Chapter 7
The Application of Supercritical Carbon Dioxide in the Extraction of Biomolecules

Natascha Cheikhyoussef

Contents

Abbreviations

BIC	Broken and intact cell
GRAS	"Generally recognized green solvent"
HBD	Hot ball diffusion
LM	Logistic model
ORAC	Oxygen radical absorbance capacity
RSM	Response surface methodology
SC	Shrinking core
SC-CO_2	Supercritical carbon dioxide
SF	Supercritical fluid

N. Cheikhyoussef (✉)
Research and Innovation, Ministry of Higher Education, Technology and Innovation, Windhoek, Namibia
e-mail: natascha.cheikhyoussef@mheti.gov.na

Inamuddin, A. M. Asiri (eds.), *Advanced Nanotechnology and Application of Supercritical Fluids*, Nanotechnology in the Life Sciences,
https://doi.org/10.1007/978-3-030-44984-1_7

7.1 Introduction

The development of green extraction processes is aimed at reducing the use of organic solvents and the energy consumption through reduced reaction and processing times that will produce safe products of good quality and purity (Chemat et al. 2019). Chemat et al. (2019) have described the six principles for identifying the green extraction process (Chemat et al. 2012) and developed accordingly the good practices guidelines for each of these principles. The principles described by Chemat et al. (2012, 2019) are (1) "innovation by selection of varieties and use of renewable plant resources", (2) "use of alternative solvents and principally water or agro-solvents", (3) "reduction of energy consumption by energy recovery and using innovative technologies", (4) "production of co-products instead of waste towards bio-refinery concepts", (5) "reduction of unit operations number and development of safe, robust and controlled processes" and (6) "aim for green extract with green values and non-denatured and biodegradable extract without contaminants". The application of supercritical carbon dioxide (SC-CO_2), a "generally recognized green solvent" (GRAS) (Rovetto and Aieta 2017; Chemat et al. 2019), for the use of the extraction of biomolecules fulfils the requirements under principle 2 and is the most common used green solvent for supercritical fluid (SF) extractions (Stuart et al. 1996; Lang and Wai 2001; Rovetto and Aieta 2017). This is also evident from the numerous review articles published in the past 20 years on the use of SFs, which have provided numerous reports on the SC-CO_2 extraction applications (Table 7.1). This phenomena is attributed to the properties of the carbon dioxide as being non-flammable, non-toxic, cheap and non-corrosive (Lang and Wai 2001; Huang et al. 2012) with the SC-CO_2 extraction process being highly selective, obtaining solvent free products with no development of co-products (Knez et al. 2019). Extracts obtained from a SF extraction have been commonly found to be of greater quality when compared to other methods (Fornari et al. 2012a). A wide array of published reviews discuss the supercritical extraction of bioactives (Table 7.1), which are essentially biomolecules possessing specific biological activities or functions (Fig. 7.1) with a great range of applications in industry (da Silva et al. 2016). De Melo et al. (2014) have described reported SF extractions from vegetable matrices of about 600 essays for the period 2000–2013, including modelling, operating conditions, scale-up and an economic assessment. A review by Khaw et al. published in 2017 focusses on SF extraction of bioactives from different natural sources. The review, including other green extraction methods, provides insights on the SC-CO_2 extraction of bioactives and operating conditions from about 40 plant species. A summary of the reported SC-CO_2 extraction parameters of bioactives, among other newer methods such as "subcritical water extraction", "ultrasound-assisted extraction" and "microwave-assisted extraction", specifically from marine macroalgae was reported by Cikoš et al. (2018). Gallego et al. (2019) have described reported bioactives extracted by subcritical and supercritical fluid extraction from various plant sources, seaweeds, microalgae and food by-products for the period from 2015 to 2019. Previously, Herrero et al. (2015) published a review on the same theme for the period 2006–2014. The bioactives extracted from these sources using

Table 7.1 Published reviews on the use of supercritical fluids for the extraction of biomolecules

