REVIEW

Current Knowledge of Content and Composition of Oat Oil—Future Perspectives of Oat as Oil Source

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Abstract

The oat oil composition is unique among cereals; however, the industrial exploitation of oat oil still needs more attention. The health claims authorized by the FDA and the EFSA have led to a significant increase in the industry's interest in oats as an industrial crop. The current focus is put on the extraction of fibre/beta-glucan or oat proteins. In contrast, the fat present in oats and especially its functional components do not attract sufficient industrial attention. The paper presents a concise analysis of the current state of knowledge about the content and composition of oat oil (perceived as oil as product, not fat content) regarding oil extraction methods and analysis. The profound study suggests that oil separation should be obviously taken into account during oat fractionation for industrial products. Such an approach will be in agreement with sustainable management of natural resources and should be taken into account when planning full utilization of each plant crop.

Keywords Oat oil · Oil extraction · Phospholipids · Glycolipids

Introduction

The world oat harvest in 2018 amounted to 23,412 tons per hectare while the area of oat cultivation in the whole globe in the years 2014–2018 ranged from 9.5 million ha to 10.1 million ha. Meanwhile, in Europe, a rising trend of area of oat harvested in the years 2015–2018 is observed (FAOSTAT, 10.08.2020). Such an opposite trend noted by FAOSTAT data suggests the intensive interest put in oat crop production in Europe (Fig. 1).

The amount of horses fed oats is constantly decreasing; therefore, the rise of cultivation area of oats can only be driven by recent findings regarding the oat ingredients.

In the past, oats were mainly treated as a phytosanitary plant or planted for horse feeding purposes (Gorash et al. 2017). Currently, oat grain is increasingly used in the food industry due to its rising use in exclusion diets, e.g. for coeliac patients (Gilissen et al. 2016; Harasym 2011) as well as in health benefits (Martínez-Villaluenga and Peñas 2017). In food production, oats are seen as a source of not only protein with the highest biological value but also minerals, vitamins, and dietary fibre (Piątkowska et al. 2010; Sang and Chu 2017), including soluble fibre fraction, especially β-glucans (Błaszczyk et al. 2015; Suchecka et al. 2015, 2016, 2017) and essential fatty acids (Halima et al. 2015; Piątkowska et al. 2010; Sahasrabudhe 1979; Zhou et al. 1999).

Oats in their unique and rich composition contain antioxidants and biomolecules (Halima et al. 2015) essential for health, compared with other basic cereals such as barley, wheat, and rice. Polyphenolic compounds, avenanthramides, tocochromanols, phytic acid, and EFAs including α-linolenic acid, melatonin, inositol phosphates, phytosterols and the water-soluble β-glucans mentioned above offer a wide range of pharmacological application especially against civilization diseases, e.g. against cardiovascular diseases (Kawka and Achremowicz 2014; Zieliński et al. 2012).

Currently, oat varieties with different chemical composition are used in oat cultivation (Gorash et al. 2017). Research is also being conducted on the improvement of quality and increase in yield of varieties containing bioactive compounds (Kawka and Achremowicz 2014). Varieties rich in β-glucans and containing specific lipids and antioxidants are

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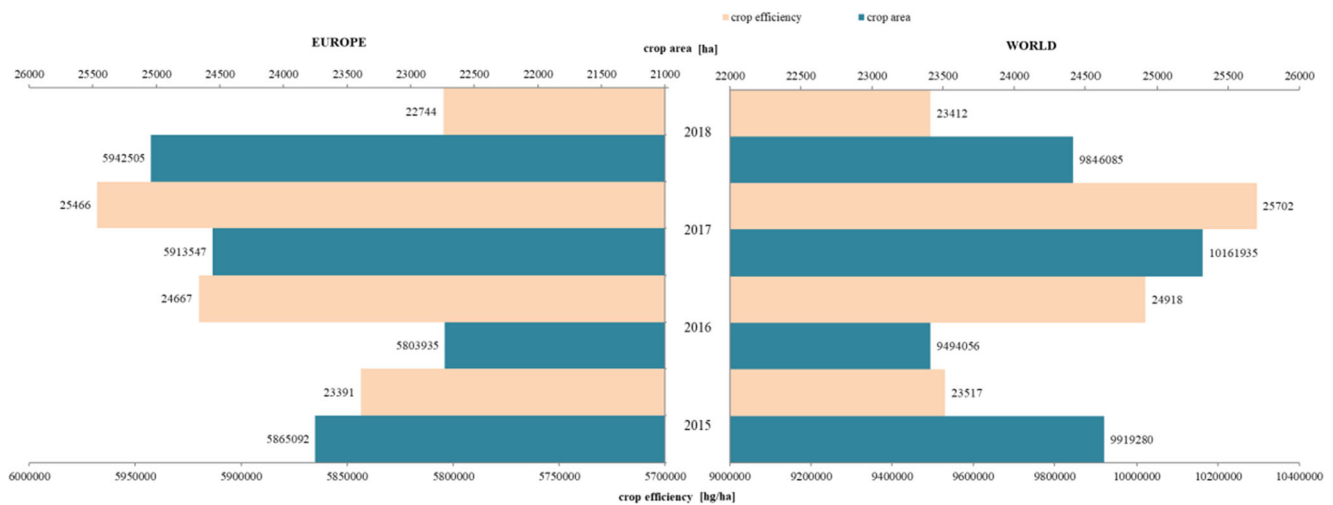
Fig. 1 Crop efficiency and crop area of oat cultivation from 2015 to 2018

useful for food and pharmaceutical industry, while feed producers prefer varieties containing higher amounts of protein and lipids (Kawka and Achremowicz 2014). The introduction of new, naked, and husked oat varieties into the cultivation creates much greater opportunities for their use in the food and pharmaceutical industries (Gorash et al. 2017).

