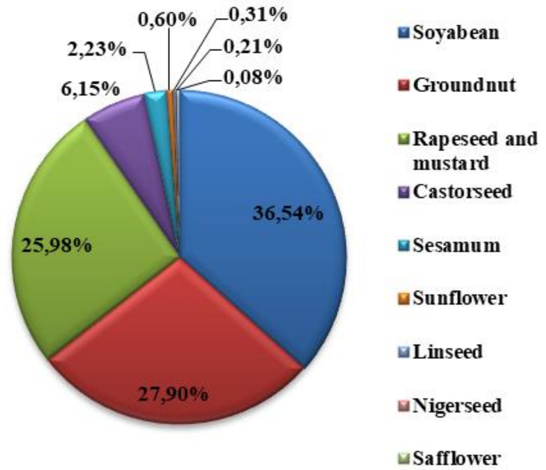
FLAXSEED PRODUCTION

Global oilseed production for the year 2020/21 is given in Figure 1a. Soybean is still the leading oilseed produced in the world followed by rapeseed, sunflower seed, peanuts, cottonseed, palm kernel and copra. In India, the total production (in terms of volume) of nine oilseeds: soybean, groundnut, rapeseed, mustard, castor seed, sesame, sunflower, linseed, niger seed and safflower was 33501 thousand metric tons in the year 2020 (Figure 1b). Out of these, flaxseed represented a mere 0.31% of the volume of oilseeds produced in India (Statista, 2021).

In 2018, the global market size of flaxseeds was USD 423.3 million and is expected to increase at a compound annual growth rate (CAGR) of 12.7% in 2019-2025 (Flaxseed Market Size & Share, 2019). The worldwide production of flaxseed was 3,068.254 tonnes in 2019, while India produced 103 thousand metric tons contributing close to 3.23% (99,070 tonnes) to the world.



a) Global oilseed in million metric tons



b) Share of oilseeds in India

Figure 1. Status of oilseed production

Figure 2 represents the world's ten major flaxseed producing countries for the year 2019 (FAOSTAT, 2019). The main reason behind this market growth of flaxseed is increasing awareness of the health benefits derived from flaxseed and its components. Flaxseeds are available mainly in two types based on their colour, brown and yellow (golden). Brown-seeded flaxseed is rich in ALA while yellow flaxseed varieties are two types: 1) omega (US developed variety) which is also high in ALA, similarly to brown flaxseed; and 2) solin (Europe developed variety) which is low in ALA (Morris, 2007).

NUTRITIONAL AND HEALTH CLAIMS RELATED TO THE CONSUMPTION OF FLAXSEEDS

Depending upon the cultivar and cultivation conditions, flaxseed contains 40-50% oil besides other components like protein (23-34%), ash (4%), fibre mucilage (5%) and lignans that are 9-30 mg/g of a defatted meal (Muir & Westcott, 2003). Flaxseeds are nutrient-rich oilseed and their detailed nutritive values per 100 g of flaxseed (on a dry matter) as given by the United States Department of Agriculture (USDA) National Nutrient Database (USDA, 2019) are presented in Fig. 3. Flaxseed is one of the best sources of plant-based ω-3 FA (ALA), phytoestrogen (lignan) and fibres. The application of flaxseed or its components in food products is associated with several health benefits such as lipid modulating properties, drop in the chances of occurrence of cardiovascular diseases and cancer, improvement in gastrointestinal health and brain function owing to anti-oxidative and anti-inflammatory activities of flaxseed components. Besides this, flaxseed contains phenols, proteins, antioxidants, flavonoids and sterols (Akter et al., 2021). Flaxseed lignans are the phytoestrogens which means that these are plant compounds that show estrogen-like biological activity and their intake offers in preventing age-related bone loss, postmenopausal osteoporosis, CVDs, etc (Arjmandi, 2001; Coelingh Bennink, Heegaard, Visser, Holinka & Christiansen, 2008).

Some researchers have carried out *in vitro* and *in vivo* studies and investigations on human subjects to understand the mechanism of and prove the claimed health benefits associated with flaxseed. The effect of flaxseed oil was investigated on four different human breast cancer cells, MCF-7, BT-474, MDA-MB-231 and MDA-MB-468, by incubating with 75 µM ALA and 1 nM 17-β estradiol for 24 h. However, MDA-MB-231 cells were also analysed after an incubation period of 6 h and 12 h. It was observed that all cells showed a reduction in their growth (highest reduction achieved i.e. 22.5% in MDA-MB-231 cells, while MCF-7 cells had less reduction i.e. 17.9%) with improved apoptosis (Wiggins, Mason & Thompson, 2015). *In-vitro* model studies were carried out by exposure of human umbilical vein endothelial cell to 100 ng/mL lipopolysaccharide from *Escherichia coli* O111:B4 along with 55.6 mg/L flaxseed oil or 55.6 mg/L ALA for 24 h. The exposure to 55.6 mg/L ALA resulted in higher inhibition of inflammatory responses such as soluble intercellular cell adhesion molecule-1, and soluble vascular cell adhesion molecule 1 compared to flaxseed oil (Shen et al., 2018). Another study was carried out for treating the cancer cell lines with media containing flaxseed oil (0.30% and 0.90% v/v). The interesting revelation of the study was that after four days of treatment with 0.3% v/v flaxseed oil, a decrease in the growth of MCF-7 breast cancer cells by 75% was observed, whereas a 99% reduction of MCF-7 cells was achieved using 0.9% v/v flaxseed oil and also disrupted mitochondrial function in B16-BL6 (murine melanoma) and MCF-7 cells was noted (Buckner, Buckner, Montaut & Lafrenie, 2019).

A study investigated by Mosavat et al. (2018) on human subjects i.e. men and women (age 40 -70 years) having body mass index (BMI) less than 35, knee osteoarthritis of grade 1 or more, based on Kellgren and Lawrence classification, and pain intensity of grade 4 or more on a 10 point visual analogue scale for minimum 4 months. These patients were made to rub 20 drops of linseed oil on the knees every 8 hours for 6 weeks. After 6 weeks, the knee pain scores were improved significantly, which were assessed using knee injury and osteoarthritis outcome score questionnaires such as scores for visual analogue scale, activities of daily living, sport and recreation and knee-related quality life and found improved scores compared to the placebo group in which liquid paraffin was used in place of linseed oil. Ahmadniay Motlagh, Aalipanah, Mazidi and Faghih (2021) studied the effect of milled flaxseed on obesity. The researchers provided 30 g of milled flaxseed in a balanced diet per day to the obese women for 12 weeks. After 12 weeks, a significant reduction in waist circumference and waist to hip ratio and increased adiposity markers, like adiponectin level to 17.15 from 12.11, was observed. However, there was no change in levels of serum lipids.