Title of the review	References
Analytical supercritical fluid extraction of natural products	Modey et al. (1996)
Compounds of agricultural significance using environmental analytical supercritical fluid extraction	Stuart et al. (1996)
Natural extracts using supercritical carbon dioxide	Mukhopadhyay (2000)
Supercritical fluid extraction in herbal and natural product studies	Lang and Wai (2001)
Supercritical extraction from solid: Process design data (2001–2003)	Meireles (2003)
Supercritical fluid extraction and fractionation of natural matter	Reverchon and De Marco (2006)
Comparative assessment of technologies for extraction of artemisinin	Lapkin et al. (2006)
Supercritical fluid extraction in plant essential and volatile oil analysis	Pourmortazavi and Hajimirsadeghi (2007)
Supercritical fluid extraction of bioactive compounds: Fundamentals, applications and economic perspectives	Pereira and Meireles (2010)
Isolation of essential oil from different plants and herbs by supercritical fluid extraction	Fornari et al. (2012a)
Principles of supercritical fluid extraction and applications in the food, beverage and nutraceutical industries	Knez et al. (2013)
Supercritical fluid extraction of vegetable matrices: Applications, trends and future perspectives of a convincing green technology	De Melo et al. (2014)
Essential oils: Extraction, bioactivities, and their uses for food preservation	Tongnuanchan and Benjakul (2014)
Supercritical carbon dioxide extraction of carotenoids from pumpkin (*Cucurbita* spp.)	Durante et al. (2014)
Extraction of triacylglycerols and fatty acids using supercritical fluids—Review	Martínez and de Aguiar (2014)
Plants, seaweeds, microalgae and food by-products as natural sources of functional ingredients obtained using pressurized liquid extraction and supercritical fluid extraction	Herrero et al. (2015)
Supercritical fluid extraction of bioactive compounds	Da Silva et al. (2016)
Supercritical fluid extraction of bioactive compounds from plant materials	Wrona et al. (2017)
Plant growth biostimulants, dietary feed supplements and cosmetics formulated with supercritical CO_2 algal extracts	Michalak et al. (2017)
Solvent supercritical fluid technologies to extract bioactive compounds from natural sources: A review	Khaw et al. (2017)
Overview on the application of modern methods for the extraction of bioactive compounds from marine macroalgae	Cikoš et al. (2018)
Recent applications of on-line supercritical fluid extraction coupled to advanced analytical techniques for compounds extraction and identification	Sánchez-Camargo et al. (2019)
Are supercritical fluids solvents for the future?	Knez et al. (2019)
Supercritical fluid extraction of essential oils	Yousefi et al. (2019)
Sub- and supercritical fluid extraction of bioactive compounds from plants, food-by-products, seaweeds and microalgae—An update	Gallego et al. (2019)
Green extraction techniques in green analytical chemistry	Armenta et al. (2019)

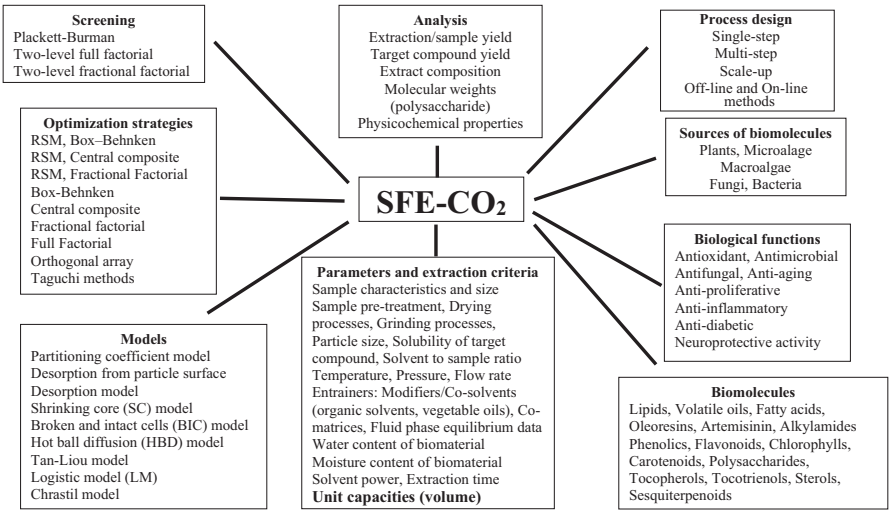

Fig. 7.1 Overview of the supercritical carbon dioxide (SF-CO_2) extraction process of biomolecules (Grosso et al. 2010; Sovová 2012; Huang et al. 2012; da Silva et al. 2016; Shukla et al. 2019; Yousefi et al. 2019)

specifically SC-CO_2, with or without co-solvents, include carotenoids, anthocyanins, phenolic compounds, polyphenolics, sesquiterpenes, antioxidant compounds, polyphenols, monoterpenes, vitamin E, cannabinoids, non-polar flavonoids, lycopene, piperine, tetrahydrocannabinol, colchicine, tocols, tocopherols, polar and non-polar lipids, oils, essential oils, oleanolic acids, ursolic acids, fatty acids, chlorophyll A, ergosterol, fucosterol, fucoxanthin and triacylglycerides (Gallego et al. 2019). Michalak et al. (2017) have presented a summary of reported biologically active compounds (fucoxanthin, beta-carotene, carotenoids, astaxanthin, canthaxanthin, chlorophyll, polyphenols, fatty acids, lipids, oil, auxins, cytokinins, micro- and macro-elements) that have been obtained via SC-CO_2 extraction from algal biomass. Algae extracts obtained by this method are proposed by Michalak et al. (2017) to be used in cosmetics and dietary feeds and as growth stimulants due to their components being solvent-free. Table 7.3 provides a summary of reported SC-CO_2 extractions of biomolecules discussed in this chapter. The chapter intends to present recent applications of SC-CO_2 extraction of selected biomolecules with potential uses in industry and provides an overview of published reports on this critical area of Green Chemistry.