Recent years have seen an increase in consumer knowledge and awareness of the nutrient content of oats (Martínez-Villaluenga and Peñas 2017; Sang and Chu 2017), which has led to a greater demand for products based on this cereal (Rasane et al. 2013). Although the production of oats worldwide has declined over the last decades, innovation in the use of this plant is increasing, creating opportunities to increase the value of yields. New methods and techniques of oat grain fractionation make it possible to exploit its potential as a raw material in many industrial sectors. Oat grains as well as their preparations can be used to produce a new generation of products in the pharmaceutical industry (Wang et al. 2011), chemical industry (Kusch et al. 2011), cosmetic industry (Harasym 2016), food (Ballabio et al. 2011; Flander et al. 2007; Gupta et al. 2010) and for medicinal and dietary purposes (Ballabio et al. 2011) (Fig. 2).

The perception of being natural is the main advantage that attracts consumers and encourages them to buy oat products that contain many functional ingredients.

Oat grains consist mainly of starch (39–55%), proteins (9–16%), lipids (2–18%) and dietary fibre (20–39%) (Frey and Holland 1999; Zhou et al. 1999). It has also been found that the oil contained in oats can have nutritional and technological potential (Price and Parsons 1975; Sahasrabudhe 1979). Oats were not used as a source of edible oil, because its amount in seeds is quite low compared with oilseeds, but it contains much higher levels of lipids than any other cereal grain, making it an excellent source of energy and unsaturated fatty acids (Wilde et al. 2019; Zhou et al. 1999).

Compared with other cereals, oat grains contain oil from 2 to 18% (Frey and Holland 1999; Halima et al. 2015). In 1979, Sahasrabudhe (1979) described the typical oat lipid composition in which they found the following: 51% of triacylglycerols, 7% of free fatty acids, 3% of sterols, 3% of sterile esters, 8% of glycolipids and 20% of phospholipids. Oat lipids can be divided into polar and non-polar fractions. Polar lipids are mainly glycolipids and phospholipids (Sahasrabudhe 1979). Non-polar lipids constitute about 80% of all lipids in oats and contain valuable fatty acids. The majority of them are palmitic acid (20%), oleic acid (35%) and linoleic acid (40%) and fat-soluble antioxidants. Youngs et al. (1977) suggested that the content of free fatty acids depends on the preparation of samples for analysis. In a grain that is ground, the lipase activity increases, thus increasing the content of free fatty acids (Kawka and Achremowicz 2014; Peterson and Wood 1997). Important factors influencing the content of lipids and fatty acids in the grain are soil-climatic conditions and hereditary characteristics during the vegetation of the plant (Frey and Hammond 1975; Karunajeewa et al. 1989; Pisulewska et al. 2011).

At present, oat oil on a larger scale is obtained during the bio-refining of oat grains to obtain more functional components such as β-glucans, while it is treated as a by-product of the target production (Liu 2014; Sibakov et al. 2011). Biorefining as a process of sustainable synergistic processing of biomass into a range of marketable food and feed ingredients, products (chemicals, materials) and energy (fuels, electricity, heat) may in the future become a key method for the production of oat oil, which can be used in many industrial areas (Harasym 2015). At present, the number of product biorefineries is limited due to the fact that some of the key technologies that are part of biorefining technology are insufficiently developed to implement in the commercial market; additionally, there is still no sustainable use of biomass in both

Fig. 2 Volume vs. value of product groups obtained from oat
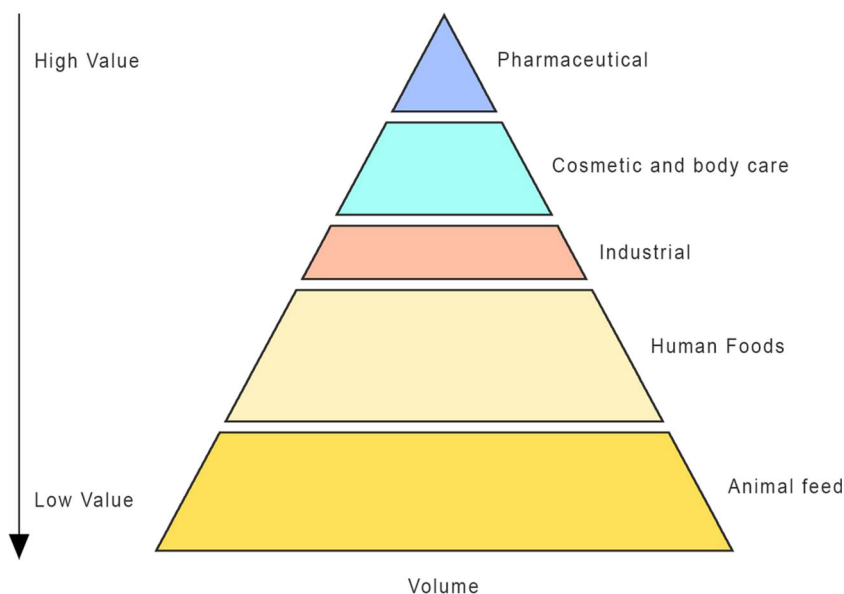
food and non-food applications (Gołębiewski 2019; Harasym 2015). Currently, agriculture is one of the largest sources of biomass, which can be used both for industrial, energy and food purposes. An example of full use of agricultural products may be oats, whose underutilized by-product stream (oat lipids) generated during grain bio-refining may be more widely used in the future and thus contribute to the development of a bioeconomy meeting the highest standards of sustainable development (17 sustainability goals) accepted by the United Nations (UN) countries in 2015 (Gołębiewski 2019; UN 2015). Therefore, the fact of examining all characteristics of the raw material, i.e. biomass in the form of oats, in order to fully and rationally use the rich composition of this cereal remains an important issue.

Composition of Oat Oil

Non-polar Lipids

Inert lipids consist mainly of free fatty acids, triacylglycerols, parts of glycerides, sterile esters and free sterols. Oat fats in 50–60% are made up of that part of the lipids where triacylglycerols are the most numerous (Halima et al. 2015). In 1989, studies confirmed significant differences in the content of both free and bound lipids, as well as in the free fatty acid fraction depending on the oat variety (Karunajeewa et al. 1989). Palmitic, oleic and linoleic acids are the main components of all oat fat fractions (Liukkonen et al. 1992; Zhou et al. 1998).