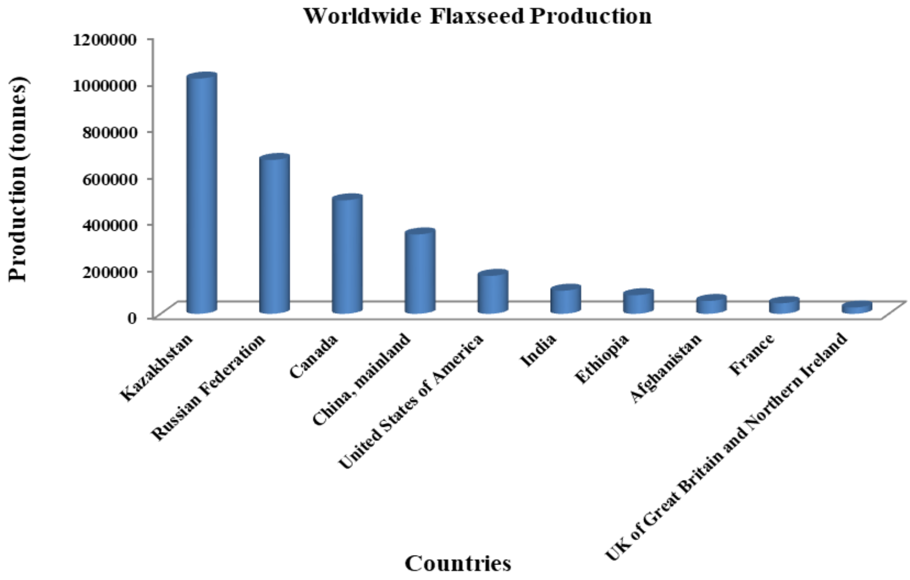


Figure 2. World's major flaxseed producing countries

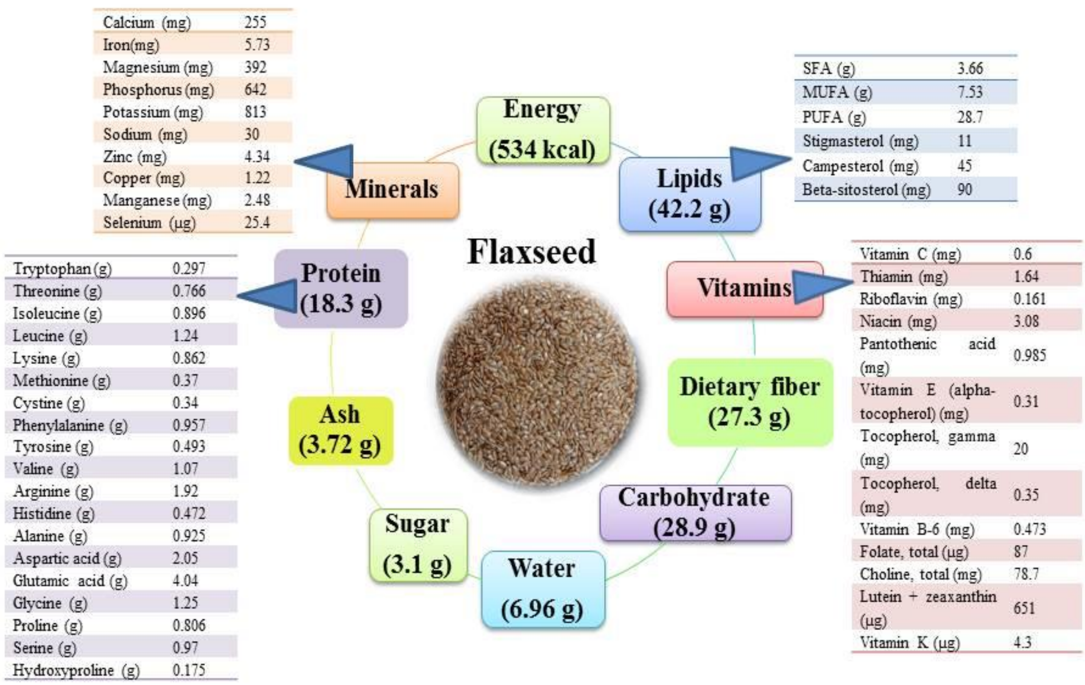


Figure 3. Detailed composition of nutrients in flaxseed (values per 100 g dry basis)

Table 2.
Studies conducted for specific health benefits of flaxseed and its components

Flaxseed component	Experimental model system	Dose	Treatment duration	Reported health effects	Reference
1. Cardiovascular diseases					
Flaxseed oil	Rats (Wistar Strain male albino)	250 and 500 mg/kg body weight along with arsenic trioxide (As_2O_3) of 4 mg/kg body weight	45 days	▪ ↓ Arsenic accumulation, level of cardiac marker enzymes i.e. creatine kinase-MB (43.33 U/L) and lactate dehydrogenase (803.5 IU/L), lipid peroxidation and cardiac structural alterations when treated with 500 mg flaxseed oil/kg body weight in combination with As_2O_3 ▪ ↑ Cardiac glutathione (GSH) content and activities of antioxidant enzymes like tissue catalase (16.03 µ moles of H_2O_2 consumed/min/mg protein), Superoxide dismutase (6.23 U/mg protein), GSH-S-Trasferase (2.71 µM of 1-chloro-2, 4-dinitrobenzene-GSH conjugate formed/min/mg protein) and GSH peroxidase (2.99 µg of GSH consumed/min/mg protein)	Varghese et al. (2017)
Flaxseed oil	Mice (Apolipoprotein-E knockout)	10% w/w in partial replacement of lard in western type lard rich diet	16 weeks	▪ Improved atherosclerosis, oxidative stress (nicotinamide-adenine dinucleotide phosphate oxidase), inflammation (TNF-α, IL-6, monocyte chemo attractant protein -1 and soluble vascular cell adhesion molecule -1) and lipid metabolism (sterol regulatory element binding protein -2, 3-hydroxy-3-methylglutaryl-CoA reductase, sterol regulatory element binding protein -1c, and acetyl-CoA carboxylase) significantly	Han et al. (2018)
2. Kidney diseases					
Flaxseed oil	Rats	15% followed by inducing cisplatin (6 mg/ kg body weight) in 0.9% saline	10 days	▪ Improved resistance to cisplatin produced deleterious effects on serum (creatinine 1.13 mg/dL, cholesterol 42.62 mg/dL, phospholipid 54.33 mg/dL, glucose 36.64 mg/dL, phosphate 3.23 µmol/mL and blood urea nitrogen 26.17 mg/dL) and urine parameters (urine flow rate13.2 ml/day, glucose 65.75 mg/dL, protein 1.78 mg/mmol creatinine, phosphate 0.595 µmol/mL and creatinine clearance 0.097 mL/min/100g body weight)	Naqshbandi, Rizwan & Khan (2013)
Flaxseed oil	Rats (Wistar-Albino male)	500 mg/kg supplementation with cisplatin (3 mg and 5 mg/kg)	10 days	▪ Administration of 3 mg cisplatin/kg with flaxseed oil showed lower creatinine (0.70 mg/dL) and urea (66.05 mg/dL) levels against 5 mg cisplatin which showed 1.40 mg/dL creatinine and 130.82 mg/dL urea ▪ Indicated down regulation in IL 6 and IL 1 β with mild brown immunostain for NF-kB and TNF α by immunohistochemistry	Kheira, El-Sayed, Elsayed & Rizk (2019)
3. Cancer					
Flaxseed oil	Mice	40 g/kg basal diet along with anti-cancer drug (trastuzumab) twice in week at a dose of 1 and 2.5 mg/kg body weight	4 weeks	▪ ↓ Growth of tumour and human epidermal growth factor receptor 2 overexpressing human breast tumours with flaxseed oil and 2.5 mg trastuzumab together	Mason, Fu, Chen & Thompson (2015)
4. Bone					
Ground flaxseed	Ovariectomi-sed rats (Sprague	100 g ground flaxseed/kg diet along with the low dose of estrogen (0.42 µg 17β	2 weeks	▪ Decrease in bone turnover and protection of lumber vertebrae bone microarchitecture.	Sacco, Chen, Ganss, Thompson & Ward (2014)

	Dawley)	estradiol/kg body weight-day)			
Flaxseed oil	Ovariectomised diabetic rats (White albino female)	Diet	8 weeks	▪ ↓ Osteocalcin level (15.38 ng/L), bone resorption marker such as deoxypyridinoline (111.41 nmol mmol) and serum bone construction markers such as insulin growth factor-1 (1369.3 ng/L) in ovariectomised diabetic rats compared to the ovariectomised rats which had 21.25 ng/L, 160.80 nmol mmol and 1470 ng/L, respectively ▪ ↑ Bone mineral density (BMD) and bone mineral content (BMC) to 0.070 g/cm^2 and 0.063 g, respectively	El-Saeed, Elghoroury, Morsy, Aly & Wafaey (2018)
Flaxseed oil	Rats (Sprague Dawley male)	Flaxseed oil substituted all soybean oil and lard in normal control diet to provide 10% of energy to one group and replaced all soybean oil and part of lard in high fat diet to provide 60% of energy to other group (normal diet contained mixture of soybean oil and lard as a source of fat without the presence of flaxseed oil)	22 weeks	▪ Bone resorption marker CTX-1 and ↑ bone formation markers ALP and P1NP in high fat diet group containing flaxseed oil (60% energy) compared to other group. ▪ ↓ Bone loss in high-fat-diet through improving osteoblastic gene and protein function (β catenin, RUNX2, osterix) in rat	Chen et al. (2019)
Flaxseed powder	Rats (Sprague Dawley strain female albino)	Flaxseed powder (30, 50 and 70 g)/kg diet with glucocorticoid (prednisone 100 mg)	8 weeks	▪ ↑ BMD (0.121 g/cm^2), BMC (0.452 g), aspartate aminotransferase and alanine aminotransferase levels in serum (221.50 U/L and ALT 49.33 U/L, respectively) with 70 g flaxseed powder/kg diet	Ragheb, Bahnasy, Abd-Elhady & Saad (2019)
5. Liver					
Flaxseed oil	Mice (male)	Ethanol containing modified Lieber-DeCarli liquid flaxseed oil diet as source of fat	6weeks	▪ Low levels of aspartate aminotransferase (109.7 U/L) and alanine aminotransferase (75.2 U/L) in mice with alcoholic liver disease ▪ ↓ *Proteobacteria* and *Porphyromonadaceae* upon consumption of flaxseed oil in ethanol than consumption of corn oil	Zhang et al. (2017)
Flaxseed oil	Piglet (male)	5% in the diet	21 days	▪ After 21 days of feeding, liver of piglets was damaged by inducing lipopolysaccharide and observed that the expression of IL-6, TNF-α and cycloxygenase 2 decreased and exhibited hepatoprotective effect	Wang et al. (2018)
6. Diabetes					
Flaxseed oil	Diabetic rats (Albino male)	1.2 mL flaxseed oil/kg body weight/day	--	▪ ↓ Insulin resistance of diabetic rats	Hussein et al. (2014)
Flaxseed oil	Human	1000 mg flaxseed oil/day to the diabetic nephropathy patients	12 weeks	▪ ↓ VLDL-cholesterol (-4 mg/dL), serum insulin level (-39.6 pmol/L) and serum triglycerides levels (-19.8 mg/dL) against placebo with 2.5 mg/dL, -7.2 pmol/L and 12.6 mg/dL, respectively ▪ ↑ Quantitative insulin sensitivity check index to 0.01 from 0.002 in placebo group	Soleimani, Taghizadeh, Bahmani, Badroj & Asemi (2017)

