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REVIEW ARTICLE

Novel seeds pretreatment techniques: effect on oil quality and antioxidant properties: a review

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Abstract Seed oil quality is a function of several attributes which include its bioactive compounds, physicochemical and functional properties. These quality attributes are important in seed oil processing as they determine the oil palatability, nutritional and market value. Besides the health, environmental and economic issues related to seed oil extraction using organic solvents such as hexane, other conventional seed oil extraction techniques such as supercritical fluid extraction, enzyme digestion and cold pressing are associated with low recovery of oil and bioactive compounds. Application of novel seeds pretreatments techniques such as microwaving, enzymatic digestion, pulsed electric field and ultrasonication do not only improve the oil yield and quality attributes, but also reduces seed oil extraction time, solvent and energy consumption. Higher phenolic compounds, carotenoids, tocopherols, phytosterols and antioxidant properties in oil from pretreated seeds offer health benefits related to the prevention of cancer, diabetes, obesity, inflammatory and cardiovascular diseases. Increased consumer interest in functional foods and the potential of seeds pretreatments in enhancing the extractability of bioactive compounds from plant material has increased the application of novel pretreatment techniques on diverse oilseeds. This review describes the commonly studied novel seeds pretreatment techniques and critically discusses their influence on the oil physicochemical attributes, oxidation indices, bioactive compounds and antioxidant properties.

Keywords Seeds pretreatment · Phenolic compounds · Tocopherols · Phytosterols · Antioxidant properties

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Introduction

The consumption of seed oil is important to human health as it provides the body with energy, essential fatty acids and fat-soluble vitamins. Seed oil also contains bioactive compounds with multiple functional properties such as antioxidant, anti-cancer, anti-diabetic, anti-obesity, anti-inflammatory, neuroprotective and nephroprotective (Follegatti-Romero et al. 2009; Boussetta et al. 2014; Koubaa et al. 2016; Talekar et al. 2018). These functional properties have stimulated research interests in seed oils' potential application in pharmaceuticals, nutraceuticals and foods (Monfalouti et al. 2010; Vermaak et al. 2011). In the food industry, seed oils are consumed directly on fruit and vegetable salad, used for cooking or as a dip for snacks such as bread.

Extraction is one of the key processes in the production of seed oil. Commonly used seed oil extraction techniques include cold pressing, solvent extraction, supercritical fluid extraction and ultrasound-assisted solvent extraction.

These extraction techniques have a variety of limitations. In addition to health, environmental and economic related concerns, common seed oil extraction techniques have a low recovery of oil and bioactive compounds. For instance, cold pressing, which requires significant energy input, produces low oil yield (Da Porto et al. 2015; Güneşer and Yilmaz 2017). Concerns such as product, human and environmental safety are attributed to the use of organic solvents such as hexane (Citeau et al. 2018; Fetzer et al. 2018). Supercritical fluid extraction, being a green technology, has thus become a primary alternative to conventional seed oil extraction techniques (Zhang et al. 2010), however, it requires high capital investment. Treatment of the oil-bearing seeds before oil extraction has presented multiple advantages which have solved some of the challenges faced by the oil extraction techniques.

Seeds pretreatment was reported to increase oil yield, oxidative oil stability, bioactive compounds recovery and formation of new functional compounds (Đurđević et al. 2017; McDowell et al. 2017; Fathi-Achachlouei et al. 2019; Mazaheri et al. 2019). Yield is a major factor in seed oil production as maximum oil extraction means that higher volumes of the product can be sold. Enhancing seed oil oxidative stability and functional compounds may improve its shelf life and market value. Commonly reported seeds pretreatment techniques include roasting, microwaving, enzymatic digestion, pulsed electric field and ultrasound exposure (Fig. 1) Increase in oil yield (27%), phenols (796%), tocopherols (14%), carotenoids (47%) and punicic acid (11%) were reported in pretreated camellia, rape, hemp, black cumin and pomegranate seeds, respectively (Zhang and Jin 2011; Tan et al. 2016; Zhou et al. 2016; McDowell et al. 2017; Đurđević et al. 2017). The value presented by seeds pretreatment to seed oil has increased researches on different types of oilseeds. The primary focus of this review is to discuss the effect of novel seeds pretreatment techniques on oil quality attributes and antioxidant properties. This review emphasises on microwaving, enzymatic digestion, pulsed electric field and ultrasound exposure as they present sustainable strategies capable of improving seed oil quality, while significantly reducing the oil extraction time, solvent and energy consumption (Fig. 1). An overview of these novel seeds pretreatment techniques and how they alter the structure of the seeds and improve lipids and bioactive compounds recovery will be presented.

Novel seeds pretreatment techniques: an overview

Enzymatic digestion

The application of enzymes disintegrates the seeds matrix by rapturing the polysaccharide-protein colloid system. Cellulase, hemicellulase and pectinase are the common enzymes required to degrade the cell wall (cellulose, hemicellulose, pectin) which act as the primary barrier to the oil accessibility. In plant cells, oil exists as oleosomes (0.2–2.0 µm in diameter), which consists of the triglycerides surrounded by phospholipids and proteins (Nikiforidis 2019). Proteases are required to breakdown the peptides bonds of the proteins surrounding the triglycerides. The knowledge of seeds composition is vital for the selection of the right enzymes. The efficiency of enzyme seeds pretreatment is dependent on factors such as temperature, pH, concentration, seed particle size, hydrolysis duration, water to seed ratio and agitation (Ricochon and Muniglia 2010). The application of a minimum amount of

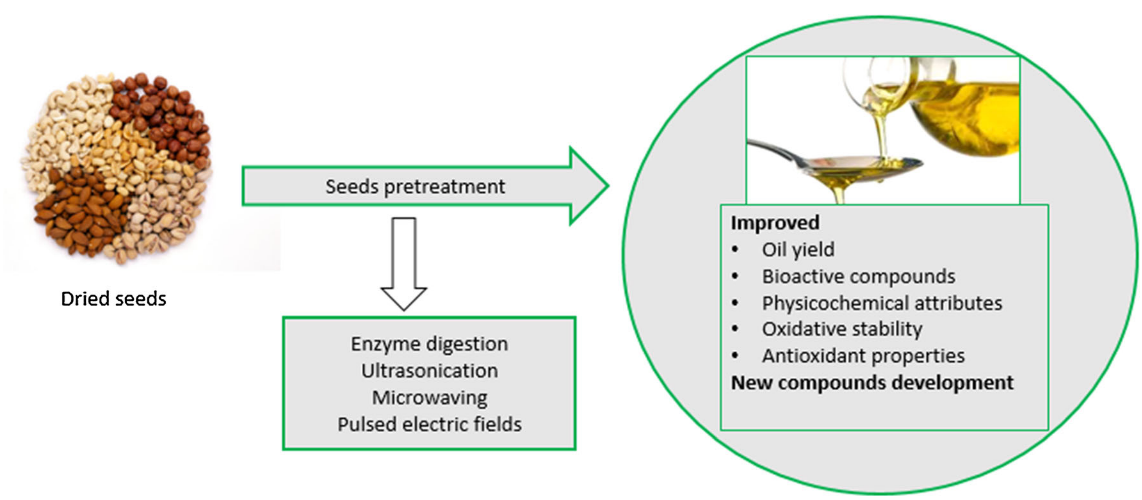

Fig. 1 Summary of the effect of novel seeds pretreatment techniques on oil quality and antioxidant properties

heat during enzyme pretreatment produces oil of superior quality compared to thermal seeds pretreatment techniques.