Phospholipids

Phospholipids (PL), which are the important structural lipids in food and cell membranes (Jacobsen 2018), are also known

as phosphatides. The structure of these compounds is mainly based on phosphatidic acids, which are 1,2-diacylated 3-glicerophosphoric acid esters associated with organic bases or other groups. Price and Parsons (1975) using column chromatography and thin layer chromatography (TLC) found that L-α-phosphatidylcholine (PC), L-α-phosphatidyl ethanolamine (PE) and L-α-lysophosphatidylcholine (Lyso-PC) are the most numerous phospholipids in the oat grains analysed). Sahasrabudhe, using the same method in the study of six different oat varieties, determined the profile of oat phosphatides: L-α-lysophosphatidyl ethanolamine (Lyso-PE) (20.4%), L-α-phosphatidyl ethanolamine (PE) (14.8%), L-α-phosphatidyl glycerol (PG) (9.5%), L-α-phosphatidylinositol (PI) (3.9%) and L-α-phosphatidylserine (PS) (3.2%), stating that the L-α-phosphatidylcholine (PC) content (29.9%) is the highest, thus confirming that the phospholipid content of different oat varieties is similar (Montealegre et al. 2012; Sahasrabudhe 1979).

The amount of phospholipids in oats shows a high variability from 6 to 26% of all lipids (Zhou et al. 1999). The main building block of this part of the lipids is phosphatidylcholine (45–51% of all phospholipids) (Youngs et al. 1977). The others are mainly phosphatidyl ethanolamine and phosphatidyl glycerol (Holmback et al. 2001). Studies have also confirmed that the phospholipid content of different oat varieties is similar (Sahasrabudhe 1979). Some studies have shown that oat-based emulsifiers have a high economic potential in the food industry due to their better sensory and physical properties than soya-based products. Phospholipids obtained from oats improve the bread volume, grain size, texture and delay the ageing process of bread (Erazo-Castrejón et al. 2001). To date, there has been little research on the content of phospholipids in oat lipids despite the fact that the role of phospholipids in the human body is significant because they participate in the growth of all body cells and are part of cell

membranes (Gangopadhyay et al. 2015; Montealegre et al. 2012). Recent research shows that phosphatides, i.e. phosphatidylcholine and N-acylphosphatidyl ethanolamine, can be used to create natural oat–based lecithin (Younes et al. 2020).

Glycolipids

Polar fractions of lipids from cereals show high glycolipid content. Compounds that can be distinguished especially in this group of fats are as follows: monogalactosyldiacylglycerols (MGDG), digalactosyldiacylglycerols (DGDG) and sulpholipids (SQDG). Digalactosyldiacylglycerols build membranes of chloroplasts of higher plants and other organelles in the cell. They are found in all tissues involved in photosynthesis, including higher plants, algae and some bacteria. The glycolipid content of oat oil ranges from 7 to 12%. Oat oil obtained by extraction of oat flour with hexane or ethanol contains a very high level of DGDG and is the most common glycolipid found in oat seeds (Andersson et al. 1997; Doehlert et al. 2010; Moreau et al. 2008). Welch reports that oat glycolipids have viscosity-reducing properties and are therefore used as emulsifiers in chocolate products (Welch 1977). Digalactosyldiacylglycerols are amphiphilic and may form lamellar crystalline phases. Recent studies have shown that the polar oat lipid fraction containing monogalactosyldiacylglycerols (MGDG) and digalactosyldiacylglycerols (DGDG) can be a promising emulsifier and form a water-oil emulsion due to their achievable anti-coalescence stability and good creaming prognosis. They can therefore be used to form lipid aggregates, such as water-oil or liposome emulsions. The latter are interesting for nutritional and cosmetic purposes and can be used in pharmaceutical applications (Moreau et al. 2008). Similar to phospholipids, glycolipids can be used to produce natural oat lecithin (Younes et al. 2020) due to their polar properties.

Oat Lecithin

Emulsion-based foods and beverages are thermodynamically unstable systems that tend to split into unmixable phases. To stop this process, manufacturers add emulsifiers, usually of synthetic origin, to such food products. However, it is the 'natural' products that do not contain synthetic food additives that are of greatest interest to consumers today (McClements and Gumus 2016; Ralla et al. 2018). In current dietary trends, the composition of food products is becoming a key issue for the consumer, which also translates into the choice of the right emulsifier to affect the stability and then the quality of the product. The increase in diversity on the food market forces the search for new solutions in the field of food preservation; therefore, there is a constant demand for emulsifiers with new properties. The answer to this may be new emulsifiers

obtained by extraction of polar lipids from previously overlooked sources, such as oats (McClements 2015; Younes et al. 2020). The European Food Safety Authority on Food and Flavour Additives (FAF) in its scientific opinion proposed the use of oat lecithin as a safe food additive in the proposed category 'Cocoa and chocolate products'. Oat lecithin as an additive is an oil extracted by means of ethanol from oat grains. This oil is then fractionated to obtain lipids with greater polarity. The lecithin thus obtained is yellow-brown in colour and has a taste of oat flakes. Oat lecithin consists mainly of non-polar lipids (58% w/w) and polar lipids (35% w/w). The non-polar fraction consists mainly of triglycerides while the polar lipids consist of 20–25% glycolipids (monogalactosyldiacylglycerols (MGDG) and digalactosyldiacylglycerols (DGDG)) and 15–20% phospholipids including phosphatidylcholine and N-acylphosphatidyl ethanolamine. This lecithin also contains saturated (mainly palmitic and steric), monounsaturated (oleic) and polyunsaturated (linoleic and alpha-linolenic) fatty acids. When used as a food additive, oat lecithin is expected to undergo the same hydrolysis and biotransformation in the gastrointestinal tract to metabolites, as is the case for the digestion of other edible oils and esterified fatty acids and lecithin (E322). In addition, Younes and others report that this additive does not show genotoxic concentrations that could cause cellular mutagenic growth and, due to the nature of the formulation (bio-refinement), no allergic risk is expected, as is the case with soya-based emulsifiers and chicken eggs (Younes et al. 2020). Oat lecithin, which is also an oat oil, and which is mainly composed of non-polar lipids, may also provide a medium for the compounds with antioxidant potential dissolved in them (Guan et al. 2018; Peterson 2001). Recent studies show that preparations based on oat oil can have a potential protective effect against certain pathological conditions due to their antioxidant properties (Halima et al. 2014; Tong et al. 2014).

