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Flaxseed oil: Extraction, Health benefits and products

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REVIEW ARTICLE

Abstract

Flaxseed is rich in α-linolenic acid (ALA), lignans, proteins and dietary fibers, which has been considered as an important food ingredient. As one of most functional ingredients in flaxseed, flaxseed oil could provide many potential health benefits, such as cardiovascular protection, anti-tumor, anti-inflammatory, live protection, diabetes treatment, etc. Besides mechanical pressing and solvent extraction for flaxseed oil, various new extraction processes, for example, microwave-assisted extraction, supercritical CO_2 extraction, subcritical extraction, three-phase partitioning, enzyme-assisted three-phase partitioning, etc., have been investigated. Currently, flaxseed oil has been incorporated into some regular food formulations including liquid or solid powder drink, meat products, baking foods, etc. However, due to high ALA in flaxseed oil, it is a great challenge for the development of flaxseed-oil based products. In present paper, the latest development of the extraction of flaxseed oil, the potential benefits of flaxseed oil, and flaxseed oil-based foods, were reviewed. Regarding the studies of flaxseed oil in our group was also highlighted.

Keywords: ALA; extraction; flaxseed; foods; health benefits

Introduction

Flaxseed (Linseed), is one of the oldest oilcrops, is grown in more than 50 countries. The meaning of flaxseed in Latin is "very useful". At present, the main flaxseed grown areas are distributed in the northern hemisphere, including Canada, mainland of China, the America, India, and Ethiopia. Among these countries, Canada and mainland of China are the largest exporters, which account for more than 30% of flaxseed trades (FAO, 2020).

Flaxseed contains many bioactive compounds including ALA, lignan, protein, mucilage, minerals, phenolic compounds, etc. (Bechlin *et al.*, 2019; Giarola *et al.*, 2019; Lan *et al.*, 2020), which can provide the potential benefits to our body, such as reducing the probability of occurrence of heart diseases and osteoporosis, anti-mammary or prostate gland tumor activities, laxative activity, anti-inflammatory activity, and alleviating menopausal symptoms, etc (Afzal *et al.*, 2020; DeLuca *et al.*, 2018; Parikh *et al.*, 2019; Soltanian and Janhorbani, 2018).

The amounts of these components in flaxseed highly depend on many factors such as flaxseed cultivars, harvest time, growth environment, processing, analysis methods, etc (Bekhit *et al.*, 2018; Liu *et al.*, 2018; Marambe and Wanadsundara, 2017). Flaxseed is one of the richest sources of phytoestrogens. In flaxseed, phytoestrogens are existing in the type of lignans (Kajla *et al.*, 2015). The major kind of lignans in flaxseed is secoisolariciresinol diglucoside (SDG). The amount of SDG contained in flaxseed varies from 294 to 700 mg/100 g whole flaxseed (Edel *et al.*, 2015; Goyal *et al.*, 2018). In the study of Gerstenmeryer *et al.* (2013), 1099 mg SDG/100 g flaxseed was observed. Flaxseed contains around 18–23% protein which is rich in amino acids including aspartic acid, arginine, cysteine, methionine, etc (Arntfield, 2018; Kaur *et al.*, 2017). Flaxseed protein shows comparable nutritive values and amino acid profiles to soya protein (Bekhit *et al.*, 2018). Flaxseed is also one of excellent sources for phenolic substances. Main types of phenolic substances in flaxseed include phenolic acid compounds, lignans and flavonoid compounds (Kajla *et al.*, 2015). Phenolic acid compounds, for example, ferulic acid, gallic acid, chlorogenic acid, hydroxycinnamic acid, glucosides, p-coumaric acid glucosides, etc., are detected in defatted flaxseed (Deng *et al.*, 2017; Wang *et al.*, 2017). Flaxseed contains many kinds of minerals (Kaur *et al.*, 2017; Oliveira *et al.*, 2017). Magnesium (3575 mg/kg), phosphorous (5269.20 mg/kg) and calcium (2020.63 mg/kg), Fe (27.89 mg/kg), Cu (5.82 mg/kg), Zn (18.39 mg/kg), were reported (Tuncel *et al.*, 2017). One of anti-nutritional compositions in flaxseed is cyanogenic glycosides, such as linamarin, linustatin, lotasutralin, neolinustatin, etc (Zhao *et al.*, 2019). The content of cyanogenic glycosides in flaxseed significantly depends on flaxseed cultivars, growth areas, processing, etc (Kajla *et al.*, 2015). Yu *et al.* (2018) reported that the content of cyanogenic glucosides in the investigated flaxseed was ranged between 5.57 and 11.34 mg HCN/100 g. Cyanogenic glycosides can release hydrogen cyanide (HCN) in the intestinal, and thus pose a potential health risk (Bekhit *et al.*, 2018; Kajla *et al.*, 2015). The presence of cyanogenic glycosides in flaxseed limits the development of flaxseed products. Therefore, the reduction of cyanogenic glycosides is highly necessary prior to the application of flaxseed in food industry. Many methods, such as enzymatic method, germination, boiling treatment, mechanical treatment, solvent method, etc., have been investigated (Bekhit *et al.*, 2018; Li *et al.*, 2019).

Generally, the content of flaxseed oil in flaxseed varies from 30 to 44%, which depends on various factors such as location, cultivars, environmental conditions, analysis methods, etc (Kaur *et al.*, 2017; Tuncel *et al.*, 2017). Zou *et al.* (2017) reported that the crude flaxseed oil contents in 13 flaxseed samples cultivated in China were ranged from 28.9 to 41.4%. Flaxseed is one of the most abundant ALA sources (Abbasi *et al.*, 2019; Lan *et al.*, 2020; Li *et al.*, 2020). The level of ALA in flaxseed oil is between 48 and 62% (Bakowska-Barczak *et al.*, 2020; Goyal *et al.*, 2018; Moghadam *et al.*, 2019). The content of ALA in flaxseed oil also is affected by environmental conditions, growing conditions and cultivars (Dunford, 2015; Wang *et al.*, 2017). Zou *et al.* (2017) found the levels of ALA in investigated flasxseed cultivars were ranged from 45.5 to 55.8%. ALA in flaxseed oil from flaxseed cultivars Zhongya1 (55.8%) and Zhongya4 (53.4%) showed a higher contents compared to that of the rest investigated flaxseed cultivars.