Flaxseed oil	Diabetic rats (Sprague Dawley male)	10% w/w in the diet compared to corn oil in the diet	5 weeks	▪ ↓ Levels of fasting blood glucose, plasma lipid (plasma triglyceride, total cholesterol, low density lipoprotein cholesterol), plasma lipopolysaccharide, glycated hemoglobin, TNF-α, IL-6, IL-17A, IL-1β and oxidative indicator (malondialdehyde) upon supplementation of flaxseed oil compared to corn oil in the diet ▪ ↑ Plasma lipid level such as high density lipoprotein cholesterol	Zhu et al. (2020)
7. Inflammatory diseases					
Flaxseed oil	Dogs (female)	100 mL/kg food or 2.4 mL/kg body weight in a diet	3 week	▪ Quantified the expression of 3 genes such as heat shock proteins (HSP90 and HSP70) and IL1β involved in inflammation in the white blood cells of dogs of two breeds i.e. greyhounds and beagles by using real-time polymerase chain reaction ▪ Down-regulated the expression of HSP90 and IL1β in greyhounds ▪ No significant effect was observed on the genes in beagles ▪ HSP70 had no change upon flaxseed oil supplementation in both breeds	Purushothaman, Brown, Vanselow, Quinn & Wu (2014)
Whole flaxseed, defatted flaxseed and flaxseed oil	Mice (male)	Whole flaxseed (10%), defatted flaxseed (6%) and flaxseed oil (4%) to the different groups with diet (45% kcal fat)	8 weeks	▪ ↓ Feed intake after 8 weeks in flaxseed oil group compared to other groups ▪ All groups showed down-regulation for IkBα, IKKβ, NF-kB, Akt2 and IL-6 also assisted in alleviating and preventing low-grade inflammation in obesity by actively working against IKKβ/NF-kB pathway	Mann & Rhee (2021)
8. Vasculopathy					
Flaxseed	Rats (Wistar female)	0.714 g/kg/d	12 weeks	▪ Feeding of flaxseed to the streptozotocin induced diabetic rats indicated phenylephrine induced contractions on isolated aortic rings in the presence of indomethacin, L-nitro arginine methyl ester and superoxide dismutase (SOD) ▪ Provided useful effects on vascular reactivity to phenylephrine changes through nitric oxide and prostaglandin dependent pathways, however in healthy rats flaxseed may have adverse effect possibly through pro-oxidant activity	Tarhan et al. (2021)

Another study was conducted on hypertensive patients (35-70 years old) by administrating 10 and 30 g of flaxseed powder for 12 weeks (Toulabi et al., 2021).

The study indicated that supplementation of 30 g of flaxseed powder reduced the total cholesterol (20.4 units), BMI (0.86), systolic blood pressure (SBP, 13.38 unit) and diastolic blood pressure (DBP, 5.6 unit) compared to the placebo group (total cholesterol 11.86 units, BMI 0.06, SBP 1.72 unit and DBP 2.39 unit).

Supplementation of flaxseed powder (30 g) and hesperidin (1 g) to the non-alcoholic fatty liver disease patients for 12 weeks further resulted in an improved fasting blood glucose (115.23 mg/dL) and lipid metabolism, whereas hepatic steatosis and inflammation such as high-sensitive Creactive protein, tumour necrosis factor (TNF) -α and nuclear factor-kappa B (NF-kB) were reduced (Yari et al., 2021).The recent *in vivo* studies conducted on the health benefits of flaxseed and its components are precisely summarized in Table 2.

APPLICATIONS OF DIFFERENT FORMS OF FLAXSEED

Flaxseed can be incorporated as whole seed, milled/powdered seed, in the form of oil and mucilage in various food products to improve their nutritional profile and subsequently provide health benefits (Fig. 4).

Flaxseed in dairy products

Dairy products are usually considered the most basic food for all ages and are an indispensable part of the human diet showing a high consumption rate. The commonly consumed dairy product includes milk, curd, ice cream, yoghurt, butter, buttermilk, *kulfi* (frozen milk product originating from the Indian subcontinent), etc. Dairy products are rich in protein and fat (around 70% being saturated), but poor in fibres. On the other hand, flaxseeds are an excellent source of PUFA, fibres and lignans. Hence, flaxseed and its components are considered to be excellent ingredients for their incorporation into dairy products for developing nutritious and healthier composite of dairy products. Additionally, since dairy products are perishable in nature and are stored at low

Figure 4. Various applications of flaxseeds

temperatures, therefore, the products fortified with flaxseed are also expected to show good storage stability (in terms of oxidation) as low temperature reduces the rate of oxidation. The following sections provide details of the various forms of flaxseed that are used in dairy products.

Flaxseed powder

Many researchers studied the effect of addition of flaxseed flour as a source of ω-3 FA and dietary fibres in different dairy products. The addition of bioactive components and fibres from acerola pulp (30%) and flaxseed flour (8%) in the whey beverages satisfactorily increased the fibre content to 4.57-5.74 g/100 g, carotenoids to 5.75-6.54 µg β carotene/g, vitamin C to 298.43-305.50 mg/100 g product and global acceptance to 6.5-7 (da Silva, Vinhal, Barcia & Pertuzatti, 2016). Low-calorie chhana balls were formulated using flaxseed as a dietary fibre source (Singh, Chauhan, Mendiratta, Agrawal & Arora, 2019). The authors observed that incorporating 5.92% roasted flaxseed flour into the chhana balls improved cooking yield by 91.80% and resulted in low water activity (0.9481), 6.36 pH and optimum overall acceptability. Also, the content of total, soluble and insoluble dietary fibres were 3.34%, 1.15% and 2.19%, respectively.

A study conducted on the formulation of *kulfi* using four different levels of flaxseed powder (5 to 20%) achieved the highest scores of around 8 (on a 9-point hedonic scale) for all sensory attributes i.e. flavour, body and texture, colour and appearance, melting resistance and overall acceptability for *kulfi* containing 5% flaxseed powder. Other parameters such as physico-chemical parameters such as total solids (42.4%), carbohydrates (25.33%), fats (15.55%), proteins (7.72%), ash (0.97%) and antioxidant capacity in ascorbic acid equivalent (36.52 µg/100g) were also determined (Siva et al., 2019).

Several authors reported the application of flaxseed flour in fermented milk products like *dahi*, yoghurt, kefir and koumiss during recent years. *Dahi* or curd is produced by the fermentation of milk using lactic acid bacteria (LAB) whereas yoghurt is produced by fermentation of milk using strains of bacteria, *Lactobacillus bulgaris* and *Streptococcus thermophilus*. Other fermented milk product includes kefir and koumiss, kefir is a fermented milk drink produced by fermenting cow's, goat's and sheep's milk using kefir grains as a starter culture. Kefir grains mainly consist of protein and polysaccharide matrix having different species of yeasts, acetic acid bacteria, LAB and mycelial fungi, whereas, koumiss is a fermented milk beverage produced by fermenting mare's milk by indigenous microorganisms. Bioactive kefir was reported to be developed by incorporating 1-3% level of crude ingredients which were extracted from dried flaxseed by maceration in 100% sterilized distilled water for about 2 days at ambient temperature followed by filtration through 0.45µm Millipore (Jeong et al., 2017). A similar study was conducted on koumiss supplemented with crude ingredients (0-3%) extracted from flaxseed and suggested that the addition of 1-2% flaxseed was optimum in koumiss based on a 5-point hedonic scale and the scores recorded for taste, flavour, colour, texture and overall acceptability were 2.9, 2.7, 4.4–4.5, 4.3 and 3.6, respectively (Kim et al., 2017).

Probiotic Greek *dahi* fortified with 15% pomegranate pulp and 2% flaxseed powder was optimized taking into account sensory scores (colour and appearance, taste, body and texture overall acceptability) which showed values close to 9 on a 9-point hedonic scale and the textural profile of firmness: 166.54 N, consistency: 0.46 N, adhesiveness: 0.81 N and cohesiveness: 0.86 (Kumar, Rasane & Nimmanapalli, 2018). Dympep et al. (2019) investigated the effects of the addition of 6 and 9% honey and flaxseed powder at three supplementation levels (in the range from 3 to 9%) into the formulation of sweetened stirred *dahi*. The optimized product contained 9% honey and 6% flaxseed powder based on the organoleptic scores in terms of flavour, body and texture, colour and appearance, and overall acceptability with values ranging between 7 to 8 points on a 9-point hedonic scale. The developed product had 32.86% total solids, 20.82% carbohydrates, 7% fats, 4.19% proteins and 0.86% ash. The study showed that flaxseed powder improved the fibre content of dahi to 5.73% and increased its antioxidant activity (7.12 mg ascorbic acid /100 g).