Ultrasonication

The ultrasound treatment technology generates ultrasound waves which produce high energy bubbles when passed through a liquid. The collapse of these cavitation bubbles on a product's surface induces the disruption of seed cell walls, particle size reduction and enhanced mass transfer of the cell content (Barba et al. 2016). Various mechanisms are involved in the cell wall disintegration and particle size reduction, which include fragmentation, erosion, capillarity, detexturation and sonoporation (Chemat et al. 2017). The efficiency of ultrasound treatment is influenced by factors such as frequency, liquid viscosity, solvent vapour pressure, external pressure, temperature and available gas (Moghimi and Farzaneh 2018). In addition to improved oil and bioactive compounds recovery, ultrasound seeds pretreatment reduces seed oil extraction time, solvent and energy consumption and overall production costs (Barba et al. 2016).

Microwaving

The microwave treatment technique involves the generation of electromagnetic radiation with frequency ranging from 300 MHz to 300 GHz (Barba et al. 2016). These microwaves penetrate the oil-bearing seeds and convert the electromagnetic energy into heat through ionic conduction and dipole rotation (Gaber et al. 2018). The generated heat energy causes a rapid increase in the temperature of the seeds and creates intracellular pressure which ruptures the oilseeds cell walls, facilitating the release of oil. The effectiveness of microwave pretreatment depends on the dielectric properties of the seeds, frequency, power level, and initial seeds temperature (Spigno and De Faveri 2009). The application of seeds microwave pretreatment improves oil yield, reduces oil extraction time, solvent usage and enhances the efficiency of seed oil extraction techniques (Boussetta et al. 2014).

Pulsed electric field

The pulsed electric field treatment technique is a non-thermal technology, which makes it a promising technique for the extraction of highly valued seed oils. Pulsed electric field treatment is applied to a material placed between two electrodes at ambient temperature or marginally higher than the ambient temperature (Barba et al. 2016). Exposing plant cells to a given electric field induces critical electrical potential across the cell membrane, which causes an electrical breakdown. This induces some structural damage to the cell membrane through the creation of pores in a phenomenon called electroporation (Moradi and Rahimi 2018). Depending on the treatment time, pulse form and pulse energy, electric field strength and temperature, the cell membrane damage can be reversible or irreversible (Sharma and Gupta 2006). Resultantly, this increases the mass transfer of cellular material into the extraction medium. Due to its non-thermal nature, pulsed electric field is a novel technique for the recovery of heat-labile bioactive compounds.

Effect of novel seeds pretreatment techniques on oil physicochemical attributes

Physicochemical attributes are important quality determinants in seed oil processing. Several physical attributes (refractive index, density) and chemical attributes (iodine value, saponification value, fatty acids) have been reported to be insignificantly affected by seeds pretreatment (Guderjan et al. 2007; Soto et al. 2007; Uquiche et al. 2008; Latif and Anwar 2009; Zhou et al. 2016; Moradi and Rahimi 2018). Attributes such as oil yield and colour have been reported to be significantly affected by seeds pretreatment (Sharma and Gupta 2006; Passos et al. 2009; Kittiphoom and Sutasinee 2015; Güneşer and Yilmaz 2017). Therefore, in this section, the review focuses on oil yield, colour and fatty acids, which are some of the most important physicochemical quality attributes of seed oil.

Oil yield

Oil yield is an important variable to seed oil processors as it is one of the key profit determinants for the business (McDowell et al. 2017). Therefore, to obtain the maximum value of the oil yield, alteration of the seed structure to enhance mass transfer of lipids from the seed matrix is essential. As shown in Table 1, oilseeds pretreatment significantly improved oil yield.

Factors such as enzyme concentration, pH, temperature, substrate particle size and digestion time significantly affect oil yield of enzyme pretreated seeds. In the study of Passos et al. (2009) enzymatic pretreatment of grape seeds at a cocktail concentration (pectinase = 569, cellulase = 29, xylanase = 21, protease = 1191 U/g sample), temperature (40 °C), pH (4.0), particle size (< 0.5 mm) and digestion time of 24 h significantly increased soxhlet hexane extracted oil yield by 192%. In the same study, increasing the treatment time and particle size to 120 h and 1.0–1.4 mm, respectively, reduced the oil yield by 30%. The study emphasised on increasing digestion time since enzymatic hydrolysis is a slow process, although this may be regarded as economically unviable. Grasso et al. (2012)

Table 1 The effect of novel seeds pretreatment techniques on oil yield

Type of seed	Pretreatment technique	Oil extraction method	Key finding	References
Grape	Enzymatic pretreatment C1: (pectinase = 569, cellulase = 29, xylanase = 21, protease = 1191 U/g sample) C2: (pectinase = 1708, cellulase = 72, xylanase = 55, protease = 2977 U/g, temperature (40 °C), pH (4.0–7.0), particle size (0.5–1.4 mm) and exposure time of 8–120 h	Solvent extraction with hexane using soxhlet apparatus	Enzymatic pretreatment at concentration: C1, temp: 40 °C , pH: 4 and extraction time of 120 h increased oil yield from 15.3 to 19.5%	Passos et al. (2009)
Soybean	Enzymatic pretreatment (α-amylase, glucoamylase, pectinase, hemicellulase, cellulase, neutral protease) at temp (16.4–83.6 °C), pH (4.45–7.15), time (1.3–14.7 h)	Solvent extraction with hexane using soxhlet apparatus	Higher oil yields (26.78%) and (28.46%) were obtained with enzymatic pretreatment at temp (50 °C), pH (5.8), time (8 h) for collets and flakes, respectively	Grasso et al. (2012)
Pomegranate	Microwave pretreatment (2450 MHz, 2 and 6 min, 100, 250, 600 W and 63–136 °C)	Solvent extraction with hexane using soxhlet apparatus	Microwave pretreatment at 600 W for 6 min increased oil yield from 27.73% (non-pretreated seeds) to 36.34% (microwaved seeds)	Đurđević et al. (2017)
Mango	Microwave pretreatment (2450 MHz, 110, 330, 550 W, 0–150 s)	Solvent extraction with hexane (70 °C) using soxhlet apparatus	Microwave pretreatment at 110 W for 150 s exhibited highest oil yield	Kittiphoom and Sutasinee (2015)
Milk thistle	Microwave pretreatment (2450 MHz, 800 W for 2 and 4 min)	Solvent extraction using hexane (25 °C) under continuous shaking	Oil yield increased from 29.43 to 32.33 and 35.41% after microwaving for 2 and 4 min, respectively	Fathi-Achachlouei et al. (2019)
Black cumin	Microwave pretreatment (2450 MHz, 1100 W, 1–3.5 min)	Cold pressing using a screw press	Black cumin seeds microwave irradiation for 3.5 min increased oil yield by 36.8%	Mazaheri et al. (2019)
Hazelnut	Microwave pretreatment (2450 MHz, 400, 600 W, 120, 180, 240 s)	Cold pressing using a hydraulic press	Microwave irradiation of hazelnuts at 400 W for 240 s enhanced oil yield from 6.1 to 45.3%	Uquiche et al. (2008)
Watermelon	Ultrasonic pretreatment (100–700 W, 10–50 °C, 5–25 s)	Aqueous enzyme extraction	Ultrasonic pretreatment at 700 W, 40 °C for 25 s showed higher extraction rate of 98%	Liu et al. (2011)
Apricot and almond	Ultrasonic pretreatment (42 kHz, 2.5, 10 and 15 min)	Aqueous enzyme extraction	Oil yield for both apricot and almond increased within the range of 19–22%	Sharma and Gupta (2006)
Hemp	Ultrasound pretreatment (20 MHz, 200 W, 10, 20 and 40 min)	Supercritical carbon dioxide extraction	Highest oil yield was exhibited by seeds pretreated for 10 min	Da Porto et al. (2015)
Cannabis	Pulsed electric fields (voltage: 7 kV; pulse intensity: 0, 3 and 6 kV/cm; pulse duration: 0.5 ms)	Cold pressing using a screw press	Application of pulse intensity of 3 kV/cm gave higher oil yield	Haji-Moradkhami et al. (2018)
Sunflower	Pulsed electric field pretreatment (1–7.0 kV/cm, 0.5–15 Hz and 10–50 µs)	Solvent extraction using hexane under continuous shaking	Pretreating seeds at 7.0 kV/cm, 15 Hz for 30 µs improved oil yield from 39.14 to 48.24%	Shorstkii et al. (2017)
Black cumin	Pulsed electric field pretreatment (3.24 kV/cm, 20 µs)	Cold pressing using a screw press	Pulsed electric field pretreatment of black cumin seeds increased oil extraction efficiency by approx. 35%	Bakhshabadi et al. (2017)
Sesame	Pulsed electric field pretreatment (40 kV, 20 kV/cm for 10 µs)	Cold pressing using a texture analyzer	Oil yield increased by 4.9% after pretreatment	Sarkis et al. (2015)
Niger	Pulsed electric field pretreatment (0–5 kV/cm, 20 µs)	Cold pressing using a screw press	Highest oil yield was obtained after pretreating seeds at 1.18 kV/cm	Mohseni et al. (2020a)