ALA is considered an essential fatty acid. Many laboratory and epidemiologic studies indicate that ALA from flaxseed oil can reduce occurred rates of heart disease, cancer, arthritis, inflammatory diseases, etc (Kheira *et al.*, 2019; Mosavat *et al.*, 2018; Zhu *et al.*, 2020). 1.1 and 1.6 g/day ALA recommended intakes for women and men, respectively, have been suggested (Goyal *et al.*, 2018). For lactating and pregnant women, ALA recommended intakes are improved to 1.3 and 1.4 g/day, respectively. Generally, the recommended dietary intake for flaxseed (about 9.0 g/per day) is suggested. The reasonable fatty acids balance for n-6/n-3 fatty acids is very important for our health. Many organizations suggest that a ratio of n-6/n-3 fatty acids is from 5:1 to 10:1 (Kumar *et al.*, 2017b). However, a ratio of n-6/n-3 fatty acids in some western countries or Chinese daily diet is far above 10:1. Thus, we need to increase flaxseed oil intake in our daily diet.

The residue from flaxseed pressing is usually regarded as “flaxseed meal”, which is rich in proteins, dietary fibers, lignans, orbitides, minerals, cyanogenic glycosides, etc. (Bekhit *et al.*, 2018). Therefore, flaxseed meal shows a great potential to be used as one of functional ingredients in food products. However, it is normally used as one of animal feed ingredients (Aziza *et al.*, 2013). Partially defatted flaxseed meal has been investigated as one of bakery ingredients (Shim *et al.*, 2015; Turner *et al.*, 2014).

Recently, flaxseed oil used as a dietary supplement has gained more consumer interests due to high level of ALA in flaxseed oil. Various flaxseed oil-based products as the form of nutraceuticals or normal foods, like flaxseed blending oils, flaxseed oil yogurt, and flaxseed oil solid drinks etc (Figure 1), are available on the market (Baba *et al.*, 2018; Bolger *et al.*, 2018; Gowda *et al.*, 2018; Manshadi *et al.*, 2019; Tang *et al.*, 2016a, 2016b, 2016c, 2016c, 2016d, 2017, 2018a, 2018b, 2018c, 2018d, 2018e, 2019a, 2019b). Therefore, in this paper, we tried to present the comprehensive development of extraction and health promoting benefits of flaxseed oil, particularly in the last 5 years (2016–2020).

Flaxseed Oil Composition

Like other edible oils, the main component of flaxseed oil is fatty acid. Other compounds in flaxseed oil, such as volatile compounds, phenolic compounds, tocopherol, phytosterols etc., have been detected. Flaxseed oil contains around 96% triacylglycerides (TAG) and 1.4%

Figure 1. Various flaxseed oil-based commercial products. (A) Flaxseed oil; (B) Flaxseed oil capsule; (C) Blending oils of flaxseed oil and sunflower seed oil; (D) Blending oils of flaxseed oil and camellia oil; (E): Blending oils capsules of flaxseed oil and walnut oil; (F) Blending oils capsules of flaxseed oil and DHA alga oil; (G) Flaxseed oil sauce; (H) Encapsulated flaxseed oil powder.

polar lipids, glyco, and phospholipids (Dunford, 2015). Fatty acids contained in flaxseed oil are given in Table 1. The main TAG in flaxseed oil is trilinolenate (35%) (Hall *et al.*, 2006). Zhang *et al.* (2017b) found that fatty acids of flaxseed oils were mainly composed of linolenic acid (53.36–65.84%), linoleic acid (10.14–16.39%), oleic acid (10.03–12.37%), stearic acid (3.98–9.85%) and palmitic acid (2.41–7.97%), respectively.

The levels and compositions of volatile compounds in flaxseed oil are one of quality evaluation factors (Wei *et al.*, 2018a, 2018b; Yu *et al.*, 2019c). Yu *et al.* (2019c) reported that a total number of characteristic aroma compounds from hot-pressed flaxseed and cold-pressed flaxseed oil was 16 and 14, respectively. The unique aroma components in hot-pressed flaxseed oil such as 2, 5-dimethylpyrazine, 2, 3, 5-trimethylpyrazine and (E)-2-hexenoaldehyde may be contributed to the roasted and greasy aroma of flaxseed oil. Acetic acid was the unique aroma component in cold pressed flaxseed oil. Wei *et al.* (2018b) found 57 volatile compounds in flaxseed oil, and constructed aromatic fingerprint of flaxseed oil.

Flaxseed oil also contains many kinds of phenolic compounds, for example, syringic acid, ferulic acid, cinnamic acid, gallic acid, etc. Deng *et al.* (2017) found the

Table 1. Fatty acid profiles of whole flaxseed and flaxseed oil.

Fatty acids	Whole flaxseed (%)			Flaxseed oil (%)	
Palmitic acid	5.96–7.18[a]	5.76–6.63[b]	5.67–6.34[c]	5.13[d]	4.66[e]
Stearic acid	4.38–5.33[a]	4.13–5.63[b]	4.28–6.35[c]	3.38[d]	4.43[e]
Oleic acid	18.51–31.19[a]	26.38–31.38[b]	22.41–31.13[c]	19.3[d]	18.5[e]
Linoleic acid	12.03–16.52[a]	13.85–14.91[b]	12.45–15.37[c]	14.0[d]	14.5[e]
Linolenic acid	42.67–58.51[a]	43.54–48.35[b]	45.09–51.09[c]	55.4[d]	55.8[e]

*Deng *et al.* (2017); Zou *et al.* (2017).
*[a] Flaxseed from Inner Mongolia (seven cultivars): Huanghuma, Longya9, 75–11–5, Lunxuan3, Lunxuan2, Neiya6, Neiya9; [b]Flaxseed from Shanxi (five cultivars): Jinya7, Jinya9, Jinya10, Jinya11, Jinya12; [c]Flaxseed from Hebei (six cultivars): Baya9 (12), Baya9(13), Baya11, Baya12(12), Baya12(13), Baya11(11); [d]Flaxseed cultivar Dingya23; [e]Flaxseed cultivar Zhongya1.

total phenolic compounds were ranged from 109.93 to 246.88 mg GAE/100 g. The phenolic levels in flaxseed oils from varieties Neiya 6, Ningya 17 and Yiya 4 were the lowest, while the highest levels were presented in Longya 9, Jinya 10, Baya 12 and Baya 11. Zhou *et al.* (2018) showed that the highest level of phenolic compounds in flaxseed oil from Canada was around 38.06 mg GAE/kg.

Total tocopherol and γ-tocopherol contents in flaxseed oil are highly related to oil content (Zou *et al.*, 2017). Zanqui *et al.* (2015) found that β-tocopherol was the only observed tocopherol, the content of which was ranged from 25.28 to 33.84 mg/100 g oil. Zhou *et al.* (2018) reported the total tocopherol content in flaxseed oil sample from Canada could reach up to 536.62 mg/kg. Recently, Tavarini *et al.* (2019) reported that flaxseed varieties did not significantly affect the levels of total tocopherols and specific vitamers. In investigated flaxseed varieties, the main form of tocopherols was α-tocotrienol. However, in the report of Tuncel et al. (2017), the dominant form of tocopherols was γ-tocopherol, which were in the range of 146.57–193.14 mg/100 g oil.