Oat Oil Antioxidant Activity

Oat oil is a source of natural antioxidants such as tocopherols, alk(en)iloresorcinols, phenolic acids and their derivatives and avenanthramides, which are unique to oats and do not occur in any other cereals (Brindzová et al. 2008). Phenolic compounds have a health-promoting potential due to their anti-inflammatory and antioxidant effects. The already mentioned β-glucans, which also have an antioxidant effect, are contained in soluble fractions of dietary fibre and take part in glucoregulation and cause a decrease in cholesterol levels in humans (Harasym 2011). Fat-soluble tocopherols, tocotrienols and vitamin E are compounds that are biologically active due to their ability to give phenolic hydrogen atoms to free radicals, which allows to interrupt destructive chain reactions and thus inhibits the growth of cancer cells (Halima et al. 2015). The most characteristic group of

antioxidants contained in oats are avenanthramides. These compounds are phenolic derivatives consisting of amides of hydroxycinnamic acid and hydroxyanthranilic acid. At least 20 different types of combinations of phenolic compounds with anthranilic acid derivatives present in oats are known, but their chemical structure has not been fully identified. Avenanthramides show anti-inflammatory, anti-atherosclerotic effects, prevent itching of the skin and inhibit the production of proinflammatory cytokines (Liu 2014). Oat oil also contains such antioxidants as: organic acids including coffee acid, ferulic acid, p-hydroxybenzoic acid, vanilla acid and sterols and flavonoids. The use of modern food processing techniques, i.e. pressure, ultrasonic, liquid or enzymatic extraction, can ensure the isolation of bioactive compounds from the oat matrix. According to epidemiological and biological studies, the consumption of oats has a beneficial effect on health by reducing oxidative stress and chronic age-related diseases and has anti-cancerogenic properties (Gangopadhyay et al. 2015). Antioxidants contained in oats can also contribute to the stability and taste of food products (Peterson 2001). Further research and development is needed to identify cost-effective ways of fractionating the rich nutrients contained in oats that can be used in various industries and, through their enormous potential and empirical value, attract consumers.

Oat Oil Recovery and Analytics

Different methods are used for the analysis of oat lipids, which may concern the determination of the total fraction as well as individual groups of lipids. The complexity of these methods is determined by the type of lipid fraction to be determined (total, free, bound), additionally, depending on the method of measurement, which can be carried out directly on the whole grain intact or after the initial extraction of grains, groats or oat flour. The choice of method for the determination of a given lipid fraction depends on the purpose of the analysis. The total amount of oat lipids equivalent to oil or fat is determined by extraction, spectroscopy or analysis of the fatty acid profile by chromatography (Zhou et al. 1999). The following Table 1 shows sample results which show significant differences in

the total content as well as in individual components of oat oil depending on the solvent systems used.

Solvent Extraction Methods

Solvent extraction is the most common method used to determine lipid content (Frey and Hammond 1975; Peterson and Wood 1997; Price and Parsons 1975; Sahasrabudhe 1979; Youngs et al. 1977). Extraction methods with gravimetric measurement using the Soxhlet apparatus or Goldfish systems are classical techniques for the isolation of fats from solid samples, e.g. ground oat groats (Zhou et al. 1999). The solvent systems used by the extractors are very diverse, ranging from single-phase non-polar solvents to multiphase polar mixtures e.g. WSB (water-saturated n-butanol), which ensure the selective separation of the fat fraction. Nevertheless, there are few solvent systems that extract fats effectively. Non-polar solvents such as hexane or ether are effective for the isolation of so-called inert fats from cereal grains, while they are weak solvents for polar lipids, in particular phospholipids bound to cell membranes, which are effectively extracted by polar solvents (Zhou et al. 1999). Sahasrabudhe examined seven solvent extraction systems and showed significant differences in total lipid content and for different lipid groups. Table 2 below shows the results of the total oat oil content tests depending on the purpose of the test and the type of oat samples for polar solvent extraction.

Extraction Methods with Supercritical Carbon Dioxide

Recent discoveries prove that extraction with supercritical carbon dioxide (SC-CO$_2$) (Pisulewska et al. 2011) may be an effective method to extract non-polar oat lipids in the future. Andersson et al. using this type of extraction developed the process of obtaining digalactosyldiacylglycerols (DGDG) from oats, thus confirming that this method can be used to extract selected components of oat oil (Andersson et al. 1997). By optimizing the fractionation process on the nozzle, to which two streams, a solution of oat oil and supercritical carbon dioxide is fed coaxially. During the extraction process, a spray jet is produced, which facilitates contact with the

Table 1 Total lipid content and lipid composition extracted by various solvent systems in groat of Hinoat variety

	Ethanol	Methanol (85%)	WSB	Chloroform/methanol (2:1)	n-hexane/diethyl ether (8:2)	Isopropanol	n-hexane
Total lipid content	8.84	8.03	6.93	6.31	6.29	5.96	5.57
Sterol esters	2.04	tcs	2.09	0.13	0.64	nd	0.88
Triacylglycerols	3.58	3.19	3.13	3.39	3.61	3.21	3.61
Partial glycerides	1.09	1.5	0.67	0.68	1.3	1.18	0.68
Glycolipids	0.38	0.68	0.10	0.60	0.34	0.49	0.08
Phospholipids	1.69	2.64	0.92	1.55	0.38	1.06	0.31

nd not detected, tcs traces, WSB water saturated butanol (Sahasrabudhe 1979)