also used a multi-enzyme mixture (α-amylase, glucoamylase, pectinase, hemicellulose, cellulase and protease) to pretreat soya bean prior oil soxhlet extraction using hexane. The authors found out that oil yield significantly increased by 85% and 8% when the soya bean flakes and collects were pretreated at pH 5.4, 38 °C for 9.7 h and at pH 5.8, 43.5 °C for 5.8 h, respectively. Li et al. (2012) reported that enzymatic digestion (enzyme cocktail: cellulase, xylanase, pectinase, protease at 2.0% w/w, 40 °C, pH 4.5 and reaction time 5 h) of silybum marianum seeds before solvent extraction using hexane (soxhlet) improved oil yield by 10.47%, further highlighting the importance of enzyme concentration, pH, treatment time and temperature in seeds pretreatment.

The impact of seeds microwave pretreatment on oil yield was evaluated. Đurđević et al. (2017) reported that microwave pretreatment of ground pomegranate seeds (1 > mm) at 100 W for 2 min significantly enhanced the yield of soxhlet hexane extracted oil by 23%. However, increasing the microwave power (250 and 600 W) and time (6 min) did not significantly increase the pomegranate seed oil yield, indicating that 100 W and 2 min was the optimum condition. In another study, microwaving mango seeds at 110 W for 150 s prior to oil extraction with hexane using the soxhlet apparatus significantly increased oil yield by 80% (Kittiphoom and Sutasinee 2015). It was also observed that increasing the microwave power to 330 and 550 W and time beyond 90 and 30 s, respectively, burnt the mango seeds. In agreement with other studies, Fathi-Achachlouei et al. (2019) reported that microwave pretreatment of milk thistle seeds at 800 W for 2 and 4 min improved the hexane extracted (soxhlet) oil yield by 10 and 20%, accordingly. The significance of both microwave power and time on oil yield was also reported from other studies (Table 1).

According to Liu et al. (2011), ultrasonic pretreatment of water melon seeds at 547 W, 48 °C for 23 s prior to aqueous enzyme extraction increased the oil yield by 21% when compared with the untreated sample. Further increasing the ultrasound power, temperature, and time decreased the oil extraction rate. A similar study by Da Porto et al. (2015) reported that ultrasound pretreatment (20 kHz, 200 W, 10, 20 and 40 min) of hemp seeds for 10 min improved yield of oil extracted using supercritical carbon dioxide extractor by 25% which was the optimum oil yield. When the ultrasound time was increased to 20 and 40 min the oil yield significantly decreased. The authors attributed the significant decrease in oil yield to fatty acids degradation and isomerisation at high temperatures caused by prolonged ultrasonication. In a previous study, ultrasonic pretreatment (42 kHz, 2.5, 10, 15 min) of apricot and almond seeds followed by aqueous enzyme extraction significantly enhanced oil yield between 19 and 22% (Sharma and Gupta 2006).

Due to the fact that pulsed electric field pretreatments do not cause significant changes in the structure of the oilseeds, the oil yield is relatively lower compared to ultrasound, microwave and enzyme pretreatments. Haji-Moradkhani et al. (2019) studied the effect of pulsed electric field pretreatment of cannabis seeds (voltage: 7 kV; pulse intensity: 0, 3 and 6 kV/cm; pulse duration: 0.5 ms) on cold pressed oil and reported that highest increase in oil yield (28%) was achieved when a pulse intensity of 3 kV/cm was applied on the cannabis seeds. In a similar study, pulsed electric field pretreatment of sesame seeds (40 kV, 20 kV/cm and 10 μs) significantly improved the yield of cold pressed oil by 4.9% when compared with the untreated sample (Sarkis et al. 2015). The findings were comparable to the results reported by Shorstkii et al. (2017) on pulsed electric field pretreatment (7.0 kV/cm, 15 Hz and 30 μs) of sunflower seeds and oil extraction with hexane using the soxhlet apparatus as can be seen in Table 1.

Colour

Colour is one of the most important parameters for determining visual acceptance of fresh and processed food materials, including seed oil, and thus influences consumer's preference (Pathare et al. 2013). Although seed oil colour is attributed to the presence of pigments such as chlorophyll and carotenoids, products of caramelisation and Maillard reaction that are formed during processing also affects seed oil colour. The effect of seeds pretreatment on oil colour is presented in Table 2.

Microwave pretreatment (2450 MHz, 500 W, 5, 10 and 15 min) of sunflower seeds significantly affected the oil colour (Zhou et al. 2016). For instance, increasing the microwave time from 5 to 10 min and then 15 min changed the oil colour from light yellow to yellow and brown, respectively. Similarly, Tan et al. (2016) reported that increasing microwave time from 5 to 15 min changed the palm oil colour from light orange to dark orange. High microwave power and prolonged seeds heating might cause degradation and isomerisation of carotenoids. Alternatively, increased microwave pretreatment at high power levels promotes the formation of browning substances caused by Maillard non-enzymatic reactions, caramelisation and phospholipid degradation. Establishing the appropriate microwave power and time is thus important to avoid the development of unwanted colour substances which deteriorates the seed oil colour.