Deng *et al.* (2017) found that the amounts of phytosterols in 32 flaxseed varieties were varied from 56.52 to 125.12 mg/g. Zhou *et al.* (2018) indicated that flaxseed oil sample from Canada had the highest content of phytosterol, which was 3671.16 mg/kg.

Unsaponifiable lipid constituents in flaxseed oil generally are hydrocarbons, terpene alcohols, sterols, tocopherols and other phenolic compounds. El-Beltagi *et al.* (2011) showed that unsaponifiable matter content was not significantly different between investigated flaxseed cultivars. The mean of total hydrocarbons in flaxseed was 86.05% while the mean of total sterols was 13.95%. C_{26} and C_{28} hydrocarbons were main components in all flaxseed cultivars.

Extraction of Flaxseed Oil

At present, the most common methods to extract flaxseed oil are mechanical pressing and solvent extraction (Sharma *et al.*, 2019; Shim *et al.*, 2015). Fresh unrefined oil from pressing flaxseed has a nutty flavor and the colour varying from yellow to orange. As other edible oils on the market, it needs to be purified through the process of settling, alkali refining, degumming, bleaching, winterization and deodorization. Sometimes, home-made cold pressed oils can be consumed for cooking directly without further refining processing (Shim *et al.*, 2015). Flaxseed oil extraction can be affected by several factors such as pretreatment of flaxseed, moisture content of flaxseed, cultivars, pressing conditions, etc (Dunford, 2015).

The dehulling process for flaxseed

The dehulling of oilseeds can improve oil extraction yields and quality. Main substances in flaxseed hull are the mucilage and crude fiber (Kaushik *et al.*, 2016). Several dehulling process for flaxseed such as dry mechanical process, wet process (assisted by mechanical means) and sprouting process have been developed (Lan *et al.*, 2020; Lv and Huang, 2015). Traditionally, the mucilage is removed by wet process aided with mechanical stirring. High extraction temperature can improve the yield of the mucilage in contrast with cold water extraction (Kajla *et al.*, 2015). However, the wet extraction process is not a good choice for removing the hull of flaxseed because it has too many operation sequences (Sharma *et al.*, 2019; Piva *et al.*, 2017). Therefore, other dehulling methods need to be developed.

Dry dehulling process has been proposed since 1939, but only significant progress has been made recently. Particularly in China, it has been applied in industry since 2017. Factors such as moisture content in the seed, the pretreatment for the seed, dehulling time, etc., can significantly affect dehulling efficiency (Shim *et al.*, 2015). Recently, Zhang *et al.* (2020) employed acidic moisture-conditioning plus low temperature drying as a pretreatment for flaxseed before the extraction of flaxseed oil was carried out. The results indicated flaxseed oil recovery rate 83.27% was obtained under the pretreatment with 0.30 M citric acid and drying at 70°C for 1 h. Zheng *et al.* (2005) found that the reduction of moisture content would result in a significant improvement of the temperatures of flaxseed oil and meals. When moisture content was above 7.5%, the temperature of expressed oil was 49–50°C, whereas when moisture content was reduced to 6.1%, the expressed oil temperatures could reach to 67°C. The opposite relationship between flaxseed moisture content and oil yield was found. Singh *et al.* (2011) found that oil yield significantly increased from 44.4 to 81% when moisture content in flaxseed decreased from 13.8 to 6.5%.

Mechanical pressing for extracting flaxseed oil

Due to the high levels of ALA in flaxseed oil, it is necessary to avoid the high temperature during pressing. Generally, flaxseed oil obtained through cold pressing has high levels of ALA (Kulkarni *et al.*, 2017). Several types of flaxseed oil press have been developed, which are ranged from the simple hydraulic press to the more sophisticated continuous screw press (Bekhit *et al.*, 2018). However, cold pressing can also bring negative impacts on the quality of oil. Due to low pressing temperature, microorganisms may not be killed completely during the pressing, which can decrease the quality of flaxseed oil (Shim *et al.*, 2015). Additionally, due to low mass transfer under cold pressing, the contents of vitamins, phospholipids, phytosterols and antioxidants in oil are lower. These compounds are contributed to the stability of flaxseed oil. So, to prolong the shelf life of flaxseed oil, it is highly suggested that flaxseed oil should be kept in a container with dark color, and incorporated with the antioxidants (Tanska *et al.*, 2018).

To overcome the drawbacks of cold pressing, the ways such as flaxseed pressed under more aggressive conditions, heating or enzyme treatments for flaxseed prior to pressing, have been adopted (Dunford, 2015). Kasote *et al.* (2013) utilized a single screw expeller to extract flaxseed oil. The results showed that the oil yield was improved with the increase of the number of consecutive pressing steps. Compared to the oils from three consecutive pressing steps, the oils with the highest ALA levels were obtained by double pressing. Anwar *et al.* (2013) showed that the oil yield for enzyme-assisted cold pressing flaxseed was higher than that for without-enzyme treated flaxseed. The extraction methods did not affect most of investigated physicochemical properties of flaxseed oils. Furthermore, the oil from enzyme-treated flaxseed showed better oxidative stability compared to that from without-enzyme treated flaxseed. The authors suggested that enzyme-assisted cold pressing was a good choice for extracting flaxseed oil with high yield and quality.

New extraction methods for flaxseed oil

Although the mechanical pressing method is quite popular for flaxseed oil processing, a drawback of this technique is the low extraction recovery of the oil. To improve the yield of extracted oil, many new extraction methods, for example, ultrasound-assisted extraction, microwave-assisted extraction, supercritical CO_2 extraction, subcritical extraction, three-phase partitioning, enzyme-assisted three-phase partitioning etc., have been developed (Kulkarni *et al.*, 2017; Ren *et al.*, 2015; Rombaut *et al.*, 2017; Piva *et al.*, 2018; Sharma *et al.*, 2019; Suri *et al.*, 2020; Szydlowska-Czerniak *et al.*, 2020; Tan *et al.*, 2016).

Three-phase partitioning process has been developed to extract flaxseed oil, which is usually performed through adding salt and *t*-butanol to aqueous extracts (Kulkarni *et al.*, 2017; Sharma *et al.*, 2019). Tan *et al.* (2016) utilized enzyme-assisted three-phase partitioning method to extract flaxseed oil, and showed that the yield of flaxseed oil could reach up to 71.68% under the optimized conditions. Kulkarni *et al.* (2017) reported that flaxseed oil extraction yield from three-phase partitioning, ultrasonic-pretreated three-phase partitioning, enzyme-pretreated three-phase partitioning was 22.46, 27.05 and 26.24%, respectively. Amongst the methods investigated, the combination enzyme-pretreated and three-phase partitioning may be the most suitable method to extract flaxseed oil.