Table 2 Total content of oat oil by solvent extraction

Oat species/variety and fraction	Sample preparation	Solvent	Conditions	Determination methods	Objective	Oil content (%)	Other compounds	Ref
American variety 'Chief'	Oat samples were ground in the cyclone mill 'Udy' and sifted through a sieve of 0.024 in.	Chloroform/methanol/water (1:1:0.9 v/v/v)	Ground sample mixed with chloroform: methanol: water (1:1:0.9 v/v/v), extracts evaporated to dry and dissolved in diethyl ether for 96 h	• Thin layer chromatography (TLC) • Gas chromatography (GC)	Identification/quantitative determination	6.6	• Fatty acids • Glycolipids • Phospholipids	Price and Parsons (1975)
445 American varieties of 5 diploid species: A. brevis, A. ludoviciana, A. pilosa, A. strigosa, A. wiestei; 1 tetraploid species: A. barbara; 3 hexaploid species: A. fatua, A. sativa, A. sterilis	Samples for spectroscopic testing (NMR) were dehulled; samples for chromatography were dried in a vacuum dryer at 105 °C then ground.	Heptane	Soxhlet extraction; ground sample mixed with heptane, then with 1 M sodium methoxide	• Nuclear magnetic resonance imaging method (NMR) • Gas chromatography (GC)	Identification/quantitative determination assessment of extract of oat oil in terms of cost-effectiveness of the process	2.0–11.0	• Fatty acids	Frey and Hammond (1975)
3 British varieties: 1 hulled variety: Condor; 2 naked varieties: Caesar, Nuprime.	20 g of the sample was ground with petroleum ether	Petroleum ether	Sample was occasionally mixed during 1 h with petroleum ether; the solvent was evaporated at 50 °C	• Gas chromatography (GC) • Titration of thiosulphate	Identification/quantitative determination quality control of changes during storage	–	• Fatty acids • Peroxide number	Welch (1977)
7 Latvian varieties 3 naked: S-156, 33793, 33805 4 hulled:	Samples were ground.	–	Soxhlet extraction	• Gas chromatography (GC) • Liquid chromatography (HPLC)	Identification/quantitative determination	4.0–10.7	• Fatty acids • Vitamin E	Sterna et al. (2014)

Table 2 (continued)

Oat species/ variety and fraction	Sample preparation	Solvent	Conditions	Determination methods	Objective	Oil content (%)	Other compounds	Ref
St. Līva, Laima, Arta, St. Dārta.								
2 American varieties: Dal, Forker	Oat samples were hand-dehulled and ground	WSB diethyl ether	Ground sample was extracted with diethyl ether in the Goldfish extractor for 7 h; then, the extract was evaporated at 50 °C under vacuum, the residue was extracted with WSB for 0.5 h and re-evaporated, and then a mixture was dissolved in chloroform	• Thin layer chromatography (TLC) • Gas chromatography (GC).	Identification/quantitative determination	–	• Fatty acids • Glycolipids • Phospholipids	Youngs et al. (1977)
12 Canadian varieties: Exeter, Garry, Hinoat, OA-290-5, Gemini, Random Terra, Elgin, Dal, CI-3387, Lodi, CI-4492	samples were immediately dehulled and groats were stored at −20 °C; 100 g of groats was ground in a coffee grinder (Braun No. 4024).	A. hexane; hexane/diethyl ether (80:20 v/v); chloroform/methanol (2:1 v/v/) B. WSB (1:5 scales/v); ethyl alcohol/water (80:20); isopropyl alcohol (1:5 scales/v)	A. Ground samples (40-50 g) were extracted for 16 h separately with: hexane, hexane/diethyl ether (80:20 v/v), methanol (85%), chloroform/methanol (2:1 v/v); B. Ground samples (50 g) were extracted separately with: WSB (1:5 scales/v) for 1 h vigorously stirring at RT; ethyl alcohol/water (80:20) or isopropyl alcohol (1:5 scales/v) under the return cooler. The extracts were evaporated dry on the rotary evaporator. The extracts were then dissolved in a two-phase chloroform/-methanol/water mixture (2:1:0.8) and the chloroform layer was evaporated to dry on the rotary evaporator	• Thin layer chromatography (TLC) • Gas chromatography (GC) • Column chromatography	Identification/quantitative determination the effect of used method on results	4.2–11.7	• Fatty acids • Glycolipids • Phospholipids	Sahasrabudhe (1979)
11 Australian varieties: West, Swan, Avon,	Samples were ground in a laboratory mill and then	A. diethyl Ether B. WSB, chloroform	A. Soxhlet extraction of 3.0 g of sample with diethyl ether for 16 h, evaporation of solvent on the rotary	–	Identification/quantitative determination impact of location (geographical location) and environment	–	• Fatty acids • Associated lipids • Free lipids	Karunajeewa et al. (1989)

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Table 2 (continued)

Oat species/ variety and fraction	Sample preparation	Solvent	Conditions	Determination methods	Objective	Oil content (%)	Other compounds	Ref
Moore, Bulban, Cooba, Barmah, Hill, Coolabah, Algeribee Stout	sifted through 0.5 sieve		evaporator. The residue has been dried at 100 °C. B. Soxhlet extraction of 3.0 g of sample with WSB for 5 h, butanol evaporation on rotary evaporation, the residue dissolution in chloroform and anhydrous Na_2SO_4 addition, filtration on tissue paper and washing the residue three times with chloroform. The chloroform fraction evaporation to dry in the rotary evaporator and drying in a dryer at 100 °C to a constant weight					
Finnish variety	Flour was made from hulled and dehulled oat grains by grinding	Chloroform/methanol (2:1 v/v/)	Extraction in chloroform/methanol (2:1 v/v) for 8 h. Mixture centrifuged for 10 min to remove solids. Extraction was repeated for 2 h. The extracts were combined and evaporated to dry on the rotary evaporator. Extracts were dissolved in chloroform/methanol mixture (100:1 v/v)	• Thin layer chromatography (TLC) • Gas chromatography (GC)	Identification/quantitative determination	—	• Fatty acids • Glycolipids • Phospholipids	Liukkonen et al. (1992)
3 Norwegian varieties Kapp, Mustang, Save	Hulled and dehulled grain were analysed; the grains were soaked, dried and ground.	A. diethyl ether B. diethyl ether (HCl addition)	A. Soxhlet extraction with diethyl ether B. Soxhlet extraction after acid hydrolysis. Acid hydrolysis was done by heating 3 g of flour in 50 ml of 3 M HCl in boiling water for 1 h. The mixture was filtered, and the residue was rinsed with distilled water (pH 4–6), dried and extracted with diethyl ether.	• Gas chromatography (GC)	Identification/quantitative determination the effect of determination methodology on results	A. 7.6–8.6 B. 8.8–10.1	• Fatty acids	Moltenberg et al. (1995)
6 Finnish varieties:	Grains were dried at 105 °C	Chloroform/methanol (2:1 v/v)	Extraction with chloroform/methanol (2:1 v/v)	• Nuclear magnetic resonance imaging (NMR)	Identification/quantitative determination; impact of location	6.1–7.9	• Fatty acids	Saastamoinen et al. (1989)