Guderjan et al. (2007) applied pulsed electric field (5.0 kV/cm and 60 pulses, 7.0 kV/cm and 120 pulses for 30 μs) on rapeseeds. The authors reported that the oil

Table 2 The effect of novel seeds pretreatment techniques on the oil colour

Type of seed	Pretreatment technique	Key finding	References
Rape	Pulsed electric field (5.0 kV/cm and 60 pulses, 7.0 kV/cm and 120 pulses for 30 µs)	Increasing the pulsed electric field increased the seed oil lightness and yellowness	Guderjan et al. (2007)
Cannabis	Pulsed electric fields (voltage: 7 kV; pulse intensity: 0, 3 and 6 kV/cm; pulse duration: 0.5 ms)	Increasing the pulse intensity to 6 kV/cm improved the oil colour index from 119.8 to 167.2	Haji-Moradkhani et al. (2018)
Rape	Pulsed electric fields (5.0 kV/cm and 60 pulses, 7.0 kV/cm and 120 pulses for 30 µs)	Higher lightness and yellowness were exhibited by oil from seeds pretreated at 7 kV/cm and 120 pulses	Guderjan et al. (2007)
Walnut	Microwave (2450 MHz, 600 W for 1, 2 and 4 min)	Microwaving seeds for 2 and 4 min produced oil higher in yellowness	Zhou et al. (2016)
Orange	Microwave (360 W, 30 min with 3 min pauses after every 3 min)	Microwave pretreatment decreased the oil lightness and yellowness	Güneşer and Yilmaz (2017)
Palm	Microwave pretreatment (1000 W, 2450 MHz, 5, 10, 12, 13, 14, 15 min)	Increasing the microwave time decreased the oil yellowness	Tan et al. (2016)
Hemp	Enzyme digestion (Protex 7L, Alcalase 2.4L, Viscozyme L, Kemzyme, Natuzyme, 40 °C, 6 h, 45% moisture)	Digestion seeds with Natuzyme and Protex 7L produced seed oil with greater yellowness	Latif and Anwar (2009)
Black cumin	Ultrasound pretreatment (30, 60, 90 W, 25 kHz, 30, 45, 60 min)	Higher colour index was exhibited by oil from seed pretreated at 30 W for 30 min	Moghimi and Farzaneh (2018)

lightness and yellowness significantly increased when compared to the oil from untreated rapeseeds. Higher lightness (approx. 40) and yellowness (approx. 35) were exhibited by oil from seeds pretreated at 7 kV/cm and 120 pulses. Haji-Moradkhani et al. (2018) also reported that cannabis seed oil colour index significantly improved by 1.4 folds after increasing the pulse intensity from 0 to 6 kV/cm pretreatment of the seeds, which was the best oil colour index in the study (Table 2). The authors believed that the improved colour index was due to increased porosity of the cannabis seeds cells by pulsed electric field pretreatment, which led to improved release of oil carotenoids from the seeds matrices.

Moghimi and Farzaneh (2018) studied the impact of ultrasound pretreatment (25 kHz, 30, 60 and 90 W, 30, 45 and 45 min) of black cumin seeds on the extracted oil colour index. The authors reported that increasing the ultrasound power from 30 to 90 W and time from 30 to 60 min significantly increased the oil colour index by 7 and 19%, respectively. The findings indicate that varying ultrasound time had more effect on the oil colour index than varying power. Latif and Anwar (2009) investigated the effect of enzyme pretreatment (Protex 7L, Alcalase 2.4L, Viscozyme L, Kemzyme and Natuzyme, 40 °C, 6 h) on hemp seeds and found out that the oil yellowness significantly increased between 25 and 27% for all the enzymes. The significant increase in oil yellowness was attributed to increased dissociation of carotenoids from the carotenoprotein complexes as a result of enzyme pretreatment (Kha et al. 2013). However, the oil yellowness was not significantly different among the enzymes.

Fatty acids

Maximum recovery of fatty acids during oil extraction is essential to enhance the seed oil nutritional quality. The effect of seeds pretreatment on the oil fatty acid composition has been well investigated. There is a general agreement among authors that seeds pretreatment has an insignificant effect on fatty acids composition, which could be beneficial from a nutritional point of view (Lee et al. 2004; Epaminondas et al. 2011; Wroniak et al. 2016; Moradi and Rahimi, 2018).

Durdevic et al. (2017) studied the effect of pomegranate seeds microwave pretreatment (2450 MHz, 100, 250, 600 W, 2, 6 min) on fatty acids composition. Stearic acid, palmitic acid, oleic acid, linoleic acid and punicic acid the primary fatty acids in pomegranate seeds oil did not significantly change after seeds microwave pretreatment. Similar findings were reported by Güneşer and Yilmaz (2017), Soto et al. (2007) and Moradi and Rahimi (2018) from microwave, enzyme and ultrasound pretreated orange, borage and sunflower seeds, respectively. However, combing the pretreatments techniques was reported to affect the oil fatty acid composition significantly. In their study on microwave-pulsed electric field pretreatment (microwave time: 0–200 s, pulse intensity: 0–5 kV/cm) of niger seeds, Mohseni et al. (2020a) reported that the quantity of oleic and linoleic acids significantly decreased. In contrast, the levels of palmitic acid and stearic acid significantly increased. The authors believed that the decrease in oleic acid and linoleic acid was due to thermal degradation.

Effect of novel seeds pretreatment techniques on oil oxidation indices

Peroxide value, acid value, free fatty acids and conjugated dienes

Peroxide value, acid value, free fatty acids and conjugated dienes are primary products of fatty acids oxidation and essential quality parameters of seed oil quality. There is an inverse relationship between the palatability of seed oil and the level of primary products of oxidation. Low levels of peroxide value, free fatty acids, acid value and conjugated dienes indicate high oil palatability and longer shelf life. Therefore, applying seeds pretreatment conditions that minimise the oxidation of fatty acids and maximise the extraction of antioxidative compounds is essential.

The effect of pretreating moringa seeds with microwaves (100 W, 30, 60, 90 s) on the oil peroxide value and the acid value was studied (Da Porto et al. 2015). The authors found out that microwave pretreatment of moringa seeds for 90 s reduced the acid value and increased peroxide value by 41% and 22%, respectively. The level of conjugated dienes did not significantly change after moringa seeds microwave pretreatment suggesting minimum degradation of the hydroperoxides. Uquiche et al. (2008) also investigated the effect of microwave pretreatment (400 W, 2450 MHz, 240 s) with hazelnuts. They established that acid value significantly increased by 17%, while the level of peroxide value was not significantly affected. Similar observations were reported with microwave pretreated (457 and 607 W, 5 min) rapeseeds (Ramos et al. 2017). Despite the increase in peroxide value and acid value after seeds microwave pretreatment, the levels in all the studies conformed to the Codex Alimentarius commission standard on seed oil, which permits a maximum of 15.0 meqO_2/kg oil peroxide value and 4.0 mg KOH/g acid value for unrefined oils (Codex Alimentarius 1999).