Supercritical carbon dioxide (SC-CO_2) is very suitable for the extraction of heat sensitive and fat-soluble compounds (Dabrowski *et al.*, 2019; Sharma *et al.*, 2019). Kulkarni *et al.* (2017) reported oil yield from SC-CO_2 was 30.03%. The best quality of flaxseed oil was obtained from SC-CO_2. Dabrowski *et al.* (2019) investigated the effect of selected parameters in SC-CO_2 such as flow rate (6–12 mL/min), temperature (40–80 °C) and extraction time (2–6 h) on the recovery of flaxseed oil. The authors reported the recovery of flaxseed oil was highly associated with extraction parameters, and changed from 28.7 to 92.3%.

Subcritical fluid extraction has been employed to extraction flaxseed oil due to its advantages of used solvent. A good yield of flaxseed oil can be obtained when subcritical propane process is used. Flaxseed oil obtained from subcritical propane presented low acidity, showing a better quality compared to flaxseed oil from mechanical extraction (Piva *et al.*, 2018). Piva *et al.* (2017) employed three methods to extract flaxseed oil, and showed that subcritical propane extraction had a higher yield (28.39%) compared to other methods.

To improve extraction efficiency, accelerated solvent extraction (ASE) has been employed to extract flaxseed oil. ASE uses organic or aqueous solvents at improved temperatures and pressures to extract flaxseed oil. Khattab and Zeitoun (2013) indicated flaxseed oil yield from ASE (41.9%), was similar to that from conventional solvent extraction (42.4%), and higher than that from supercritical CO_2 (36.49%). The oils obtained from ASE and supercritical CO_2 method exhibited similar physicochemical characteristics.

Ultrasonic power as an assistant tool has also been employed to extract flaxseed oil. The main advantages of ultrasonic assisted extraction are less solvent usage and faster extraction process as in contrast with those of the methods without ultrasonic power (Dunford, 2015; Sharma *et al.*, 2019). Zhang *et al.* (2008) studied the effect of some operating parameters on the recovery of flaxseed oil, and showed that the yield of flaxseed oil increased as ultrasonic power increased, and decreased with the increase of extraction temperature. The flaxseed oil recovery rate could reach 84.9%.

The microwave pre-treatment for flaxseed is an interesting alternative to conventional pressing extraction method. Compared to conventional extraction method, the microwave-assisted extraction shows many advantages, such as shorter processing time, lower solvent usage and higher yield etc (Fathi-Achachlouei *et al.*, 2019). Suri *et al.* (2020) reported that the treatment of microwave roasting for flaxseeds at 540 W for 10 min could improve flaxseed oil yield, oxidative stability and antioxidant activity of flaxseed oils. Szydlowska-Czerniak *et al.* (2020) optimized the microwave pre-treatment of flaxseed for the extraction of flaxseed oil by response surface methodology. The results showed that microwave treated flaxseed oil presented higher oxidation stability and antioxidant activity compared to those of untreated flaxseed oil. Also, Lv *et al.* (2020) investigated the effect of microwave pre-treatment for flaxseed on yield and storage stability of flaxseed oil. The results showed that microwave pre-treatment could improve the yield and polyphenol content of flaxseed oil, and it could delay the oxidation rate of flaxseed oil, thereby improving the storage stability of flaxseed oil.

Health Promoting Benefits of Flaxseed Oil

Flaxseed oil in cardiovascular diseases and atherosclerosis treatment

Cardiovascular disease (CVD), one of the disorders of heart and blood vessels, is recognized as the leading health threats in worldwide countries (Goyal *et al.*, 2018). Recently, many studies have showed that flaxseed oil has an ability in reducing CVD risk *in vitro* or *in vivo* (Table 2).

Hypercholesterolaemia and inflammatory are major risk factors in the development of CVD. Tzang *et al.* (2009) indicated flaxseed oil presented a hypocholesterolemic ability in contrast with other oils (coconut oil, butter) did. Higher faecal contents of triacylglycerol and cholesterol in flaxseed oil group were observed. Atherosclerosis refers to one kind of the diseases that caused by depositing and accumulating of the lipids in blood cell walls. The formation and development of atherosclerosis are attributed to many factors such as interleukin 1-b, hypercholesterolemia, tumor necrosis factor, eicosanoids cytokines, platelet-activating factor and reactive oxygen

Table 2. Impact of flaxseed oil ingestion on reducing incidence of cardiovascular diseases.

Amount ingestion of flaxseed oil	Model system	Results	References
7.0% flaxseed oil	Hamsters	Flaxseed oil group showed higher triacylglycerol and cholesterol in faeces.	Tzang *et al.* (2009)
10% flaxseed oil	Mice	Replacement of lard with flaxseed oil significantly improved atherosclerosis, oxidative stress, and lipid abnormalities.	Han *et al.* (2018)
Flaxseed oil and α-lipoic acid (8.0 g/kg)	Rats	Simultaneous feeding flaxseed oil and α-lipoic acid could reduce the levels of LDL-C, TC and plasma TG.	Xu *et al.* (2012)
0–55.6 mg/L flaxseed oil	Human umbilical vein endothelial cell	ALA in flaxseed oil at high concentrations could inhibit inflammatory responses induced by lipopolysaccharide in human umbilical vein endothelial cells.	Shen *et al.* (2018)
250 and 500 mg/kg	Rats	Dietary flaxseed oil could significantly decrease the arsenic accumulation, as well as reduce cardiac structural alterations.	Varghese *et al.* (2017)

species. Han *et al*. (2018) reported that the partial substitution of lard using flaxseed oil significantly relieved atherosclerosis symptoms, improved oxidative stress, and reduced the abnormalities of lipid and inflammation. The authors indicated that dieting flaxseed oil can be considered to be as a dietary therapy in the treatment of atherosclerosis. Shen *et al.* (2018) showed that ALA in flaxseed oil at high levels could reduce inflammatory responses in lipopolysaccharide-induced human umbilical vein endothelial cells. Varghese *et al.* (2017) investigated the protective activity of flaxseed oil against the cardiac toxicity induced by As_2O_3. The results showed that dietary flaxseed oil could significantly decrease the arsenic accumulation and cardiac structural alterations.

Cancer treatment by flaxseed oil

At present, many scientists are interested in building the relationship between flaxseed dietary and cancer risk. Many studies demonstrate that flaxseed oil shows the inhibition growth ability of many kinds of cancers, such as colon cancer, mammary tumor, breast cancer, etc., even at a more advanced stage of cancer (Table 3). Buckner *et al.* (2019) showed that flaxseed oil could decrease various cancer cell lines growth through a dose-dependent manner, and disrupt mitochondrial function of B16-BL6 and MCF-7 cells. In the study of Wiggins *et al*. (2015), it was also indicated that flaxseed oil could reduce the growth of breast cancer cell lines, and increase the apoptosis by modifying signaling pathways. Flaxseed oil also can improve the effectiveness of anti-cancer drugs to inhibit the growth of some types of cancer cells. Mason *et al.* (2015) found flaxseed oil could enhance the anti-human breast tumors ability of drug trastuzumab through reducing the growth of HER2-overexpressing tumors. Although many substances in flaxseed showed anti-tumor activity, more studies should be carried out to clarify the mechanisms that which components or how show the ability to reduce cancer development.