Table 2 (continued)

Oat species/ variety and fraction	Sample preparation	Solvent	Conditions	Determination methods	Objective	Oil content (%)	Other compounds	Ref
Mikkeli, P lk ne, Jokioinen, Anjala, Ruukki, Kokem ki				• Gas chromatography (GC).	(geographical location) and enviroment			
2 Australian varieties: Yarran, Mortlock	Samples were dehulled with a small dehuller and ground in a grinder	Petroleum ether 40/60	Extraction with oil ether in the Goldfish extraction system by 16 h.	• Gas chromatography (GC) • Infrared spectroscopy (NIR)	Identification/quantitative determination	8.2–10.3 7.8–9.3 9.2–11.5	• Fatty acids	Zhou et al. (1998)
32 Canadian commercial containers: fine, medium and small oat bran as well as wholegrain oat flour	The particle distribution of the raw material has been given by the manufacturer	Hexane	Samples of oat products (100 g) have been weighed and added to 400 ml of hexane. The suspension was mixed for 1 h and then filtered, hexane fractions were vaporized on the rotary evaporation. The residue was left overnight before the extraction of polyphenols. 2 g of defatted flour was transferred into 15-ml screw cap tubes, dissolved with 4 ml water (pH 2.0) and partitioned with ethyl acetate (EtOAc, 3 × 4 ml). EtOAc was removed under a stream of nitrogen gas and the polyphenol rich extracts were dissolved in 500 µL 1:1 mixture of 0.5% acetic acid in water (A) and 0.5% acetic acid in MeOH (B), filtered through 0.45 µm nylon membrane filters	• Liquid chromatography (HPLC) • Total polyphenolic content (TPC)	Identification/quantitative determination The effect of determination methodology on results	2.3–5.0	• Total phenols • Free phenolic acids • Avenanthramides	Walters et al. (2018)
7 Russian naked oat varieties: 1h07, 766h05, 41h04, 74h12,	Samples of cultivated and new varieties of naked oats were selected. Used the	Solvents were used in accordance with the following: GOST 10857-64 GOSTR ISO 5508:2010 GOST R ISO 5509:2000	Methods have been used in accordance with the following: GOST 10857-64 GOST R ISO 5508:2010 G OST R ISO 5509:2000	• Gas-liquid chromatography	Identification/quantitative determination	5.9–7.9	• Fatty acids	Batalova et al. (2019)

Table 2 (continued)

Oat species/ variety and fraction	Sample preparation	Solvent	Conditions	Determination methods	Objective	Oil content (%)	Other compounds	Ref
8h12, 857h05, 37h12o	parameters of the grain volume weight and 1000 seeds weight (~25 g)							
Mongolian and Chinese varieties of oat bran	Oat bran samples were dried at 150 °C for 5 min to inactivate enzymes and ground into powders. Samples sifted and then stored at −20 °C for further use.	Hexane	Hexane extraction at 55 °C for 2 h, the mixture was rotated at 8000 rpm for 20 min, under the N_2 stream	• High-performance liquid chromatography (HPLC) • Determined spectrophotometrically • Gas chromatography (GC)	Identification/quantitative determination of the effect of determination methodology on results	5.8	• Oryzanol • Squalene • Phytosterols • Tocopherol • Total phenol content (TPC) • Fatty acids	Guan et al. (2018)
4 Turkish varieties of oats BDMY-6, BDMY-7, Che-Chois, Y-2330	The grain has been cleaned in an air washer to remove all foreign matter	Diethyl ether	Extraction with diethyl ether in the Soxhlet a camera at (50 °C) (Büchi Universal Extraction System B-811, Essen, Germany)	• High-performance liquid chromatography (HPLC) • Gas chromatography (GC) • ICP-AES	Identification/quantitative determination	2.1–4.8	• Tocopherol • Fatty acids • Mineral contents	Musa Özcan et al. (2006)

extractor. In this case, the triacylglycerols (TG) are dissolved in CO_2, while the target product, digalactosyldiacylglycerols (DGDG), remains in the system (Andersson et al. 1997). Furthermore, by controlling the extraction process by adding a co-solvent, e.g. ethanol or isopropanol, it is possible to isolate the polar fraction of lipids (Forssel et al. 1992). Aro et al. (2007) developed a method to produce the polar oat lipid fraction by adding polar ethanol, which increased the amount of extracted polar components from grains and oat flakes. Table 3 below shows the results of the total content of oat oil depending on the purpose of the study and the type of oat samples for extraction with supercritical carbon dioxide (SC-CO_2).