According to the study of Da Porto et al. (2015) on ultrasound pretreatment (20 kHz, 200 W) of hemp seeds, exposing the hemp seeds to ultrasound waves for 10, 20 and 40 min significantly increased the conjugated dienes between 29 and 49%. The significant increase in conjugated dienes was attributed to oxidation and isomerisation of polyunsaturated fatty acids such as linoleic and α-linolenic acids. These fatty acids may undergo free radical oxidation or intramolecular sigmatropic rearrangement of the hydrogen atoms to form conjugated bonds (Fig. 2). Moradi and Rahimi (2018) reported that ultrasound (40 kHz, 100 W) and pulsed electric field pretreatment (pulse intensity: 0.8–1.1 kV/cm, time: 1 ms) of sunflower seeds did not significantly affect the seed oil free fatty acid and peroxide value. Similar observations were reported by Haji-Moradkhani et al. (2019) on pulsed electric field pretreatment (voltage: 7 kV; pulse intensity: 0, 3 and 6 kV/cm; pulse duration: 0.5 ms) of cannabis seeds, indicating that pulsed electric field pretreatment of oilseeds may not degrade the quality of extracted oil, despite the increased porosity of the cell walls and cell membranes.

Enzyme pretreatment (Protex 7L, Alcalase 2.4L, Viscozyme L, Kemzyme and Natuzyme, 40 °C, 6 h) of hemp seeds did not significantly change the oil peroxide value and free fatty acids. This phenomenon could be explained by the low temperature employed during seeds pretreatment (Latif and Anwar 2009).

ρ-anisidine value, conjugated trienes and oxidative oil stability

Seed oil hydroperoxides may further decompose to form carbonyl compounds such as aldehydes, alcohols, hydrocarbons and ketones. These secondary products of fatty acids oxidation are responsible for the development of off flavours and odour in the seed oil. The amount of aldehydes (primarily 2-alkenals and 2,4-dienals) may be measured using the ρ-anisidine value.

Zhou et al. (2016) reported an increase in oil ρ-anisidine value after walnuts microwave pretreatment (2450 MHz, 600 W, 1, 2 and 4 min). Exposing the walnuts to microwaves for 1, 2, and 4 min significantly increased the ρ-anisidine values by 1.9, 2.6 and 3.1 folds, accordingly. Similar findings were reported with oil from microwave pretreated palm and peanut seeds (Tan et al. 2016; Ali et al. 2017). Higher microwave power and prolonged exposure time may promote peroxides decomposition into secondary oxidation products, further degrading the seed oil quality.

Ultrasound pretreatment (20 kHz, 200 W, 10, 20 and 40 min) of hemp seeds significantly increased the oil conjugated trienes between 1.5 and 1.9 folds due to the creation of hot spots with high temperatures during ultrasound pretreatment (Da Porto et al. 2015). Latif and Anwar (2009) reported that hemp seeds pretreatment (40 °C, 6 h) with Viscozyme L (3%) and Kemzyme (12%) significantly decreased and increased the ρ-anisidine values, respectively. Pretreatment of the hemp seeds with Protex 7L, Feedzyme and Natuzyme did not significantly affect the oil ρ-anisidine value. In the same study, enzyme pretreatment of hemp seeds had no significant effect on the oil conjugated trienes. Increasing enzyme concentration and treatment time may significantly increase the conjugated trienes

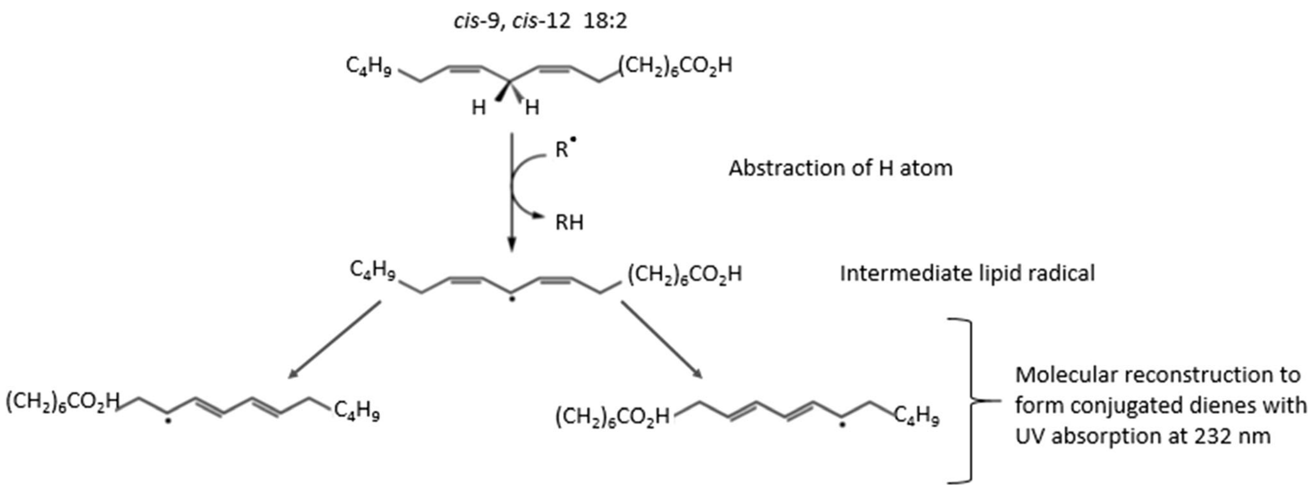

Fig. 2 Formation of conjugated dienes through free radical oxidation using linoleic acid as an example

as indicated in the study of Dandjouma et al. (2008) on enzyme pretreatment (Protamex, Celluclast, 0.1–0.4 g/ 100 substrate, 50 °C, 1–4 h) of bail (*Ricinodendron heudelotii*) seeds.

The oxidative stability of seed oil is defined as the resistance to oxidation during processing and storage and is influenced by factors such as fatty acid composition and antioxidant compounds (Hu et al. 2019). It is often measured using the rancimat method. Azadmard-Damirchi et al. (2010) study on rapeseeds microwave pretreatment (2450 MHz, 800 W, 2 and 4 min) established that microwave pretreatment for 2 and 4 min significantly increased the oxidative oil stability by 5 and 8 folds, respectively. The significant improvement in oil oxidative stability was attributed to enhanced tocopherols compounds after rapeseeds microwave pretreatment. Hu et al. (2018) also reported significant improvement in peanut oil oxidative stability after microwave irradiation (2450 MHz, 700 W, 1–5 min) of the peanuts. The authors observed that the oil oxidative stability significantly increased between 1.8 and 3 folds when microwave time was increased from 1 to 5 min. The results are in agreement with the findings of Uquiche et al. (2008), Yang et al. (2013) and Wroniak et al. (2016) from microwave pretreated hazelnuts and rapeseeds, respectively. However, Bakhshabadi et al. (2017) reported a significant decrease in the oil oxidative stability when microwave power (180–900 W) and time (1.5–4.5 min) were increased during microwave pretreatment of black cumin seeds, which was attributed to the degradation of the antioxidative compounds at high microwave power and prolonged treatment time.

In another study, Latif and Anwar (2009) established that enzyme pretreatment (Protex 7 L, Alcalase 2.4 L, Viscozyme L, Kemzyme, Natuzyme, 40 °C, 6 h, 45% moisture) of hemp seeds significantly improved the oxidative oil stability by 27% with Kemzyme, while the application of Protex 7 L, Alcalase 2.4 L, Viscozyme L and Natuzyme did not significantly improve the oil oxidative stability.