Flaxseed oil

Reduced-fat cheese was formulated by Mahrous, Mostafa and El-Kholy (2014) using the substitution of milk fat with 2% flaxseed oil and skim milk without changing flavour and texture. The prepared cheese was evaluated with high overall acceptability scores of 8.9 compared to 8.5 for cheese made with skim milk alone. Supplementation of flaxseed and blackcurrant oils in yoghurt was reported to contribute to meeting at least 10% of the recommended daily intake of 2 g/day of ALA (Dal Bello, Torri, Piochi & Zeppa, 2015).

The researchers observed a maximum ALA content of more than 200 mg/100 g in yoghurt at the end of storage. Also, the researchers concluded that the addition of oil did not influence the growth of lactic acid bacteria that were higher than 107cfu/g at 21 days of storage.

Microencapsulated flaxseed oil powder (MFOP) was optimized using the spray drying method (Goyal et al., 2015) which consisted of 12.5% flaxseed oil, 10% whey protein concentrate-80, 10% lactose, and 68.5% distilled water. The powder had peroxide value at 0.81-0.99 meq peroxides/kg which indicated high oxidative stability for up to six months when stored at 35 ± 1 ºC. The team also stated that fortification of this powder at 1% level in milk (250 mL assumed standard serving size of milk) was enough to meet 34% of the RDA of nutritional requirements of ω-3 fatty acids (ALA) during the storage period of 5 days, and provided lesser scores for sensory attributes for colour and appearance 8.33, mouthfeel 28.33, odour 16.67 and taste 35.57 using a composite scoring card. Goyal et al. (2016) evaluated *dahi* (in terms of titratable acidity, syneresis, firmness, stickiness, oxidative stability such as peroxide value, ALA content and sensory parameters) fortified with MFOP at three different levels (1, 2 and 3%). The results revealed that incorporation of 2% MFOP showed no significant difference in titratable acidity and syneresis. The lowest values were obtained for firmness (0.88-1.7N) and stickiness (0.19-0.22N) compared to the control *dahi* sample. But, the sensory parameters showed optimum scores (colour and appearance 8.60, sourness 7.33, body and texture 23.33 ad flavour 36.33) for *dahi* with peroxide value (0.41 meq peroxides/kg oil).

The prepared product was richer in ALA (10.62%) compared to the control (1.92%), and could serve as a potential delivery system of ω-3 fatty acids (FAs).

Veena, Nath, Srinivas and Balasubramanyam (2017) also developed fortified *dahi* containing 282.53 mg ALA from flaxseed oil, 415.92 mg phytosterols and 1.019 g polydextrose per 100 g *dahi* and reported good stability for 8 days of storage with no loss in the initial content of ALA, phytosterols and polydextrose. No significant difference was observed in sensory scores (colour and appearance and overall acceptability). However, physicochemical properties such as pH (4.31), consistency (10.74 N.sec) and LAB (8.45 log cfu/mL) were reduced from initial values (1 day of storage) whereas, titratable acidity (0.78% lactic acid), water holding capacity (81.39%) and firmness (1.23N) were increased from initial content after 8 days of storage which was attributed to immobilization of the liquid phase in a three-dimensional network comprised of casein micelles. Encapsulation of vitamin D_3 in the cheddar cheese in the form of emulsified particles of flaxseed oil (30 g) containing soy lecithin (2% w/w oil) improved retention to 7% and chemical stability (unsaturation and carbonyl index not modified) during storage for 3 months at 4 °C (Stratulat et al., 2015).

The ω-3 FAs from 3 different sources: flaxseed oil (15%), algal oil (15%) and fish oil (10%) were used in the emulsion form in the formulation of processed cheese spread which was prepared by blending 30-40% shredded ripened cheese (9-12 months old), 20-30% of semi ripened cheese (4-6 months old) and 30-40% of unripened cheese (0 to 1-month-old) with 2-3% salt, 5% sodium citrate, 5% sodium phosphate and 0.05% flavour followed by heating at 80-85 °C for 20 minutes. The spread prepared from flaxseed oil had higher ω-3 FAs in the form of ALA (0.848 g/100 g) compared to the spread prepared with algal oil and fish oil (Renuka, Ramasamy & Kumar, 2016). Further, some researchers observed acceptable sensory attributes in terms of colour and appearance, body and texture, flavour and overall acceptability with a value close to 8 when 2% flaxseed oil, 1% flaxseed flour and 20% fruit and sugar mixture were added to fruit yoghurt. The developed fruit yoghurt had higher ALA content (22.80%) in comparison to the control (0.45%) (Kumar, Balasubramanyam, Rao, Dhas & Nath, 2017).

Incorporation of flaxseed oil at the rate of 1.5, 2 and 2.5% and guava pulp at 5, 10 and 15%

levels was investigated for the development of functional yoghurt and the result indicated that yoghurt prepared with 2% flaxseed oil and 10% guava pulp had acceptable sensory characteristics (between 7 to 8) in terms of colour, appearance, flavour, taste, body and texture and overall acceptability (Selvakumar, Karthikeyan & Elango, 2017). Gurdian et al. (2017) incorporated flaxseed oil at various white cheese processing stages: homogenization, coagulation, and salting and evaluated its quality after 30 days of storage at 8 °C. It was observed that flaxseed oil added at the homogenization stage showed the best results in terms of low yeast and mould counts, and high lipid content with less dehydration, but showed high lipid oxidation. Fortification of yoghurt with walnut and flaxseed oil at a level of 2% separately or along with guar gum (0.025 and 0.05%) was studied (Baba et al., 2018). From the results, it was observed that walnut oil added to yoghurt with guar gum at a 0.025% level resulted in higher MUFA (26.72% oleic acid) and PUFA (36.58% linoleic acid) levels and improved sensory parameters (with overall acceptability of 8.01) than flaxseed oil fortified yoghurt.

Flaxseed mucilage

Flaxseed mucilage is a water-soluble polysaccharide that forms a viscous, gelatinous solution upon blending water and flaxseeds at the ratio of 1:20 (seed: water). Incorporation of flaxseed mucilage powder (prepared by drying the flaxseed mucilage overnight in an oven at a temperature of 40 °C), containing 20.67% protein, 18% fat and ash 0.25% along with carboxymethyl cellulose (CMC) as a natural stabilizer, was carried out in stirred yoghurt.

The study showed that a combination of CMC and flaxseed mucilage could help reduce syneresis to 0.33 mL over the control group (14.33 mL) and increase the viscosity of stirred yoghurt (Basiri, Haidary, Shekarforoush & Niakousari, 2018). Furthermore, edible coatings can be prepared using 0.5% xanthan gum and flaxseed mucilage (0.75, 1 and 1.25%) for cheddar cheese during ripening at 8 ± 2 °C for 90 days.

No significant differrence was observed for sensory parameters, tyrosine and tryptophan content in cheddar cheese prepared with 0.75% flaxseed mucilage (Soleimani-Rambod, Zomorodi, Naghizadeh Raeisi, Khosrowshahi Asl & Shahidi, 2018).

Flaxseed meal with other components

Bialasová et al. (2018) tested the effect of adding 0.6% flaxseed oil and 7.6% flaxseed meal on the growth and viability of *Lactobacillus acidophilus* CCDM 151 and yoghurt culture CCDM 21 during one month of cold storage in fermented milk. They found that the viability of both tested cultures during storage of fermented milk at 5 ± 1 °C was not influenced by 0.6% flaxseed oil supplementation, but the addition of 7.6% flaxseed meal significantly lowered their viability.

Flaxseed in bakery and confectionery products

Bakery products are usually prepared from cereal grain flours which are popular due to their low price, convenience, ready-to-eat nature and easy transportation. Despite all the advantages, bakery products are considered unhealthy if eaten in excess amounts, especially when prepared from refined wheat flour, as it contains fewer essential nutrients and fibres. Other ingredients used in the processing of bakery products include preservatives, additives, trans fats, salt and sugar. A confectionery product mainly consists of sugar and carbohydrates. Hence, several researchers have suggested the incorporation of flaxseed into baked products and confectionery items for improving their nutritional and functional status. Flaxseed can be incorporated as an additive in the form of whole seed or as flaxseed powder in these products.

Whole flaxseed

Granola bars were prepared by blending 20 and 30% flaxseed and oats along with peanuts and jaggery paste. Among them, 20% addition of flaxseed in granola bars showed optimum sensory attributes scores (close to 8) for appearance, colour, flavour, texture, taste and overall acceptability. Additionally, the utilization of flaxseed was reported to improve the nutritional quality of granola bars (Pradhan & Sethi, 2017). Cereal bar could be formulated by the addition of roasted flaxseed flour (5 to 20%) with oat flakes (Subedi & Upadhyaya, 2019). The study showed that 10% incorporation of flaxseed flour resulted in improved texture and overall acceptability than control which was prepared without flaxseed flour.

The study of Elshehy, Agamy and Ismail (2018) highlighted the nutritional value of flaxseed by adding them into biscuits at four different levels (0 to 30%) and noticed that flaxseed added at the level of 20% resulted in biscuits with optimum sensory parameters such as colour, texture, odour, taste, overall acceptability, residual after taste and total score with values being 5.63, 6.54, 6.67, 6.92, 7.02, 6.83 and 39.61, respectively. The researchers also reported that incorporation of flaxseed provided health benefits from ω-3 FAs (ALA 10.10%) as well as calcium content (175 mg/100 g) for better bone health.