Flaxseed oil in kidney diseases

The kidney plays an important role in excreting metabolites and harmful compounds that enter our body (Omar, 2018). Kidney dysfunctions are one of the serious diseases for our health, specially for older adults. At the late stage of renal disease, special treatments such as the dialysis or organ transplant, are highly needed (Table 3). Omar (2018) evaluated effect of dietary flaxseed oil on renal toxicity induced by thioacetamide in male rats. The results showed that feeding flaxseed oil could protect the changes of biochemical parameters and histopathological structures induced by thioacetamide. The speculated renal protective agent in flaxseed oil was due to the antioxidant compounds in flaxseed oil. Kheira *et al.* (2019) showed that feeding flaxseed oil could significantly down-regulate the expression levels of interleukin (IL)-6 and IL-1β in kidney compared to the control. The authors indicated that flaxseed oil could ameliorative the renal injury induced by cisplatin due to anti-inflammatory ability of ALA in flaxseed oil.

Flaxseed oil in liver health

The liver is the largest metabolic organ in our body, which is easily affected by many inflammatory compounds such as viral, bacterial, alcohol, endotoxins, etc. Flaxseed oil presents hepatoprotective activity through the inhibition of inflammatory signaling pathways. Wang *et al.* (2018) showed flaxseed oil could decrease the expression levels of interleukin-6, tumor necrosis factor α, and cycloxygenase. Zhang *et al.* (2017a) indicated dietary flaxseed oil could reduce the abnormal elevated contents of aspartate

Table 3. Impact of flaxseed oil ingestion on reducing incidence of cancer and kidney diseases.

Amount ingestion of flaxseed oil	Model system	Results	References
4.0% flaxseed oil in the diet	Mice	The activity of the anti-cancer drug of trastuzumab in reducing the growth of HER2-overexpressing human breast tumors was improved further in flaxseed oil group.	Mason *et al.* (2015)
0.30 or 0.90% flaxseed oil	Cell lines	Flaxseed oil could induce the apoptosis of B16-BL6 murine melanoma and MCF-7 breast cancer cells, and thus led to the disruption of mitochondrial function in B16-BL6 and MCF-7 cells.	Buckner *et al.* (2019)
4.0% flaxseed oil in the diet	Mice	Flaxseed oil could reduce the growth, and increase apoptosis in breast cancer cell lines.	Wiggins *et al.* (2015)
2.0 g flaxseed oil/kg body weight/day	Mal rats	Flaxseed oil in the diet showed the protection ability against the changes of biochemical parameters and histopathological structures induced by thioacetamide.	Omar (2018)
15% flaxseed oil in the diet	Rats	Flaxeed oil could ameliorate the impact of cisplatin on the injury of rat kidney.	Naqshbandi *et al.* (2013)

aminotransferase and alanine aminotransferase in mice. It is suggested that dietary flaxseed oil could ameliorate alcoholic liver disease through its anti-inflammation activity and gut microbiota modulating ability. Also, Wang *et al.* (2016) demonstrated dietary flaxseed oil decreased the elevation of plasma endotoxin content, and suppressed the inflammation induced by endotoxin.

Flaxseed oil in bone health

The investigation of effect of flaxseed oil on the health of bone may provide an alternative way to treat osteoporosis. Many studies have showed that ALA in flaxseed oil presents beneficial effects on bone metabolism (Table 4). Chen *et al.* (2019b) indicated that flaxseed oil could ameliorate bone loss induced by a high fat diet through osteoblastic function in rat primary osteoblasts. El-Saeed *et al.* (2018) showed that feeding flaxseed oil could increase the contents of bone minerals. The authors suggested the dietary of flaxseed oil could provide beneficial effect on the treatment of osteoporosis.

Flaxseed oil in diabetes

Diabetes mellitus refers to one kind of metabolic diseases with the characteristics of high levels of blood glucose. If not being treated appropriately, it can lead to the formation of many complications (Goyal *et al.*, 2018; Lim *et al.*, 2017; Soleimani *et al.*, 2017a, 2017b). Clinical evidence have showed that these complications can be controlled well through many dietary therapies. Many studies have indicated that flaxseed oil plays an important role in the treatment of diabetes (Table 5). It has been shown that feeding flaxseed oil in the diet can show a

Table 4. Impact of flaxseed oil ingestion on the health of liver and bone.

Amount ingestion of flaxseed oil	Model system	Results	References
Lieber-DeCarli liquid diets containing corn oil and flaxseed oil	Mice	Dietary flaxseed oil could reduce the abnormal elevated levels of aspartate aminotransferase and alanine aminotransferase in mice with alcoholic liver disease.	Zhang *et al.* (2017a)
Lieber-DeCarli liquid diets containing corn oil and flaxseed oil	Mice	Dietary flaxseed oil decreased the elevated content of plasma endotoxin, as well as, reduced the inflammation responses induced by endotoxin.	Wang *et al.* (2016)
5.0% flaxseed oil diet	Piglet	Flaxseed oil could decrease the expression of interleukin-6, tumor necrosis factor-α and cycloxygenase 2, and thus led to the alleviation of liver injury induced by lipopolysaccharide.	Wang *et al.* (2018)
10% flaxseed oil diet	Rats	Flaxseed oil could reduce bone loss induced by high-fat-diet through improving osteoblastic function in rat.	Chen *et al.* (2019)
Flaxseed oil in the diet	Rats	The increase of bone mineral levels was observed in flaxseed oil group.	El-Saeed *et al.* (2018)

Table 5. Impact of dietary flaxseed oil on reducing the incidences of diabetes.

Amount ingestion of flaxseed oil	Model system	Results	References
1000 mg/day omega-3 from flaxseed oil	Human	The ingestion of flaxseed oil could significantly reduce the levels of VLDL-cholesterol and serum triglycerides, and increase insulin sensitivity check index.	Soleimani *et al.* (2017a)
1000 mg faxseed oil supplements containing 400 mg ALA	Human	Flaxseed oil supplementation could improve gene expression levels of peroxisome proliferator-activated receptor gamma (PPAR-γ), tumor necrosis factor alpha (TNF-α) and lipoprotein (a) (LP(a))	Hashemzadeh *et al.* (2017)
1000 mg/day omega-3 from flaxseed oil plus 400 IU vitamin E	Human	Co-supplementation of ALA and vitamin E could significantly improve total antioxidant capacity, and significantly decrease the level of formed malodialdehyde.	Jamilian *et al.* (2017)
10% flaxseed oil in the diet	Rats	Flaxseed oil in the diet could significantly reduce the levels of fasting blood glucose, blood lipid, plasma lipopolysaccharide, glycated hemoglobin, (TNF)-α, IL-6, IL-17A, interleukin (IL)-1β.	Zhu *et al.* (2020)
1.2 mL flaxseed oil/kg/day	Male albino rats	The ingestion of flaxseed oil could decrease the level of kinase C isozymes, and improve the sensitivity of insulin of rats with diabetes.	Hussein *et al.* (2014)