Chromatographic Methods for Analysis

Chromatography as an analytical technique for separating and determining the components of oat oil was used in the 1970s and early 1980s. These methods belong to planar chromatography and allow convenient fractionation of total fat content in triacylglycerols, phospholipids, glycolipids, free fatty acids and sterols. Sahasrabudhe has determined the lipid composition in oat oil by column chromatography and thin layer chromatography (TLC) (Sahasrabudhe 1979). However, in most cases, the use of these methods to characterize the lipids in oats was excluded due to the different nature of the components and the limitations of the analytical technique, such as the repeatability of results, changes in the composition of the mobile phase during the analysis or band scattering on the chromatogram caused by a decrease in the speed of the mobile phase with distance travelled (Price and Parsons 1975). In order to determine more accurately the composition of oat oil, chromatographic methods are currently used which, depending on the type of eluent, are divided into liquid chromatography (HPLC) and gas chromatography (GC).

Gas chromatography (GC) is used to detect and identify the components of a compound mixture. This technique is very similar to fractional distillation, separating the components of a mixture based on the differences in the boiling points of the substance, which are carried out in a gaseous form and then, using a carrier gas (mobile phase), transferred to the column where the separation of the mixture follows. GC is a reliable separation method because it provides a very accurate quantitative analysis of the fatty acids contained in oat oil. Methanolysis can produce methyl esters of fatty acids which have a relatively high volatility, making their analysis by GC fast (Zhou et al. 1998). Welch using acid methanolysis in the preparation of samples for chromatographic tests estimated the exact content of fatty acids in oat oil. Compared with previous chromatographic measurements, this method has proven to be more convenient, faster and can be used on small quantities of oil samples for routine composition tests (Moltenberg et al. 1995; Sterna et al. 2014; Welch 1977).

Oat oil components with polar properties, such as glycolipids and phospholipids, are determined using more selective and precise high-performance liquid chromatography (HPLC) (Sterna et al. 2014). In this method, the mobile phase (eluent) is made up of single solvents or mixtures of solvents. The eluent, which is introduced into the column, also includes the components of the separated mixture. The choice of the mobile phase must take into account the composition of the separated mixture, the type of detector and the filling of the column. This method has been successfully used by Moreau et al. to determine the polar fraction of lipids in oat oil (Moreau et al. 2008). Liquid chromatography (HPLC) as well as gas chromatography (GC) are fast, reproducible and precise in the separation of compounds thanks to automation, but expensive due to the apparatus (detectors, columns) and the large quantities of harmful solvents and expensive standard substances used in the analysis.

Spectroscopic Methods for Analysis

Spectroscopic studies of lipid content offer the advantages of direct and rapid measurement for samples, e.g. grain, flour and chopped grain without prior preparation with the possibility of simultaneous analysis of composition (Saastamoinen et al. 1989). Brown and Craddock used nuclear magnetic resonance (NMR) to determine the oil content of 4533 samples of cut grain. The lipid content measured by this method was comparable with the data obtained during the determination of fats by non-polar solvent extraction (Brown and Craddock 1972). This method can also be successfully used for direct lipid analysis of the lipid composition of oat oil samples previously obtained by extraction. Manolache et al. determined the lipid composition of six oat oil samples using 1H-NMR by direct measurement without prior processing into fat derivatives. This method made it possible to determine the content of fatty acids (trinitrate, dinitrate, monounsaturated and saturated) contained in oat oil, thus making it possible to distinguish the oil samples and to assess them qualitatively quickly. The results obtained in the future may be used for authenticity tests for different types of cereals, as well as for pseudo-grains (Manolache et al. 2013).

Other spectroscopic methods for determining the composition of cereals include techniques based on the measurement of near, medium and far infrared oscillatory spectra. Law et al. using far infrared (NIR) determined the protein moisture and fat content of grain. Over the next decades, this method has become one of the most used methods for continuous monitoring and control of product quality in the food industry. The infrared spectroscopic examination enables rapid analysis of samples without prior preparation for measurement and is also non-invasive. The advantages are also low costs and no use of harmful organic solvents in the determination. In addition to these advantages, this method has one major disadvantage due

Table 3 Total oat oil content results for extraction of supercritical carbon dioxide (SC-CO$_2$)

Species/variety and fraction	Sample preparation	Solvent	Conditions	Determination methods	Objective	Oil content (%)	Other compounds	Ref
4 varieties 2 hulled: Krezus, STH 7105; 2 naked: Polar, STH 7505 family.	Samples were ground in a laboratory grinder (type WTŻ–1).	SC CO$_2$ Purity of 4.5 (99.995%).	Extraction with SC CO$_2$ at 100 °C, CO$_2$ flow was 1.5 dm^3/min (after decompression), CO$_2$ pressure 9000 psi, extraction time 50 min (10 min static extraction and 40 min dynamic extraction)	• Gas chromatography (GC)	Identification/quantitative determination; impact of location (geographical location) and environment and the genotype of the plant.	3.9–5.8	• Fatty acids	Pisulewska et al. 2011
German variety	Grains were milled primarily extracted with isopropanol at 73 °C. Crude oat oil, after solvent removal under vacuum, was degummed with hot water (1:10 w/w) by mixing at 65 °C for 30 min. Centrifugation at 13,000 rpm for 30 min removed hydrated polar lipids. Polar and non-polar fractions were dried by freeze-drying. Fifteen grams of crude oat oil was dissolved in 300 ml of hexane and ultrafiltrated. Hexane was removed in a vacuum evaporation.	SC CO$_2$ Isopropanol	The lot size ranged from 250 to 1 kg. The extraction pressure ranged from 250 to 600 bar, while extraction temperature between 40 and 55 °C. The separator pressure was 70 bar and the extracted non-polar lipids were collected through the lower separator valve at specified intervals, while polar lipids were collected from the extraction vessel after the process.	• Gas chromatography (GC) • Liquid chromatography (HPLC) • Karl-Fisher titration (AOCS) • Iodometric titration for number of peroxides (AOCS) • Insoluble substances in acetone—gravimetrically	Identification/quantitative determination; examination of the effect of the method on the properties of extracted components.	—	• Triglycerides • Fatty acids, phospholipids • Glycolipids • Water • Tocopherols • Peroxide number	Forssel et al. (1992)
Swedish oat bran	—	SC CO$_2$ acetone	1 kg of bran was heated under a return cooler with acetone (1.5 l) for 1 h. The procedure was triplicated. Fifty-two grams of oil was obtained. Then, the oil was fractionated by SC-CO$_2$ for triacylglycerols (TG) and digalactosyldiacylglycerols (DGDG) at 400 atm.	• Liquid chromatography (HPLC)	Identification/quantitative determination	—	• Triacylglycerols (TG) • Digalactosyldiacylglycerols (DGDG)	Andersson et al. (1997)
Finnish variety	Samples were dehulled with a homogenizer or dehulled and mechanically flattened into in the local mill. Both materials were stored at 4 °C prior the analysis.	SC CO$_2$ Ethanol (96%, v/v).	1 kg of sample was extracted at 70 °C and pressure of 450 bar; the flow was 0.4 l/min for 5 h. Then, the extraction was replicated with ethanol addition. The mass ratio of SC-CO$_2$ to EtOH was 10:90. SC-CO$_2$-EtOH extraction	• Gas chromatography (GC) • Liquid chromatography (HPLC) • Weight analysis	Identification/quantitative determination	—	• Triacylglycerols • Fatty acids • Sterols • Carotenoids • Ash	Aro et al. (2007)