Flaxseed flour

Cracker was manufactured by using a flour blend of wheat, flaxseed and finger millet in the ratio of 3:1:1. A nutritious final product with higher calcium (70.3 mg/100g), dietary fibres (46.7 g/100g) and polyunsaturated fatty acids (11.04 g/100g) content was obtained (Athawale, Thorat & Shukla, 2015). The effect of multi-grains powder (blend of barley, oats, flaxseed, and soybean) at 10, 15 and 20% levels was studied on cookies and results indicated that the cookies prepared from 15% multi-grains powder had optimal overall acceptability and improved protein content by 1.5 times and dietary fibres by 1.8 times (Rajiv & Soumya, 2015). Roozegar, Shahedi, Keramet, Hamdami and Roshanak (2015) investigated the effect of addition of coated and uncoated ground flaxseed (5, 15 and 25%) to wheat flour in the preparation of taftoon bread. The coating was done using 10% Arabic gum solution with ascorbic acid and hydrogenated fat which were stored at 25 °C for 80 days to prevent oxidation of flaxseed oil. The results revealed that increased dough development and dough stability time was obtained with the addition of 25% ground flaxseed coated with arabic gum. Further, less water absorption was achieved when 25% ground flaxseed coated with hydrogenated fat was used. The sensory properties of the bread with 5 and 15% coated and uncoated ground flaxseed showed good acceptability.

According to Lalmuanpuia, Singh and Verma (2017), flaxseed flour at 10, 15 and 20% levels along with 5% dried carrot pomace could be used to fortify cookies. It was observed that the addition of flaxseed flour at a 15% level produced cookies with optimum sensory parameters in terms of colour and appearance, flavour and taste, body and texture; and overall acceptability (with a score ranging from 7 to 8). The effect of the addition of flax-seed flour and defatted flaxseed flour at three different levels (5 to 15%) was evaluated for the preparation of pan bread and observed that 5% addition of full flaxseed flour and defatted flaxseed flour had optimum sensory parameters in terms of taste, crust colour, crumb colour, aroma, texture and overall acceptability ranging between 8 and 9 (Mansour, Galal & Abu El-Maaty, 2018). Furthermore, up to 25% substitution of wheat flour with defatted flaxseed flour was successfully applied in biscuits which received the sensory characteristics scores for appearance (9.66), colour (9.66), odour (9.66), texture (9.50), taste (9.50) and overall acceptability (47.83) compared to control showing the overall acceptability score of 48.91 (Omran, Ibrahim & Mohamed, 2016). Similar work was carried out that showed acceptable sensory characterristics (flavour and taste of 45, body and texture of 44, colour and appearance of 44 and overall acceptability of 45) in biscuits made from 75% flaxseed flour and 25% wheat bran flour (Tiwari & Mishra, 2019). Research on the development of functional biscuits was carried out using partial replacement of whole wheat flour with rye, oat, barley or a mixture of all these along with milled flaxseed at the rate of 10% based on flour (Čukelj et al., 2017). The results revealed that the lignans (comprised of secoisolariciresinol, lariciresinol, pinoresinol and syringaresinol) were found to be higher (117 mg/kg) in flaxseed enriched biscuits than the control biscuits (3.6 mg/kg). Man et al. (2021) conducted a study with partial replacement of wheat flour with 10, 25 and 40% roasted flaxseed flour in the formulation of biscuits. The biscuits prepared with 25% roasted flaxseed flour did not produce an aftertaste compared to that enriched with 40% flaxseed flour. They observed that hardness was decreased with the addition of more roasted flaxseed flour which may be due to the high- fat content of flaxseed flour which can lead to a high lubricating function and interruption of the gluten network.

Preparation of cookies using raw and roasted flaxseed flour in combination with refined wheat flour at different ratios was studied by Kaur et al. (2019). The researchers observed that cookies prepared at an ingredient ratio of 70:30 (refined wheat flour: roasted flaxseed flour) exerted increased gumminess and fracturability to about 19.30 N and 80.83 N, respectively while, other textural properties such as hardness (12.01 N), chewiness (2.48 N), resilience (0.256) and springiness (0.27 mm) decreased. Additionally, high protein content was observed in cookies made by using 30% raw flaxseed flour (9.25%) compared to those with 30% roasted flaxseed flour (9.13%) and the control (4.08%). Also, the fibre content was found to be 2.37% and 2.10% in cookies with raw and roasted flaxseed flour. The development of protein-enriched cookies using roasted flaxseed flour at supplementation levels in the range of 5 - 40% was demonstrated by Ahmad, Zulfiqar and Chatha (2020). The authors indicated that cookies with 5% roasted flaxseed flour received the best sensory scores for colour (8.00), texture (7.92) and flavour (8.00) along with overall acceptability (8.00) compared to control and other formulations.

Wirkijowska et al. (2020) developed a functional wheat bread enriched with by-products of flaxseed such as flour and marc (obtained afer cold-press extraction of oil). The authors confirmed that the addition of flaxseed by-products i.e. flour and marc at the rate of 15% increased the yield of bread by 146.6% and 148.4%, respectively compared to the control bread (137.5%), while 10% addition of marc resulted in reduced caloric value by 10% compared to standard bread. Formulation of flatbread was studied using kocho flour (produced from the pseudo stem of the enset crop) and ground flaxseed with 95:05, 90:10 and 85:15 ratios (Irena, Abera, Legesse & Tassew, 2021). Among these, bread prepared from a combination containing 10% ground flaxseed showed higher overall acceptability of 6.48. However, the combination containing 15% flaxseed showed high nutritional properties i.e. 4.3% crude protein, 6.78% crude fat, 4.01% crude fibre and 388.82 kcal energy. Besides these, it also had improved mineral content such as calcium (123.30 mg/100 g), phosphorus (136.85 mg/100 g), zinc (1.89 mg/100 g) and iron (2.99 mg/100 g). The incorporation of full-fat and defatted flaxseed flours increased the phenolics, antioxidant capacity and dietary fibre content of bread. In addition to this, supplementation of micro fluidized flaxseed flour improved functional properties in bread (Saka, Baumgartner & Özkaya, 2021). Supplementation of 5% ground flaxseed hulls in wheat bread increased phenolic content by 93%, radical scavenging ability (ABTS) by 176% and reducing power (FRAP) by 220% over the bread at a lower enrichment level with ground flaxseed (Sęczyk, Świeca, Dziki, Anders & Gawlik-Dziki, 2017). In addition to this, the authors observed that the use of flaxseed hulls at high enrichment levels resulted in reduced loaf volume and low sensory scores that could be due to the formation of darker colour with 5% flaxseed hull compared to control. But, bread with 4% flaxseed hulls showed a satisfactory overall acceptability score of 7.6 points.

Flaxseed oil

The effect of replacement of shortening with flaxseed oil (5 to 50% level) in the formulation of cookies was studied (Rangrej, Shah, Patel & Ganorkar, 2015). The authors indicated that sensory properties were not affected significantly when the replacement of shortening was at 30% flaxseed oil level. Also, the study showed that prepared cookies had a shelf life of up to 21 days when stored at 45 °C and had 14.14% ω-3 FA. Replacement of 100% shortening butter with flaxseed oil and fortification with 5% germinated soy flour in the formulation of functional bread with good sensory parameters: crust colour (7.2 points), crumb colour (7.5 points), taste (7 points), texture (6.9 points), flavour (6.9 points), overall acceptability (7.2 points) when compared to the breads fortified with 10 and 15% of germinated soy flour (Mishra, 2016).

Flaxseed mucilage

The application of flaxseed mucilage (1.60%) as a fat replacer in the production of the low-calorie cake was investigated (Bitaghsir, Kadivar & Shahedi, 2014). The authors reported that the use of flaxseed mucilage reduced the lipid content of the cake by 76.40% without affecting product quality. Flaxseed mucilage (obtained by dispersing 100 g flaxseed in 1 L water followed by 15-minute boiling and freeze-drying for 72 h) as a structure-forming agent was evaluated in gluten-free bread at supplementation levels of 1.2, 1.8 and 2.4% of total starch (Korus, Witczak, Ziobro & Juszczak, 2015). An increase in storage and loss moduli was observed with increasing supplementation levels of flax mucilage. In addition, the bread with higher linseed mucilage was more appealing than the control, made by using guar gum and pectin.

Flaxseed meal

The nutraceutical and sensorial properties of sourdough bread were improved by fortify-cation with flaxseed cake at 5, 7.5 and 10% levels. Fortification at 7.5% flaxseed cake resulted in a bread with the best properties, taking into account three series of information: sensory, physico-chemical and nutritional properties. Frankness i.e. the absence of any off-flavours of crumb's odour was most compromised when 10% flaxseed cake was added to sourdough bread (Sanmartin et al., 2020).