The authors, in their findings, agreed that pretreatment temperature and duration are critical factors in influencing the seed oil stability to oxidation. Depending with the type of seeds, higher microwave power and prolonged microwave or ultrasound exposure time may result in the degradation of fatty acids and formation of primary and secondary oxidation products.

Effect of novel seeds pretreatment techniques on oil bioactive compounds

Tocopherols

Tocopherols are essential natural antioxidants that are crucial in maintaining seed oil quality during processing and storage through prevention of lipid oxidation which may result in rancidity and off-flavours development. Table 3 illustrates the effect of seeds pretreatment on oil tocopherols.

The type of enzyme is one of the most important factors that influence the recovery of tocopherols compounds from the seeds matrices. For instance, Latif and Anwar (2009) evaluated the effect of five different enzymes (Protex 7 L, Alcalase 2.4 L, Viscozyme L, Kemzyme, Natuzyme, 40 °C, 6 h, 45% moisture) on the extractability of tocopherols from hemp seeds. The authors reported that α-tocopherol (23%) and δ-tocopherol (8%) were optimally recovered using Kemzyme. On the other hand, hemp seeds pretreatment with Natuzyme significantly increased the total tocopherols and γ-tocopherol by 14 and 18%,

Table 3 The effect of novel seeds pretreatment techniques on the oil tocopherols

Type of seed	Pretreatment technique	Key finding	References
Sunflower	Ultrasound (US) and pulsed electric field (PEF) pretreatment	PEF pretreatment enhanced the recovery of tocopherols	Moradi and Rahimi (2018)
Walnut	Microwave pretreatment (600 W, 2450 MHz, 0–4 min)	Microwave pretreatment for 1 min resulted in highest tocopherols	Zhou et al. (2016)
Rape	Microwave (800 W, 3, 7 min)	Tocopherols decreased when seeds were microwave heated for 3 min and increased when microwave time was increased to 7 min	Wroniak et al. (2016)
	Microwaving (2450 MHz, 800 W, 0–7 min)	Seed oil individual and total tocopherols decreased beyond 5 min of microwave heating time	Yang et al. (2013)
Chia	Microwave (2450 MHz, 180, 360, 540, 720, 900 W, 15 min)	Tocopherols decreased with increase in microwave power	Ozcan et al. (2019)
Milk thistle	Microwave (2450 MHz, 800 W, 2 and 4 min	Total and individual tocopherols increased with increase in microwave heating time	Fathi-Achachlouei et al. (2019)
Niger	Microwave (900 W, 0–200 s) and pulsed electric fields (0–5 kV/cm, 20 µs)	The amount of α-tocopherols and Δ-tocopherols significantly improved	Mohseni et al. (2020a)
Rape	Microwave (2450 MHz, 540 W, 0, 100, 200 s) and pulsed electric fields (0–5 kV/cm, 0.5 ms)	The δ-tocopherols increased from 0.00 to 30.07 ppm after seeds pretreatment	Mohseni et al. (2020b)
Hemp	Enzyme digestion (Protex 7 L, Alcalase 2.4 L, Viscozyme L, Kemzyme, Natuzyme, 40 °C, 6 h, 45% moisture)	Higher total tocopherols were manifested in oil from seed digested with Natuzyme	Latif and Anwar (2009)
Borage	Enzyme pretreatment (Olivex and Celluclast at 0.3% enzyme to substrate ratio, 45 °C for 9 h)	The α-tocopherols varied from 1480 (untreated seeds) to 1494 mg/kg (enzyme treated)	Soto et al. (2008)
Goldenberry	Enzyme pretreatment (Cellulase EC, Pektinase L 40 (1:1), 50 °C , pH: 4.3, enzyme concentration: 2% (w/w), 2 h)	The β-tocopherols and γ-tocopherols varied from 2.10–2.11 g/kg and 1.08–1.10 g/kg respectively after seeds enzyme pretreatment	Ramadan et al. (2008)
Tiger nut	Enzyme pretreatment (Alcalse, α-amylase and Viscozyme enzymes at pH 8 and 40 °C for 6 h)	The level of α-tocopherols improved from 145.7 to 159.5 µg/g	Ezeh et al. (2016)
Rape	Pulsed electric field (5.0 kV/cm and 60 pulses, 7.0 kV/cm and 120 pulses for 30 µs)	Higher α-tocopherols was exhibited by oil from seed pretreated at 7 kV/cm and 120 pulses Higher α-tocopherols was exhibited by oil from seed pretreated at 7 kV/cm and 120 pulses	Guderjan et al. (2007)

respectively, which represented the optimal recovery of the respective tocopherols. Seeds enzyme digestion results in the breakdown of the bonding forces between the tocopherols and seeds matrices, thereby increasing their release into the oil phase (Uddin et al. 2018). The application of Protex 7L, Viscozyme and Feedzyme did not significantly affect the content of total tocopherols. The use of enzyme mixtures was reported to improve the recovery of bioactive compounds due to their synergistic effect on the seed matrix (Grasso et al. 2012). In this regard, the study of Ezeh et al. (2016) on tiger nuts pretreatment with Alcalase, α-amylase and Viscozyme enzymes at pH 8 and 40 °C for 6 h significantly increased the level of α-tocopherol by 9%. However, the level of β-tocopherol did not significantly improve after enzyme pretreatment an observation which was also reported by Soto et al. (2008) and Ramadan et al. (2008) on borage and goldenberry seeds (Table 3).

Fathi-Achachlouei et al. (2019) investigated the potential of microwave pretreatment (800 W, 2 and 4 min) in improving tocopherols recovery from milk thistle seeds. The α-tocopherol, β-tocopherol, γ-tocopherol, δ-tocopherol and total tocopherols significantly increased by more than 55% after treating the seeds with microwaves for 2 min. Although increasing the microwave time to 4 min reduced the tocopherols, the levels were significantly higher than those from milk thistle seeds not microwaved. Ozcan et al. (2019) pretreated chia seeds with microwaves. The authors observed that increasing microwave power between 180 and 900 W at a constant time of 15 min significantly decreased the tocopherols of pretreated chia seeds. For instance, chia seeds microwave irradiation at 180, 540 and 900 W significantly decreased α-tocopherol by 2, 3 and 7%, respectively. The findings suggest that microwaving chia seeds for 15 min cause significant degradation of the tocopherol compounds. Findings from other authors on the effect of seeds microwave pretreatment on the extracted oil tocopherols are shown in Table 3.

Moradi and Rahimi (2018) reported that ultrasound (40 kHz, 100 W) and pulsed electric field pretreatment (pulse intensity: 0.8–1.1 kV/cm, time: 1 ms) of sunflower seeds slightly but significantly decreased the oil α-tocopherol (1%), whereas the concentration of β-tocopherol, γ-tocopherol and total tocopherol were not significantly affected. In the seed matrix, tocopherols may exist as either free, esterified or glycosylated compounds which may affect their extractability (Uddin et al. 2018). Previous studies by Guderjan et al. (2007) on pulsed electric field pretreatment (5.0 kV/cm and 60 pulses, 7.0 kV/cm and 120 pulses) of rapeseeds concurred with findings of Moradi and Rahimi (2018). Increasing the PEF intensity increased α-tocopherol content but had no significant effect on γ-tocopherol. Integrating pretreatment techniques is a novel and promising technology to optimise the extraction of valuable compounds from plant materials. For example, Mohseni et al. (2020a) established that integrating microwave (900 W, 0–200 s) and pulsed electric field (0–5 kV/cm, 20 µs) and pretreating niger seeds increased the oil α-tocopherol and Δ-tocopherol by 2.8%. Similar observations were reported by Mohseni et al. (2020b) with rapeseeds (Table 3).