health promoting benefits for diabetics through modulating insulin sensitivity in phospholipids membranes, modulating gut microbiota, or reducing inflammation in the body. Hashemzadeh *et al.* (2017) found that dieting flaxseed oil could improve the gene expression amounts of peroxisome proliferator activated receptor gamma (PPAR-γ), tumor necrosis factor alpha (TNF-α), lipoprotein (a) (LP(a)) in type II diabetic patients with coronary heart disease. Soleimani *et al.* (2017a) showed that flaxseed oil supplementation could significantly reduce the amounts of VLDL-cholesterol and serum triglycerides, and increase insulin sensitivity checking index. Zhu *et al.* (2020) investigated effect of adding flaxseed oil in the diet on rats with type II diabetes mellitus. The results indicated dieting flaxseed oil could significantly reduce the concentrations of fasting blood glucose, blood lipid, plasma lipopolysaccharide, glycated hemoglobin, TNF-α, IL-6, IL-17A, interleukin (IL)-1β and malondialdehyde (MDA), in contrast with the control. Jamilian *et al.* (2017) studied impact of ALA and vitamin E co-supplementation on biomarkers of oxidative stress and inflammation in women with gestational diabetes. The results showed that ALA and vitamin E co-supplementation could significantly improve total antioxidant ability, and significantly decrease the level of MDA.

Flaxseed oil in arthritis and inflammation

Arthritis, one kind of joint disorder diseases involved joint pain, is usually caused by inflammatory substances and joint wear (Mosavat *et al.*, 2018). Many studies have showed that flaxseed oil with an anti-inflammation ability, has a potential application in the treatment of arthritis (Table 6). Mosavat *et al.* (2018) found that flaxseed oil was effective in the treatment of knee oseoarthritis, especially in the aspects of ameliorating the severe symptoms and functional status, because of anti-inflammatory ability of flaxseed oil.

Flaxseed oil in brain health

Many flaxseed oil-based products are claimed as "health for brain". Some studies have showed that flaxseed oil plays an important role in maintaining nerve function and metabolism activity of brain tissue. Tian *et al.* (2011) studied the changes of brain tissue in young mice fed polyunsaturated fatty acids with different ratios during maternal pregnancy and lactation. The results indicated dieting flaxseed oil could significantly increase the expression levels of brain neuron-specific enolase, myelin basic protein and glial fibrillary acidic protein. The authors indicated that higher intake amounts of n-3 polyunsaturated fatty acids with n-6/n-3 fatty acids at around 1–2:1, was more helpful to the development of early brain. In the study of Ismail *et al.* (2016), flaxseed oil presented neuroprotective activity in rats' brain induced by gamma-irradiation or carbon tetrachloride.

Flaxseed oil in obesity

Obesity has been popular in many countries, which is highly related to some chronic diseases, for example, type II diabetes, cardiovascular disease, cancer, metabolic syndrome, etc (Moura-Assis *et al.*, 2018; Yu *et al.*, 2017). Akrami *et al.* (2018) clearly showed that dieting flaxseed oil or sunflower seed oil could significantly reduce the weight of the patients. In addition, feeding flaxseed oil significantly decreased waist circumference of the patients. Yu *et al.* (2017) reported that feeding medium

Table 6. Impact of flaxseed oil ingestion on rheumatoid arthritis and inflammatory diseases.

Amount ingestion of flaxseed oil	Model system	Results	References
Flaxseed oil and fish oil (n-6/n-3 fatty acid ratio of 5:1)	Mature female cats	The dietary of flaxseed oil and fish oil could improve the level of skin leukotriene LTB5, and reduce the skin leukocyte proliferative response.	Park *et al.* (2011)
1–3 mL flaxseed oil/kg with regular diet	Albino rats	The dietary of flaxsee oil could significantly reduce protein exudation and leucocyte migration levels in peritoneal fluid.	Kaithwas and Majumdar (2010)
2.4 mL flaxseed oil /kg body weight	Female dogs	The dietary of flaxseed oil could significantly down-regulate the expression of inflammatory genes, for example HSP90, IL1β etc.	Purushothaman *et al.* (2014)
20 drops every 8 h	Men and women with ages 40–70 yeas old	Flaxseed oil was effective in improving clinical parameters of knee oseoarthritis.	Mosavat *et al.* (2018)
15 mL flaxseed oil/day	Humans	The dietary of flaxseed oil did not significantly influence on the levels of the inflammatory markers, for example adiponectin, TNF-α, and C-reactive protein.	Kontogianni *et al.* (2013)

dose of flaxseed oil could effectively inhibit the metabolic activation of adipose tissue macrophages, and thus improved tissue insulin signaling.

Flaxseed oil in ulcerative colitis treatment

Ulcerative colitis is one kind of chronic inflammatory bowel diseases, which can greatly affect work and daily lives of the patients (Nascimento *et al.*, 2020). Zhou *et al.* (2020) showed that flaxseed oil could decrease the inflammation in colon, and recovered the microbiota profiles in rats at a certain extent. The authors indicated that flaxseed oil could be used as a beneficial agent for the management of ulcerative colitis possibly through regulating the levels of inflammatory factors and gut microbiota. Morshedzadeh *et al.* (2019) evaluated impact of flaxseed oil on serum contents of metabolic parameters, inflammatory markers and the severity of disease in the patients with ulcerative colitis. The results showed that the parameters of IL-6, interferon gamma, waist circumference significantly decreased, and the parameter of transforming growth factor beta increased significantly in flaxseed oil group compared to the control.

Flaxseed Oil-Based Products

Flaxseed has been used as a dietary supplement in our daily life for many years. Whole or milled flaxseeds can be conveniently used as additives in dough, batters, and various baked products. Furthermore, flaxseed flour can be served as wheat flour or egg substitute especially in some baked products such as breads, muffins and cookies etc. As one of the main constituents in flaxseed, flaxseed oil is gaining popularity because of the high level of ALA (Bekhit *et al.*, 2018; Mohseni and Goli, 2019). However, the development of flaxseed oil-based is a challenging work because ALA in flaxseed oil is highly sensitive to external factors, for example, oxygen, light, high temperature, etc (Bekhit *et al.*, 2018; Mohseni and Goli, 2019). If flaxseed oil is in an improper storage, it is easily emerging rancidity, and leads to poor sensory quality. Therefore, flaxseed oil is usually stored in dark bottles. Regarding the applications of flaxseed oil in various foods, many studies have been carried out in laboratory scale. Flaxseed oil has been added into many kinds of baked foods, beverages, meat products and many other foods (Baba *et al.*, 2018; Bolger *et al.*, 2018; Farbod *et al.*, 2015; Gowda *et al.*, 2018; Goyal *et al.*, 2016; Kumar *et al.*, 2017a; Reddy *et al.*, 2016; Ramel *et al.*, 2017; Osuna *et al.*, 2018; Veena *et al.*, 2017). At present, soft capsule of flaxseed oil has also been sold as a functional food supplement in China. Furthermore, some flaxseed oil-based products developed in our group, such as flaxseed instant powder, flaxseed yogurt, flaxseed baked products, have been available on the market.