Flaxseeds in meat products

Meat and meat products are a good source of nutrients such as proteins and fat-soluble vitamins and show a higher level of bioavailability of minerals as compared to other nutritional sources. The processed and semi-cooked meat products include corn beef, meatloaf, sausages, curries, bacon, ham, cutlet-mix, chicken-n-ham and salami. However, meat products are deficient in ω-3 FAs (except fish products) and lignans. The growth of food awareness among consumers has increased global meat production demands for developing newer healthier meat products possessing superior functional and nutritional values. Fortification of flaxseed in meat products not only improves nutritive value but also reduces the fat content.

Flaxseed powder

The effect of addition of flaxseed flour (5-10%) was evaluated alone and in combination with various antioxidant additives like 0.05% ascorbic acid, 0.03% sodium citrate and 0.02% α-tocopherol on inhibiting lipid oxidation and protein fractions of minced meat in semi smoked sausages (Gurinovich, Sannikov & Patrakova, 2018). The study confirmed that maximum synergistic effect was achieved using two combinations: a) flaxseed flour and sodium citrate and b) flaxseed flour, sodium citrate, and α-tocopherol. Flaxseed flour (4%) and essential oils like thyme (0.05%), oregano (0.05%) and rosemary (0.01%) were incorporated in the preparation of spent hen chicken nuggets and achieved organoleptic scores close to 8.0 for all the parameters i.e. colour and appearance, flavour, texture, tenderness, juiciness, and overall acceptability values (Ahlawat, Sharma, Bishnoi, Ahlawat & Yadav, 2019).

Beef patties were produced by the addition of 2.5% golden flaxseed and by-product to improve its nutritional properties like enhancing PUFA/SFA ratio, reducing ω-6/ω-3 ratio and providing healthier food for consumption as the flaxseed oil possess PUFA/SFA ratio of 6.38 and low ω-6/ω-3 ratio of 0.38 (Novello, Schiessel, Santos & Pollonio, 2019). The quality of beef sausage was investigated by incorporating flaxseed at 0, 3 and 6% levels and tomato powders at 0, 1.5 and 3% individually (Ghafouri-Oskuei, Javadi, Asl, Azadmard-Damirchi & Armin, 2020). The researchers observed that both the sausages prepared by addition of 3% each of flaxseed and tomato powders had acceptable sensory scores based on a 5-point hedonic scale and found that the resultant product made with 3% flaxseed powder had 8.1% linolenic acid whereas, sausages with 3% tomato powder resulted in 7.7% linolenic acid.

Flaxseed oil

Partial replacement of beef fat with 5% flaxseed oil and rice bran at 5, 10 and 12.5% was carried out in beef burger patties which showed that sensory parameters comparable to that of the control were exerted by patties made with 5% flaxseed oil and 5% rice bran. However, partial replacement of 5% flaxseed oil and 12.5% rice bran in beef burger patties markedly reduced their lipid content to 8.12% over the lipid content (23.85%) when only beef fat was used. Besides that, a reduction in total saturated fatty acids from 51.75 to 24.57 g/100g lipids, an increase in dietary fibres from 1.25% to 7.23%, and nutritional properties such as unsaturated fatty acids (77.84 g/100 g lipid) and unsaturated to SFA ratio of 3.17 was also observed (Ibrahium, Hegazy & El-Waseif, 2015). Reddy, Jayathilakan and Pandey (2016) developed designer chicken shreds with 20.51 mL rice bran oil and 2.57 mL flaxseed oil which were se-lected using the quadratic fit model. The pre-pared product had 7.70% ω-3 FA, 29.54% ω-6 FA and ω-6/ ω-3 ratio of 3.8:1.

The effect of the addition of fish oil and flaxseed oil as ω-3 FA sources in the development of chicken surimi was studied (Wang et al., 2016). From the study, it was observed that incorporation of flaxseed oil increased total ω-

3 FAs and ω-3/ ω-6 FA ratio, whereas fish oil provided only long-chain PUFAs. Also, the use of fish oil showed greater lipid oxidation compared with flaxseed oil during storage at temperature range from -15 to -10 °C.

Reduction in saturated and monoenoic fatty acids by 12% and an increase in the contribution of polyene fatty acid by 70% were achieved along with the increase in phytosterols in liver pâté (animal fat) by replacing fat with flaxseed oil (20%) and flaxseed extract (0.05%) with good oxidative stability (Bilska, Waszkowiak, Błaszyk, Rudzińska & Kowalski, 2018).

Flaxseeds in extruded and other food products

Extruded products include snacks, ready-to-eat cereals, crisp bread, etc. Consumer acceptability toward buying these extruded products has increased in recent years due to their convenience, inexpensiveness, attractive appearance and texture.

Flaxseed can be added to a range of extruded products for providing health benefits as it contains ω-3 FAs, fibre, phytoestrogen, etc. Other edible products including chips, jam, spread, mayonnaise, soup mix etc. also could be fortified with flaxseed and/ or its components. Hence, fortification of foods with flaxseed is helpful to develop nutritionally rich confectionery products.

Whole flaxseed

Bhardwaj, Peter, Bharti, Rani and David (2019) optimized the preparation of jam blended with the pulp of apple along with carrot pulp and flaxseed powder in a ratio of 90:10 based on the high sensory scores (around 8 or more for flavour and taste, colour and appearance, body and texture and overall acceptability). The prepared jam exerted significantly higher reducing power according to FRAP assay.

Flaxseed flour

Fortified pasta was produced from refined wheat flour fortified with 20% flaxseed powder as a source of ω-3 FA and 10% vallarai *(Centella asiatica* L.*)*, commonly known as Gotu kola/ Kodavan/ Indian pennywort (a source of saponins). The resultant pasta had high FRAP antioxidant activity. The ingredients such as soy flour (10%), flaxseed powder (20%) and vallarai (10%) were selected along with rice flour for developing extrudates which also showed high FRAP antioxidant activity (Gomathy, Balakrishnan & Dhivya, 2014). Extruded bean snack fortified with flaxseed powder (0-20% level) was developed and showed no significant difference in propanal values (which determines the secondary oxidation products) when fortified with 5-10% flaxseed (Vadukapuram, Hall, Tulbek & Niehaus, 2014). The authors also reported that the consumption of 28 g extrudate fortified with 10% flaxseed was enough to meet 33% of RDA of ALA. Three different types of noodles prepared by supplementation of texturized defatted flour, namely 10% sunflower, 20% soybean and 10% flaxseed were prepared with high overall acceptability scores of 7.55, 8.42 and 8.15, respectively. Also, the noodles prepared with all three types of flour resulted in improved protein content than the control (Bhise, Kaur & Aggarwal, 2015).

The addition of flaxseed flour at the rate of 10-20% could be used in the preparation of wheat chips to increase ω-3 FAs i.e. ALA to 6.709% and 1.112% using 20 and 10% flaxseed flour, respectively. However, higher taste scores were achieved when wheat chips were prepared using flaxseed flour at a 10% level and by frying at 180 °C for 52 s (Yuksel, Karaman & Kayacier, 2014). According to Kaur and Das (2015), a nutritious and functional dry soup mix could be produced using 46.29% whole barley flour, 23.14% roasted flaxseed powder and 30.55% seasoning. The results revealed that the developed product had low glycemic index (52.89 by *in vitro* and 55.457 by *in vivo* test), high antioxidant activity (FRAP and DPPH assays) and contained 25.6% ω-3 FA. Flaxseed powder up to 8% could be added to low-fat mayonnaise without affecting sensory parameters and results indicated that obtained product had high content of alpha-linolenic acid. However, acid and peroxide values increased during storage for three months but were less than 0.29 mg KOH/g oil and 2.07meq O2/kg oil, respecttively (Shirmohammadi, Azadmard & Zarrin, 2015).

A study conducted on the preparation of gluten-free pasta from 67% brown rice flour, 20% amaranth flour, 10% flaxseed flour and 3% whey protein concentrate (WPC-70) was prepared and it was reported that the prepared product had high dietary fibres, protein and phosphorus (Aastha et al., 2017).

Development of spaghetti hydrated to 30-32% was prepared using semolina, whole wheat, and flaxseed flour in the ratio of 39:51:10 (de la Peña & Manthey, 2017). De Oliveira Giarola, Pereira, Prado, de Abreu & de Resende (2019) evaluated the effects of golden flaxseed flour at levels of 0, 1, 2, and 3% (w/w) on ice recrystallization in uvaia *(Eugenia pyriformis* Cambess*)* diet sherbets fortified with iron and reported that golden flaxseed flour added at the level 1 and 2% showed good quality product with improved rheological properties with higher shear stress and ice crystal size were 13.93 µm and 14.84 µm, respectively with a relative frequency bet-ween 75% and 90%.

Flaxseed oil

Application of flaxseed oil powdered microcapsules produced by spray drying method using oil-in-water double-layer emulsions and designed with whey protein concentrate and sodium was shown by Fioramonti, Stepanic, Tibaldo, Pavón and Santiago (2019). The shelf life of 6 months was reported for flaxseed oil powdered microcapsules when stored at -18 °C and 4 °C and 6 weeks at 20 °C.