Phenols

Seed oil is a good source of phenolic compounds. In addition to antioxidant properties, these bioactive compounds possess biological activities which include anti-inflammatory, anti-microbial, anti-atherosclerosis, and anti-cancer activities. Improved extraction of these bioactive compounds from the seed matrix is therefore vital to enhance the oil functional properties.

In line with this, the potential of rapeseeds microwave pretreatment (800 W, 2 min) in enhancing the oil phenolic compounds was evaluated (McDowell et al. 2017). It was found that total phenolic compounds and sinapic acid significantly improved by 9.23 and 1.98 mg/kg, respectively. Canolol, a derivative of sinapic acid significantly increased from 0.02 to 7.14 mg/kg after rapeseeds microwave irradiation. The authors suggested that canolol was formed from the decarboxylation of sinapic acid through the catalysis of microwave pretreatment. Minor phenolic compounds identified in the rapeseed oil, which include 4-HBA, trans-cinnamic, p-coumaric, syringic acid and vanillic acid, were insignificantly affected by rapeseeds microwave pretreatment. Also, microwave pretreatment (360 W, 30 min) of orange seeds significantly increased the total phenolic compounds by 1535 µg gallic acid equivalent (GAE)/100 g (Güneşer & Yilmaz 2017). These results concurred with findings from microwave pretreatment (800 W, 4 min) of milk thistle seeds, where total phenolic compounds significantly increased by 53.03 mgGAE/100 g (Fathi-Achachlouei et al. 2019).

The effect of pulsed electric field seeds pretreatment on the extracted oil phenolic compounds was investigated. For instance, Guderjan et al. (2007) managed to significantly increase the recovery of phenolic compounds by application of pulsed electric field (5.0 kV/cm and 60 pulses, 7.0 kV/cm and 120 pulses) on rapeseeds. In the same study, the authors established that the recovery of phenols was dependent on the treatment intensity. Applying a pulse intensity of 5.0 kV/cm with 60 pulses and 7.0 kV/cm with 120 pulses significantly enhanced the total phenolic compounds by more than 3 and 4 folds. Similar observations were reported by Haji-Moradkhani et al. (2019) on pulsed electric field pretreatment (voltage: 7 kV; pulse intensity: 0, 3 and 6 kV/cm; pulse duration: 0.5 ms) of cannabis seeds. Moghimi & Farzaneh (2018) studied the influence of ultrasound pretreatment on black cumin seeds. The authors reported that total phenols (121.10 ppm) were optimally recovered when the black cumin seeds were ultrasound pretreated at 90 W for 60 min.

Studies on the impact of seeds enzyme pretreatment on extracted oil phenolic compounds reported varied results. Pretreatment of borage seeds with an equal mixture of Olivex and Celluclast at 0.3% enzyme to substrate ratio, 45 °C for 9 h significantly enhanced the methanol oil extracts total phenolic compounds from 76.71 to 123.42 g Catechin/kg (Soto et al. 2008). In another study, Ezeh et al. (2016) reported that total phenols significantly decreased from 17.9 to 13.2 µgGAE/g oil after pretreating tiger nuts with Alcalse, α-amylase and Viscozyme enzymes at pH 8 and 40 °C for 6 h. In contrast with other studies, Ramadan et al. (2008) observed that total phenolic compounds did not significantly increase after enzyme pretreatment [Cellulase EC, Pektinase L 40 (1:1), 50 °C, pH: 4.3, enzyme concentration: 2% (w/w), 2 h] of goldenberry seeds. The findings from the different studies suggest that the type of seeds, enzymes and treatment conditions have a significant effect on the extractability of the phenolic compounds from the seeds matrices.

Phytosterols

The ability to lower low-density lipoprotein cholesterol and plasma cholesterol absorption, reduce the risk of certain types of cancers and boost immune function has made phytosterols valuable food components (Guderjan et al. 2007).

According to Zhou et al. (2016), microwave pretreatment (2450 MHz, 600 W for 1, 2 and 4 min) of walnuts had a negative impact on the oil phytosterols. Pretreating walnuts with microwaves for 1 min significantly reduced total phytosterols by 40.52 mg/kg, β-sitosterol (21.26 mg/kg), Δ5-avenasterol (1.63 mg/kg), campesterol (8.33 mg/kg), clerosterol (0.22 mg/kg), stigmasterol (7.22 mg/kg) and sitosterol by 1.33 mg/kg. Further increasing the microwave time to 4 min more than doubled the phytosterols losses. Therefore, the optimal microwave time for walnuts for phytosterols was 1–2 min, was marginal losses were observed. Contrarily, Fathi-Achachlouei et al. (2019) reported enrichment of phytosterols with milk thistle seeds microwave pretreatment (800 W, 2, 4 min). It was observed total phytosterols significantly increased from 1816 to 2422 μg/g after treating milk thistle seeds with microwaves for 4 min. Beta-sitosterol the primary phytosterol in milk thistle seed oil significantly increased from 630 to 788 μg/g. Other reported phytosterols, which included cholesterol, campesterol, stigmasterol, clerosterol and Δ7-sterol also significantly improved after seeds microwave pretreatment. Microwave pretreatment of dehulled rapeseeds at 800 W for 6 and 8 min also significantly enhanced brassicasterol, campesterol, stigmasterol, β-sitosterol, Δ-avenasterol and total phytosterols between 5 and 14% (Rekas et al. 2017).

Other authors have studied the effect of applying ultrasound waves (40 kHz, 30 min) on rapeseeds for phytosterols content improvement (Zdanowska et al. 2019). The study reported that rapeseeds ultrasound pretreatment significantly increased the oil brassicasterol, campesterol, β-sitosterol and total sterols by 57.5, 146.20, 209.50 and 412.40 mg/100 g, respectively. Pulsed electric field (5.0 kV/cm and 60 pulses, 7.0 kV/cm and 120 pulses) pretreatment of rapeseeds slightly increased the total phytosterols. Seed oil total phytosterols from non-hulled rapeseeds increased from 619 to 641 mg/100 g after increasing the pulsed electric field to 7.0 kV/cm and 120 pulses (Guderjan et al. 2007). The increase in phytosterols could be attributed to the increased porosity of the seeds cell walls and membranes with increased pulse intensity resulting in the improved release of phytosterols from the fatty acid esters conjugates (Uddin et al. 2018). However, in the study of Ramadan et al. (2008), it was reported that enzyme pretreatment [Cellulase EC, Pektinase L 40 (1:1), 50 °C, pH: 4.3, enzyme concentration: 2% (w/w), 2 h] of goldenberry seeds did not significantly affect the phytosterols content of the extracted oil, indicating that the applied enzymes did not cause a significant breakdown of the bonding forces between the phytosterols and the seeds matrices.