Flaxseed oil

Generally, flaxseed is roasted between 105 and 160°C for several hours prior to flaxseed pressing (Yang *et al.*, 2011). Yu *et al.* (2019a) investigated effect of different pretreatment processes such as normal-pressure roasting, microwave and high-pressure roasting, on the properties of obtained flaxseed oil. The results showed that the quality of obtained flaxseed oil pretreated through the combination of microwave and high-pressure roasting, were better compared to those of pressed flaxseed oil pretreated by normal-pressure frying (170°C, 45 min). In addition, obtained flaxseed oil pretreated by high-pressure roasting had a pleasant flavor. In the same group, Yu *et al.* (2019b) studied the impact of roasting temperature for flaxseed on the quality of obtained flaxseed oil. The results showed that flavor of pressed flaxseed oil changed from nutty aroma to strong burnt taste, and the color became darker, as roasting temperature increased. The roasting temperature could significantly affect the stability of ALA in flaxseed oil. What's more, the contents of V_E, total phenols and polysterols decreased gradually with the increase of roasting temperature.

Many studies have showed that that the content of ALA in flaxseed oil significantly reduces after being treated at high temperature, and results in the reduction of the nutritional values of flaxseed oil. Hall *et al.* (2006) found the quality of flaxseed oil did not decrease when the temperature was below 177°C. However, when the cooking temperature was more than 177°C, ALA content was significantly reduced. Chen *et al.* (2019a) reported the content of ALA in flaxseed oil decreased significantly at high temperature (250°C). After flaxseed oil was heated at 200 or 250°C for 2 h, ALA content decreased by 6.1 and 57.7%, respectively. The authors suggested heating temperature for flaxseed oil should be controlled under 200°C, and heating time should not be too long. This information may be good for Chinese cook because stir frying is a very popular cooking method. Even so, we highly recommend flaxseed oil had better be cooked at low temperature (<180°C).

The levels of antioxidants in the oils can significantly influence the oxidation stability of flaxseed oil (Shadyro *et al.*, 2020). There are some antioxidants such as tocopherols, phenolic acids, flavonoids, etc., in flaxseed oil (Kajla *et al.*, 2015). Heating treatment can destroy these natural antioxidants, thus leads to the reduction of oxidation stability (Kajla *et al.*, 2015; Yu *et al.*, 2019a). To improve the storage stability of flaxseed oil, various antioxidants, for example flaxseed extracts, α-tocopherol mixture, etc., have been applied for the protection of flaxseed oil (Mohanan *et al.*, 2018; Shadyro *et al.*, 2020; Sielicka and Malecka, 2017).

Encapsulation of flaxseed oil

Due to the poor storage stability of flaxseed oil, encapsulation technology for flaxseed oil has been investigated (Fioramonti *et al.*, 2019; Goyal *et al.*, 2018). Recently, many flaxseed-based products have been developed in our group, some of which are commercialized. The product of flaxseed instant powder based on this technology has been available since 2014 (Lv and Huang, 2015). However, many consumers give us the feedback that protein content in flaxseed instant powder is too low. Therefore, we have updated the formulation of flaxseed instant powder. In new formulation, around 10% milk protein was added. The new product of flaxseed instant powder enriched with milk protein has been available in 2019. Flaxseed instant powder can be used as a functional additive (Tang *et al.*, 2016, 2017, 2018, 2019). Many normal foods incorporated with flaxseed instant powder such as biscuit, sweet, snack bar, milk tablet, liquid drinks, etc., have been developed.

The co-encapsulation technology refers to encapsulation more than one bioactive components at the same time, which has been widely used as a delivery system (Eratte *et al.*, 2015, 2016, 2018). Co-encapsulation process can low production cost, and improve the product quality. Products containing encapsulated ω-3 oils or probiotics have been available. At present, there are some products composed of the mixture encapsulated ω-3 oils and encapsulated probiotics on the market. Products containing with co-encapsulated ω-3 oils and probiotics are not available so far. Regarding the studies on the co-encapsulation of ALA and probiotics is still limited. Eratte *et al.* (2015, 2016) co-encapsulated ω-3 oil and probiotics using the combination of complex coacervation and by spray drying technology. The results showed that oxidative stability and cell viability were highly improved. Stratulat *et al.* (2014) co-encapsulated vitamins E, A and CoQ_{10} in flaxseed oil emulsion stabilized with calcium caseinate, and studied the stability of the encapsulated bioactives in cheese milk. The results indicated that the stability of co-encapsulated bioactives in cheese milk could be remained during the investigated storage periods.

Blending oil

As is well known, one particular oil can not satisfy all the nutritional requirements (Hashempour-Baltork *et al.*, 2016; Torri *et al.*, 2019). Therefore, in order to satisfy commercial requirements, oils need to be modified. Among modification methods for oils, blending oils may be one of the simplest methods to modify fatty acid profile, physicochemical and nutritional properties which can reach to the requirement of industrial applications (Hashempour-Baltork *et al.*, 2016). Presently, many blending oils with improved stability and nutritional properties have been marketed. In our group, blend oil made from flaxseed oil and grapeseed oil, has been commercialized (unpublished work). Blending flaxseed oil with palm oil was used to prepare fat spreads (El-Waseif *et al.*, 2013, 2014). The results showed that ω-3 content in fat spreads was significantly improved due to the presence of flaxseed oil. As a result, oxidation stability of fat spread samples contained flaxseed oil was lower than the control. Sensory evaluation results indicated that incorporation flaxseed oil into fat spread did not significantly impact the sensory properties. Meinhart *et al.* (2017) showed the stability of blend oils (soybean, flaxseed and safflower oils: 75: 20: 5 g/100 g) was higher compared to that of soybean oil. Additionally, the obtained blend oil with lower n-6/n-3 ratio, had higher nutritional values compared to the pure soybean oil. The authors suggested the blend oils could improve the nutritional quality of frying oil, and enhance the intake of ω-3 in our daily diet. Kumar *et al.* (2017a) studied the stability of ALA in the blend oils of coconut oil and flaxseed oil (70/30) during deep-fat frying of snack food. The authors found ALA content in obtained snack food was around 27.48% when it was fried at 140°C for 360 s.