The application of flaxseed oil as a medium for the extraction of carotenoids from carrot bio-waste has been demonstrated by Tiwari, Upadhyay, Singh, Meena and Arora (2019) followed by the preparation of table spread with extracted carotenoids (Kamble, 2019). It was found that the developed spread had 13.7g ALA /100g of fat which meets about 80% of its RDA. Spray-dried flaxseed oil microcapsules using soy protein isolate and modified starch as a coating material and optimum emulsion were prepared with 30% oil load and 30% total solids for encapsulation of flaxseed oil. The ALA content in the oil extracted from microcapsules was found to be 61.67% (Tambade, Sharma, Singh & Surendranath, 2020).

Flaxseed meal

The addition of 5, 10 and 15% flaxseed meal extract in native and denatured form as a substitute for the oil phase in low-fat mayonnaise was studied by Drozłowska, Łopusiewicz, Mężyńska and Bartkowiak (2020). The best sensory attributes scores were achieved with 5% flaxseed meal extract (native) having colour, odour, consistency, mouthfeel, viscosity, taste and overall acceptability scores of 4.8, 4.6, 4.8, 4.8, 4.6, 4.8 and 4.7, respectively using 5-points hedonic scale. Other studies conducted on the application of flaxseed and its components in different food commodities are briefly shown in Table 3.

Feeding livestock with flaxseed and/or its components as an innovative approach for enhancing the nutritive status of foods from animal origin

Several authors have studied the feeding of flaxseed and/or its components on the performance of chicken and egg fatty acid composition. Cherian and Quezada (2016) conducted a study on the feeding of 10% camelina or flaxseed in a control diet of Lohman brown hens for a period of 16 weeks. The results revealed that hens fed with camelina or flaxseed had higher egg production and immunoglobulin Y concentration in eggs. Also, they observed higher total ω-3 FAs of 3.12% and 3.09% in eggs from camelina or flaxseed fed hens compared to 1.19% in eggs from control diet-fed hens. Similar results have been reported by Spasevski et al. (2019) who observed that addition of flax-corn meal co-extrudate (at levels 13.50% and 22.50%) to corn-soybean meal-based diet significantly increased tocopherols, ALA, docosahexaenoic and eicosapentaenoic acids, and decreased the ω-6/ω-3 ratio in eggs compared to those originated from eggs fed on control diets. A study was conducted by Westbrook and Cherian (2019) for a period of 120 days to evaluate the effect of supplementation of carbohydrase enzyme (0.05-0.1%) on FA composition of eggs from brown layer hens fed with 10% flaxseed. They found higher FA composition, total ω-3 FAs (5.43%), ALA (2.91%) in eggs from hens on a diet supplemented with flaxseed and 0.1% enzyme in comparison to eggs from hens fed on a control diet (2.03% of total ω-3 FAs and 0.59% of ALA, respectively) and a 9-fold increase in hepatic ALA in the liver of hens. The effect of supplementation of flaxseed in the forage diet of dairy cows was studied on the quality of milk and Raclette cheese (Bocquel et al., 2016). The workers observed that the supplementation of flaxseed resulted in an increased proportion of ALA to 1.32 g/ 100 g in milk from the control group (0.92 g/100 g). However, hardness in cheese was reduced to

Table 3.
Studies conducted on application of flaxseed and its components in different food commodities

Application	Product Name	Flaxseed components	Effects	Reference
Dairy products	Yoghurt	Flaxseed powder 2.63%	▪ Shown optimum sensory scores and textural properties	Mousavi, Heshmati, Daraei Garmakhany, Vahidinia & Taheri (2019)
		Flaxseed powder 1%	▪ ↑ Sensory scores as compared to 3% and 5% addition of flaxseed powder ▪ ↑ Other parameters such as pH, acidity, water holding capacity, viscosity, antioxidant activity (DPPH scavenging activity), PUFAs, ω-3 FA ▪ ↓ SFA, ω-6 to ω-3 FA ratio and atherogenic index.	Marand, Amjadi, Marand, Roufegarinejad & Jafari (2020)
		Extruded flaxseed powder 2%	▪ ↓ Syneresis ▪ ↑ Textural properties, ω-3 FA and total dietary fibre content	Ahmad et al. (2020)
	Low fat yoghurt	Flaxseed flour 0.5%	▪ ↑ Functionality and showed reduced viscosity with more syneresis at higher concentration of flaxseed flour	Foutohi & Manafi Dizaj Yekan (2021)
	Ice cream	Microencapsulated flaxseed oil powder 4%	▪ Showed that serving of 100 g of developed ice cream was able to meet ~ 45% of RDA of ALA (1.4 g ALA/day)	Gowda, Sharma, Goyal, Singh & Arora (2018)
Bakery and confection-nary products	Synbiotic dark chocolate	Fermented flaxseed (6 g flaxseed inoculated with 10^9 cfu/mL of lactic acid bacteria followed by 4 days incubation)	▪ Developed product used fermented flaxseed as a prebiotic and *Leuconostoc mesenteroides* as a probiotic ▪ Showed maximum antioxidant activity of 90 U/mL and 200 µg Trolox/mL when measured by DPPH and FRAP assay, high nutritive value and benefits for human gut health	Waghmode, Gunjal & Patil (2020)
	Cupcake	Flaxseed sprouts powder 2%	▪ ↓ Hardness and more porous crumb structure in a cupcake containing 2% xanthan gum	Cakmak, Mama & Yilmaz (2021)
	Gluten free pizza dough	Flaxseed flour	▪ ↓ Fermentation time from 24 h to 1 h and provided high nutritive properties such as protein of 46.89% calculated from daily norm value that is 75 g which was higher than control (21.75%) and fat of 14.73% on daily norm basis of 83 g against 5.11% in control, sensory and functional properties	Sapozhnikov, Kopylova, Gurova & Bolshakov (2021)
	Functional bread	Hybrid microcapsules of flaxseed oil (2 g/mL) + garlic oil (2 g/mL) 5%	▪ ↑ Oxidative stability of bread fortified with combination of flaxseed oil and garlic oil when studied in terms of thiobarbituric acid value	Kairam, Kandi & Sharma (2021)
Meat products	Fish burger	Flaxseed flour 10%	▪ ↑ General acceptability scores to 8.3with 10% flaxseed flour while less scores was found in control and burger with 5% and 15% flaxseed flour ▪ ↑ Protein, energy and cooking yield ▪ ↓ Moisture retention	Duman (2020)
Extruded and other products	Panjiri	Flaxseed flour 10%	▪ Shown good sensory properties in terms of colour 7.4, flavour 7.4, taste 7.4, texture 7.7, odour 7.1 and overall acceptability 7.4 compared to the other formulations (15, 20 and 25%) but it was not higher than control	Karwasra, Kaur, Sandhu, Siroha & Gill (2021)

5.76 N from 8.08 N (control group) and resulted in an undesirable crack formation in cheese. The flaxseed supplementation to the diet (by substituting 1 kg of concentrate with an equal quantity of whole flaxseed in the diet) of Italian Simmental cows did not affect the milk yield and composition but cacioricotta cheese produced from this milk was reported to contain increased monounsaturated (29.67%) and ω-3 FAs (0.90%) (Santillo et al., 2016). The health benefits of the flaxseed as poultry feeds in terms of meeting human requirements of ω-3 FAs through ω-3 enriched foods like eggs were highlighted by Moghadam and Cherian (2017).

No major changes in the sensory characterristics and cholesterol content of white and dark meat were noticed when chicken feed was supplemented with extruded flaxseed at the rate of 6%. However, the nutritional characteristics of both types of meat were improved in terms of α-linolenic acid (Živković et al., 2017; Živković et al., 2018). Recently, a study has been conducted by Bennato et al. (2020) to evaluate the effect of diet supplementation with 10% extruded linseed in comparison with a conventional diet for goats and the results revealed an increase in milk production.

It was reported that cheese processed from such experimental milk had lower content of monounsaturated fatty acids (18.46% of total FA) and polyunsaturated fatty acids (2.51%) and increased saturated fatty acids (79.03%). Moreover, the aromatic profile of ripened goat cheese was positively affected by the dietary intake of linseed.

COMMERCIALLY AVAILABLE FLAXSEED PRODUCTS

Some flaxseed products are commercially available for the application of various food products such as bread, cookies, snack product, crackers, bars, dairy products and many more.

The main goal of utilization of these products are the convenience, health benefits as they contain ω-3 FAs, lignans, dietary fibres and proteins. The different flaxseed products are compiled in Table 4 and food products enriched with flaxseed in Table 5 as available commercially and accessed online.

INDUSTRIAL NON-EDIBLE PRODUCTS FROM FLAXSEED

Flaxseed oil

A high yield of biodiesel (98.6%) was obtained from 50 g flaxseed oil with transesterification process at methanol to oil ratio of 5.9:1, temperature of reaction of 59.2 °C, reaction time of 33 minutes and potassium hydroxide as catalyst with weight 0.51% (Danish, Ahmad, Ayoub, Geremew & Adeloju, 2020).