Carotenoids

Carotenoids do not only impart desirable colour to seed oil but also prevent or reduce the risks to be affected by cardiovascular disease, age-related cataract, macular degeneration and cancers (Young and Lowe 2001). Oilseeds are not good sources of dietary carotenoids, and thus maximum recovery of these antioxidant compounds from the seeds matrices is important. Mazaheri et al. (2019) reported that microwave pretreatment (1100 W, 1–3.5 min) of moisture adjusted black cumin seeds significantly improved the seed oil carotenoids concentration between 12 and 62%. The carotenoids bind to seed protein during the thermal pretreatment process to form carotenoids-protein complexes. Protein denaturation due to thermal pretreatment causes fragmentation of the carotenoids-protein complexes releasing the carotenoids in the oil as suggested by Mazaheri et al. (2019). The work reported by Roselló-Soto et al. (2015) on pulsed electric field pretreatment (40 kV, 10 μs) of olive seeds showed that treating olive seeds with pulsed electric field before oil extraction did not significantly affect the total carotenoids.

Effect of novel seeds pretreatment techniques on oil antioxidant activity

Antioxidant activity of seed oil represents the presence of naturally occurring or newly formed antioxidant compounds during the seed pretreatment process. Improving the antioxidant activity of seed oil through seeds pretreatment is essential to enhance the oil suitability for pharmaceutical, cosmetics and food preservation application. The effect of seeds pretreatment on the oil antioxidant properties is summarised in Table 4.

McDowell et al. (2017) studied the impact of rapeseeds microwave and established that the oil DPPH radical scavenging significantly increased by four folds after rapeseeds microwave pretreatment (800 W, 2 min). Similarly, significant improvement (33%) in DPPH radical scavenging after orange seeds microwave pretreatment (360 W, 30 min) was reported by Guneser and Yilmaz (2017). Rekas et al. (2017) reported similar findings with microwave pretreated (800 W, 6 and 8 min) rapeseeds (Table 4). Depending on the type of seeds, microwave power and time, treatment of oilseeds with microwaves may reduce the oil antioxidant activities. Juhaimi et al. (2018) reported a 34% decrease in DPPH inhibition of apricot seed oil when the microwave power was increased from 540 to 720 W with 5 min heating time of the apricot seeds. The results are in agreement with findings from oil extracted from microwave pretreated chia seeds that exhibited 89.47% decrease in antioxidant activity after

Table 4 The effect of novel seeds pretreatment techniques on oil antioxidant activity

Type of seed	Pretreatment technique	Key finding	References
Rape	Microwave (800 W, 2 min) and ultrasound pretreatment (40 kV, 10 µs)	The oil DPPH radical scavenging increased from 60.6 to 215.3 mmol/kg after seeds microwave pretreatment. Ultrasound pretreatment of rapeseeds did not significantly affect the oil DPPH radical scavenging ability	McDowell et al. (2017)
Orange	Microwave (360 W, 30 min with 3 min pauses after every 3 min)	Antioxidant capacity increased from 12.43 to 16.51 µm Trolox/100 g	Güneşer and Yilmaz 2017)
Rape	Microwave (800 W, 6 and 8 min)	DPPH radical scavenging was highest when dehulled seeds were microwaved for 8 min	Rekas et al. (2017)
Apricot	Microwave (360, 540, 760 W, 5 min)	The oil antioxidant capacity improved with increase in microwave power	Juhaimi et al. (2018)
Chia	Microwave (180, 350, 540, 720, 900 W, 15 min)	The oil antioxidant activity decreased with increase in microwave power	Ozcan et al. (2019)
Rape	Pulsed electric field (5.0 kV/cm and 60 pulses, 7.0 kV/cm and 120 pulses for 30 µs)	DPPH radical scavenging of the oil increased approximately between 7 and 12%	Guderjan et al. (2007)
Olive	Ultrasound (amplitude: 20 and 100%, 10 min)	No significant effect on the oil antioxidant activity was observed after seeds ultrasound pretreatment	Roselló-Soto et al. (2015)
Goldenberry	Enzyme pretreatment (Cellulase EC, Pektinase L 40 (1:1), 50 °C , pH: 4.3, enzyme concentration: 2% (w/w), 2 h)	The oil DPPH radical scavenging increased after enzyme pretreatment	Ramadan et al. (2008)

DPPH, 2,2-Diphenyl-1-picryl hydrazyl

increasing the microwave power from 180 to 900 W (Ozcan et al. 2019). The decrease in the oil antioxidant activity could be related to the degradation of the phenolic compounds, which also significantly decreased with the increase in microwave power.

The potential of the pulsed electric field to improve rapeseed oil antioxidant activity was also evaluated (Guderjan et al. 2007). It was observed that the application of pulsed electric field (5.0 kV/cm and 60 pulses) increased the oil DPPH radical scavenging by approx. 7%. Increasing the pulsed electric field magnitude to 7.0 kV/cm and 120 pulses enhanced DPPH radical scavenging by approx. 12%. In another study, ultrasound pretreatment (20 kHz, 200 W) of hemp seeds significantly decreased the oil antiradical capacity by 57, 25 and 26% after pretreating the seeds with ultrasound waves for 10, 20 and 40 min, respectively (Da Porto et al. (2015). However, ultrasound (amplitude: 20 and 100%, 10 min) and pulsed electric field pretreatments (40 kV, 10 µs) of rape and olive seeds, respectively, did not significantly improve the oil antioxidant activity (Roselló-Soto et al. 2015; McDowell et al. 2017) (Table 4). Other authors have investigated the pretreatment of goldenberry seeds with enzymes on the oil DPPH radical scavenging ability (Ramadan et al. 2008). It was reported that inhibition of DPPH radicals after 30 min was 53.5 and 49.7% for enzyme pretreated (Cellulase EC, Pektinase L 40 (1:1), 50 °C, pH: 4.3, enzyme concentration: 2% (w/w), 2 h) and untreated goldenberry seeds, respectively, indicating a 7% increase in DPPH radical scavenging ability more than the oil from untreated seeds. These findings suggest that the antioxidant activity of seed oil depends on the microwave power, pulse intensity and exposure time.

Conclusion

This review paper examined the effects of novel seeds pretreatment techniques on the oil physicochemical, bioactive compounds and antioxidant properties. Microwave, ultrasound, pulsed electric field and enzyme pretreatment of oilseeds is vital for improved oil quality. However, the quality of the oil is dependent on technical parameters such as microwave power, ultrasound power, pulse intensity and exposure time. Also, the type of enzyme, pH, temperature, enzyme concentration and treatment time influences the oil yield and quality. Application of these novel seeds pretreatment techniques to various oilseeds improved oil yield, colour, tocopherols, phenols, phytosterols, carotenoids and antioxidant activities of the extracted oil with a slight increase in peroxide value, acid value ρ-anisidine value and fatty acids conjugation, indicating that these novel seeds pretreatment techniques may not significantly degrade the oil quality.

Furthermore, new bioactive compounds are formed during seeds pretreatment, for instance, canolol in rapeseed oil. The fatty acid composition and content was insignificantly affected by seeds pretreatments, which is relevant from the nutritional point of view. Improvement of the oil antioxidant properties after seeds pretreatment is a desirable development given the oil application in functional foods and nutraceuticals formulation.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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