In food products

Foods based on flaxseed oil such as breads, cookies, drinks, ice cream, salad dressings, sausages, egg sticks, yoghurts, fat spreads, surimmi, cheese, etc., have been reported (Manshadi *et al.*, 2019; Ramel and Marangoni, 2017). Various food products incorporated with flaxseed oil are showed in Table 7.

Table 7. Applications of flaxseed oil in foods.

Food types	Additions	References
Alaska pollock surimi	10% oil (flaxseed: algae: menhaden, 8: 1:1)	Debusca *et al.* (2013)
Cheese	1.0% flaxseed oil	Aguirre and Canovas (2012)
Shortening & cookies	0–50% flaxseed oil	Rangrej *et al.* (2015)
Bread	1.0, 2.5, 5.0 and 10% flaxseed oil (powder)	Gokmen *et al.* (2011)
Ice cream	4.0% flaxseed oil powder	Gowda *et al.* (2018)
Milk	4.0% flaxseed oil	Tang *et al.* (2016a, 2016b, 2016c, 2016d)
Solid drink powder	50% flaxseed oil	Tang and Bian (2018c, 2018d)
Yoghurts	2.0% flaxseed oil 2.0% flaxseed oil plus flaxseed flour 1.0%	Tang (2019a, 2019b) Kumar *et al.* (2017)

Bakery products

Many studies have investigated the potential applications of flaxseed oil in various bakery products (Osuna *et al.*, 2018). Although most of the studies are focused on the laboratory scale, the results indicate bakery products may be ideal formations for the applications of flaxseed oil due to huge consumption of bakery products. Rangrej *et al.* (2015) prepared cookies incorporated flaxseed oil with different replacement ratio, and showed that the physical properties of cookies such as weight, diameter, thickness, spread ratio and breaking strength etc., improved as the replacement ratio increased. The acceptable quality of cookies was affected if shortening replacement with flaxseed oil was more than 30%.

Milk and milk products

Milk and milk products are good candidates for flaxseed oil fortification due to their high consumption frequency and low storage temperature (4°C) (Bermudez-Agurirre and Barbosa-Canova, 2011). Bermudez-Agurirre and Barbosa-Canova (2011) incorporated flaxseed oil into selected cheeses (queso frsco, cheddar and mozzarella), and found the obtained cheese exhibited a good storage stability, which could storage around 16 days under refrigerated conditions. Goyal *et al.* (2016) fortified indian yoghurt *dahi* by the incorporation of flaxseed oil powder, and showed that acidity of *dahi* fortified by flaxseed oil was higher compared to that of the control after 12 days of storage. Around 21% ALA in fortified *dahi* was reduced after being stored for 15 days. Also, Veena *et al.* (2017) fortified *dahi* by using flaxseed oil, phytoserols and polydextrose. The results showed that pH and acidity of *dahi* were not influenced by the incorporation of functional compounds. What's more, fortified *dahi* and control samples presented similar mouthfeel. Fortified *dahi* contained 282.53 mg ALA, 415.92 mg phytoserols and 1.019 g polydextrose. Fortified *dahi* also presented highly chemical stability after 8 days of storage. Baba *et al.* (2018) fortified yogurt with flaxseed and walnut oils using guar gum as a stabilizer. The authors found syneresis and antioxidant properties of fortified yogurt improved, whereas the viable count in yogurt reduced, compared to the control yogurt. The sensory evaluation results indicated overall quality of yogurt fortified by walnut oil was better compared to that fortified by flaxseed oil. Kumar *et al.* (2017b) prepared fruit yogurt by incorporating flaxseed oil, flaxseed flour and fruits, and showed that the addition amounts of flaxseed could significantly affect sensory property of yogurt. The maximum addition of flaxseed oil into yogurt was 2.0%. ALA content in optimized fruit yogurt samples could be reached up to 22.80%.

Meat products

Bolger *et al.* (2018) showed the addition of flaxseed oil into chicken sausages affected the physical properties of the sausage matrix depended on the addition type of flaxseed oil. Encapsulated flaxseed oil form could induce greater significant influence on the physical properties of the sausage than other types of flaxseed oil. Reddy *et al.* (2016) investigated the possibility of rice bran oil and flaxseed oil in the development of designer chicken shred. The results showed that obtained chicken shred was with a good overall acceptability. Therefore, the authors suggested that flaxseed oil and rice bran oil can be utilized to produce healthy chicken foods. Bilska *et al.* (2018) fortified liver pate using flaxseed oil and flaxseed extract, and indicated the level of the saturated and monoenoic fatty acid was significantly reduced by 12% after the replacement of animal fat with flaxseed oil. What's more, the replacement also could increase phytosterols contents in liver pate. Debusca *et al.* (2013) fortified Alaska pollock surimi seafood by incorporating 10% ω-3 blending oil (flaxseed: algae: menhaden, 8: 1: 1). The results showed that the rheological and textural properties of obtained surimi were significantly improved after the incorporation of ω-3 blending oils. In the study of Pietrowski *et al.* (2011, 2012), impact of the addition of ω-3 blending oils (flaxseed, algae, menhaden and krill) on texture property of surimi seafood was studied. The results showed that texture property of surimi was not significantly influenced after being incorporated ω-3 blending oils.

Ice cream

Ice cream may be an ideal food system for incorporating flaxseed oil due to its low storage temperature (-18 °C). Gowda *et al.* (2018) prepared ice cream incorporated with flaxseed oil powder, and revealed that ALA content in fortified ice cream deceased 18.74–21.38% after 120 days of storage. The author concluded that flaxseed oil powder could be incorporated into ice cream at 4.0% level.

Conclusion

Among the bioactives in flaxseed, research scientists and consumers are interested in flaxseed oil, particularly ALA in flaxseed oil. At present, flaxseed oil-based products have been available. Though we've made some achievements, more investigations should be carried out in the future. Firstly, many consumers do not sufficiently realize the potential advantages of flaxseed oil for our health. Therefore, we need to improve cognitive ability for flaxseed oil in the future. Secondly, the high value-added flaxseed oil based products are still limited, and should be developed. Thirdly, because of poor stability of ALA in flaxseed oil, application of flaxseed oil in food industry still is facing a great challenge. In order to minimize oil oxidation, many advanced techniques, for example the production technology of nano-emulsion (micro-fluidization, microwave, high power ultrasound etc.), spray drying, etc., should be attempted to protect flaxseed oil, and will further expand the utilization of flaxseed oil. In addition, although more evidence have indicated flaxseed oil has health promoting benefits, many more studies need to be carried out to resolve the results regarding the mechanisms of flaxseed oil for disease treatment. Furthermore, the production of ALA enriched animal origin products by feeding flaxseed oil enriched diet, should be developed further.

Conflict of interests

None.

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Compliance with Ethics statements

This is a review paper, which does not include animal or human experiments.

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