Flaxseed mucilage

Hadad and Goli (2018) evaluated the spin ability of flaxseed mucilage by electro spinning and produced amorphous nanofibers with high thermal stability using flaxseed mucilage (3%) and polyvinyl alcohol solution (12%) at the ratio of 60:40. Composite hydrogel was made using cellulose and flaxseed gum which showed maximum stability with a temperature of 332.6 °C for thermal decomposition, good swelling capability and was useful for hemostatic and wound healing functions (Deng et al., 2020).

Flaxseed meal

Ghosal and Bhowal (2021) produced 0.11 g/L bioethanol using fermentation by baker's yeast in 10 g flaxseed meals which was pre-treated with 6% sulphuric acid followed by enzymatic hydrolysis using cellulose enzyme.

FUTURE PROSPECTS

Flaxseeds are a rich source of alpha-linolenic acid, lignans, fibres and protein. Furthermore, they possess good antioxidant properties. Therefore, flaxseeds are utilized as a functional ingredient for the fortification in several food products such as dairy, bakery, meat, extruded food products, etc. Flaxseed enriched food products were not used effectively, but in the recent past these are becoming more popular due to their many health benefits.

Several products or available flaxseed oil were investigated. However, the main challenge for using flaxseed oil is the oxidative stability of developed flaxseed enriched products. To overcome these problems advanced techniques like nanoemulsion, spray drying, microencapsulation have been attempted. Furthermore, there is a need to explore detailed composition and nutritional benefits

Table 4.
Commercially available formulations having flaxseed component as an ingredient

Product origin	Product Name	Product Description	Features	Applications
Glanbia Nutritionals (Ireland)	Bargain700EF Bargain701EF	Blend of pea, chia, and flaxseed protein Blend of soy and flaxseed proteins	80% protein, vegan, non GMO, gluten-free, enhanced texture, flavour, and shelf-life	Extruded and baked bars, clusters
	Harvestpro Flax protein 35	Heat-treated natural flax protein concentrate	26-36% flax protein concentrate, contains ALA ω-3, non-GMO, hormone-free, allergen-free, gluten-free and >25% fibres	Beverages, bars, bakery products
	Harvestpro Flax 30	Heat-treated natural flax protein concentrate	35% flax protein concentrate, non-GMO, hormone-free, allergen-free, gluten-free and 32% fibres	
	LinPro 140	Flax protein powder	Allergen-free	Protein fortification, bars, clusters, cereals and beverages
	OptiSol 3200	Blend of whey protein concentrate and flaxseed meal	Replaces up to 20% of total eggs	Cheesecakes
	OptiSol 3400	Blend of whey protein concentrate and flaxseed meal	Replaces up to 100% of liquid and dry eggs	Cakes, muffins and brownies
Shape Foods Inc. (Canada)	Flax meal	Flax powder	Kosher and Halal certified, rich in ω-3 fatty acids, lignans, protein, and dietary fibres, gluten-free	Flax bread, muffins, tortillas, pasta and pizza
	Cold pressed flax oil	Flaxseed oil	Kosher and Halal certified and rich in ω-3 fatty acids	Processed foods
Natunola Health Inc. (Canada)	Natunola Omega-3 Flax 70	Made up of 70% flax kernel and 30% flax hull and whole seed	High ω-3, non-GMO, gluten free, cholesterol and trans-fat free	Bars, cookies, breads, muffins, crackers, snack foods and cereals
	Natunola Omega-3 Flax 50	Made up of 70% flax kernel	High ω-3, non-GMO, gluten free and high fibres	Muffins, bread, cookies, crackers, bars and cereals snack foods
	Natunola Flax Flour	Flaxseed powder	High fibres, ω-3, gluten free and non-GMO	Breads, muffins, cookies, cereals, crackers, snack foods and pasta
	Natunola Omega-3 Flax Meal	Ground flaxseed	High ω-3, non-GMO, cholesterol and trans-fat free	Bread, muffin, cookies, cereals, crackers, snack foods and bars
Natunola health's delight (Canada)	Shelled flax kernel	Shelled flax with 70% kernel	Kosher Certified, gluten free, fibres, lignans, provided 1.5 g of ω-3 per 5 g of serving and trans fat free	Sprinkle on muffin and bread dough before baking
	Shelled flax meal	Flaxseed powder with omega	Kosher Certified, gluten free, fibre, lignan, provided 1 g of ω-3 per 5 g of serving and trans fat free	Baked products
	Instant oatmeal with shelled flax	Shelled flax	High ω-3 and fibres	Instant food
NOW Real Food (United States of America)	Flaxseed meal (Organic golden and organic flaxseed)	Flaxseed	Good source of essential fatty acids and fibre	Cereals, pancakes, muffins, breads, meatloaf, meatballs, and even yogurt

Note: Besides these, other branded foods having flaxseed component as an ingredient are available in the market of United States and New Zealand [https://fdc.nal.usda.gov/fdc app.html#/] Accessed on November 30, 2021

Table 5.
Some of the commercially available food products containing flaxseed or its components

Product origin	Product Name	Flaxseed component used	Product Features
Good Karma Foods	Flax milk *(Available in three flavours viz. unsweetened, chocolate and vanilla)*	Flaxseed	1100 mg ω-3 and 7 g proteins
	Yoghurt *(Strawberry flavour)*	Flax milk	800 mg ω-3 and 5 g proteins
Nutralite	Vegetable fat spread	Flaxseed oil	70% fat content and 600 mg ALA/100g
Earth Balance	Natural buttery spread	Flaxseed	320 mg ALA
Pure eggs	Omega -3 eggs	Flaxseed diet to hens	Rich in alpha linolenic acid
Goldenlay	Omega -3 free range eggs	Flaxseed fed to hens	250 mg ω-3
Organic Valley	Omega-3 free range large and extra-large eggs	Flaxseed diet to hens	Rich in ω-3 FAs
Biona Organic	Rye omega golden linseed bread	Flaxseed	0.7 g ω-3/100 g of serving
Voortman Bakery	Oatmeal dark chocolate flaxseed cookies	Flaxseed	500 mg of ALA ω -3 FAs/20 g of serving
eQuia	Toast omega-3	Flaxseed	800 mg of ALA /3 pieces of toast
Delba	Famous German flaxseed bread	Flaxseed	High fibre and cholesterol free
Raised & Rooted	Nuggets made with plants	Golden flaxseed	Polyunsaturated fats 7 g/90 g of serving
RW Garcia	Crackers *(Available in four types: harvest, kale, sweet beet and sweet potato)*	Flaxseed	Cholesterol and gluten free

of other components of flaxseed such as using lignans, mucilage and proteins and subsequently formulations of new products available commercially. The effect of flaxseed fortification in food on changes in functional, nutritional and antioxidant properties and its mechanism with body metabolism is still required to be studied through *in vivo* analysis to avail the health benefits of flaxseed and/ or its components.

CONCLUSIONS

The current review provides information on the production, nutritive value and health benefits of flaxseeds as well as nutritional and functional characteristics of food products fortified with flaxseed and/ or its components. Incorporation or supplementation with flaxseeds may improve the functional and nutritional properties of food products as being an abundant source ω-3 FA, lignans, proteins and fibres. The present review provides the recent food, feed and non-food industrial application of flaxseed and/or its components, and also offers evidence on commercially available flaxseed-based ingredients and products.

ACKNOWLEDGEMENTS

The authors are thankful to Director, National Dairy Research Institute, Karnal and this review was written as a part of DST/SEED project "Development of flaxseed-rich probiotic dairy foods to address menopause symptoms" with code no. SEED/WS/2018/58.

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SVEOBUHVATAN PREGLED PRIMENE LANENOG SEMENA U INOVATIVNOJ HRANI I INDUSTRIJSKOJ PRERADI OD 2014. GODINE DO DANAS

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Sažetak: Laneno seme je seme biljke uljarice lana (*Linum usitatissimum*). Ono predstavlja vredan izvor mnogih bioaktivnih jedinjenja poput omega-3 polinezasićenih kiselina, proteina, lignana, prehrambenih vlakana i fitohemikalija. Ovaj rad daje pregled rezultata brojnih *in-vivo* i *in-vitro* studija sprovedenih u svetu na humanim subjektima i životinjskim modelima vezano za zdravstvene koristi povezane sa konzumacijom lanenog semena u raznim oblicima. Rad se detaljno osvrće i na primenu lanenog semena u raznim oblicima (celo zrno, prekrupa, brašno, ulje) u različitim prehrambenim proizvodima, hrani za životinje i neprehrambenim proizvodima. Značajna karakterisitka ovog preglednog rada je osvrt na nova otkrića u vezi sa zdravstvenim efektima lana i njegovih komponenata kao i aktuelnih podataka o komercijalno dostupnim proizvodima koji su obogaćeni semenom lana ili njegovim komponentama. Autori su imali nameru da pruže sveobuhvatan pregled najnovijih informacija o primeni lana posle prve detaljne studije objavljene 2014. godine.

Key words: *omega-3 masne kiseline, in-vivo studije, prehrambeni proizvodi, hrana za životinje, komercijalni proizvodi*

Received: *19 December 2022/* ***Received in revised form:*** *09 May/01 June 2022/* ***Accepted:*** *01 June 2022*

Available online: *June 2022*