Table 3 (continued)

Species/variety and fraction	Sample preparation	Solvent	Conditions	Determination methods	Objective	Oil content (%)	Other compounds	Ref
Mexican stock of fodder oats for cattle	Oat samples were ground in a mill (SK100 comfort Retsch, Germany) and sieved (Ro-Tap®RX-29-E, USA) using seven sieves with pore sizes between 75 and 710 μm. Two fractions with different particle sizes were generated. Large particle size (>250 μm) and small particle size (<250 μm).	SC CO$_2$ purity (99.99%).	was carried out at 70 °C, 400 bar pressure; the flow was 0.25 l/min for 6 h. Half of the ground oats were alkaline hydrolysis with modifiers to release the FA and polyphenols. NaOH (1 M) was used in a ratio of 1:7 (40 °C/90 min) and then neutralized with citric acid (2 M). After hydrolysis, the samples were dried at 50 °C for 8 h and stored at 20 °C at 4 °C. Extractions were carried out using an extractor of supercritical fluid. Extraction time was controlled by cycles (static time + dynamic time). There were four cycles used for all experiments; extraction time ranged from 40 to 80 min.	• Gas chromatography–mass spectrometry (GC–MS) • Liquid chromatography (HPLC) • Oxygen radical absorbance capacity (ORAC) • Total polyphenolic content (TPC)	Identification/quantitative determination; examination of the effect of the method on the properties of extracted components.	–	• Polyphenols • Fatty acids • Antioxidant capacity	Fernández-Acosta et al. (2019)
32 Canadian commercial containers: fine, medium and small oat bran as well as wholegrain oat flour	The particle distribution of the raw material has been given by the manufacturer	SC–CO$_2$	Extractions were carried out using an extractor of supercritical fluid. The system consisted of two pumps, one for CO$_2$, and the other for a co-solvent, an automated pressure regulator, one extractor and two tanks. Oat samples of 100 g were placed in an extraction vessel; CO$_2$ was pumped at 15 g/min. Pressure was set to 350 bar, and the manifold temperature was maintained at 50 °C. The extraction time was 5 h. The oil was collected up to 50 ml of the tube, weighed, and rejected. The residue was used to extract soluble phenolic compounds in water-alcoholic extraction.	• Liquid chromatography (HPLC). • Total polyphenolic content (TPC)	Identification/quantitative determination the effect of determination methodology on results	3.1–5.3	• Total phenols • Free phenolic acids • Avenanthramides • Antioxidant activities	Walters et al. (2018)

to the difficulty to interpret raw spectra, which often requires knowledge of advanced techniques (Roggo et al. 2007). Most near-infrared (NIR) oil determinations are based on the examination of the bands at 1722, 2306, and 2346 nm, which correspond to the combination vibrations for the first supernatant $(CH2)n > 4$ and similar type (Zhou et al. 1999). So far, few studies using NIR method for the measurement of oat components and its application in routine analyses have been published. This technique can be successfully used for the determination of fat and protein content in oats (Lemons et al. 2008).

Measurement in the mid-infrared (MIR) range, which covers the range from 400 to 4000/cm, as well as Raman scattering are good tools for testing and identifying lipids. These methods allow to easily analyse the composition of mixtures by assigning reference bands for the tested compound. In addition to determining the nature of a given substance, quantitative analyses can also be performed. These techniques allow the examination of important parameters concerning lipid mixtures such as the degree of lipid unsaturation, the presence of trans C=C isomers and the type of fats present in the sample. Manolache et al. examined six oat oil samples in the medium infrared range. The area between 3050 and 4000/cm was eliminated as it had no significant effect on the test result (water and noise band). Six bands were obtained from the spectral range of 2800 and 3050/cm, while between 600 and 1800/cm, the next twenty-five most important bands were derived from specific bond vibrations and CHn groups entering the structures of the tested lipids. In total, each of the measured spectra was represented by thirty-one characteristic bands (Manolache et al. 2013).

Conclusion

Oat grain lipids on an industrial scale are isolated to obtain valuable oil due to its high-quality components (Pisulewska et al. 2011; Sahasrabudhe 1979). Oats as a phytosanitary plant have been used as feed in the past due to their high protein and fat content. Although the cultivation of oats has declined dramatically over the last 70 years, especially on mechanized farms, this cereal still remains important for the economies of developed and developing countries for special uses. So far, research on this crop has focused on the determination of nutrients such as fats, proteins and starch. Further research is needed to determine new functional compounds in oats as well as to find innovative solutions for the already known oat ingredients (Rasane et al. 2013). The oil contained in oats has not been used much so far, but thanks to the development of new methods and techniques for the fractionation of lipids, it allows to use its potential in the food industry (Erazo-Castrejón et al. 2001), cosmetics (Harasym 2016) and pharmaceuticals (Moreau et al. 2008).

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