7.2 Design and Optimization of the Supercritical Carbon Dioxide Extraction Process

In order to ensure high extraction efficiencies and to obtain high quality and purified extractions (Chemat et al. 2019; Yousefi et al. 2019), the design and the optimization strategies are critical. In particular, with SF extractions, the aim is on the reduction

of extraction time, amount of solvent, energy usage, costs, waste produced and the environmental impact (Chemat et al. 2019; Yousefi et al. 2019). Figure 7.1 presents a summary of the various components of the SC-CO_2 extraction process of biomolecules. Understanding the mass transfer mechanisms of the extraction process is imperative for starting the design of the extraction process (Huang et al. 2012) and in choosing the appropriate mathematical model to be applied (Kumhom et al. 2011). The development of mathematical models for the SC-CO_2 extraction process was reported by various research groups (Table 7.2). These models are generally described as the models that are based on "heat transfer analogies", models based on "differential mass balances", empirical models and the shrinking core model

Table 7.2 Reported theoretical models for supercritical fluid extraction

Title of the publication	References
Mathematical modeling of sunflower seed extraction by supercritical CO_2	Perrut et al. (1997)
Mass transfer modelling of apricot kernel oil extraction with supercritical carbon dioxide	Özkal et al. (2005)
Mathematical modelling of supercritical CO_2 extraction of volatile oils from aromatic plants	Grosso et al. (2010)
Prediction of isoflavone extraction from soybean meal using supercritical carbon dioxide with cosolvents	Kumhom et al. 2011
Theoretical models for supercritical fluid extraction	Huang et al. (2012)
Kinetic study of the supercritical CO_2 extraction of different plants from the *Lamiaceae* family	Fornari et al. (2012b)
Modeling the supercritical fluid extraction of essential oils from plant materials	Sovová (2012)
Effects of high water content and drying pre-treatment on supercritical CO_2 extraction from *Dunaliella salina* microalgae: Experiments and modelling	Mouahid et al. (2016)
Modeling of the kinetics of supercritical fluid extraction of lipids from microalgae with emphasis on extract desorption	Sovová et al. (2016)
Supercritical carbon dioxide extraction of *Calendula officinalis*: Kinetic modeling and scaling up study	López-Padilla et al. (2017)
Modeling of the kinetics of supercritical fluid extraction of lipids from microalgae with emphasis on extract desorption	Sovová et al. (2016)
Broken-and-intact cell model for supercritical fluid extraction: Its origin and limits	Sovová (2017)
Supercritical carbon dioxide extraction of pomegranate (*Punica granatum* L.) seed oil: Kinetic modelling and solubility evaluation	Natolino and Da Porto (2019)
New developments in the modelling of carotenoids extraction from microalgae with supercritical CO_2	Sovová and Stateva (2019)
Extraction of vetiver (*Chrysopogon zizanioides*) root oil by supercritical CO_2, pressurized-liquid, and ultrasound-assisted methods and modelling of supercritical extraction kinetics	Santos et al. (2019)
Evaluation of the effects of temperature and pressure on the extraction of eugenol from clove (*Syzygium aromaticum*) leaves using supercritical CO_2	Frohlich et al. (2019)

Table 7.3 Reported publications on the supercritical carbon dioxide extraction of biomolecules

Primary source for biomolecule(s)	Target biomolecule(s)	References
Chlorella vulgaris	Carotenoids, lipids	Mendes et al. (1995)
Artemisia annua L.	Artemisinin, artemisinic acid	Kohler et al. (1997)
Sargassum hemiphyllum (turn.) C. Ag. J.	Lipids	Cheung et al. (1998)
Red seaweed	*n*-3 fatty acids	Cheung (1999)
Cunninghamella echinulata	Fungal oil containing γ-linolenic acid	Certik and Horenitzky (1999)
Echinacea angustifolia	Alkylamides	Sun et al. (2002)
Botryococcus braunii *Chlorella vulgaris* *Dunaliella salina* *Arthrospira maxima*	Alkadienes Carotenoids β-Carotene γ-Linolenic acid	Mendes et al. (2003)
Foeniculum vulgare	Volatile oil	Coelho et al. (2003)
Artemisia annua L. leaves	Artemisinin	Quispe-Condori et al. (2005)
Artemisia annua L.	Artemisinin	Lin et al. (2006)
Nannochloropsis sp.	Lipids	Andrich et al. (2005)
Artemisia annua L.	Scopoletin, artemisinin	Tzeng et al. (2007)
Blakeslea trispora NRRL 2895 and 2896	Lycopene	Choudhari, Singhal (2008)
Haematococcus pluvialis	Astaxanthin	Krichnavaruk et al. (2008)
Italian coriander seeds	Volatile oil	Grosso et al. (2008)
Santolina chamaecyparissus	Volatile oil	Grosso et al. (2009a)
Satureja montana	Volatile oil (thymoquinone)	Grosso et al. (2009b)
Ampelopsis grossedentata stems	Bioactive compounds	Wang et al. (2011)
Soybean meal	Isoflavone	Kumhom et al. (2011)
Chlorella vulgaris microalgae	Lipids	Dejoye et al. (2011)
Citrus grandis (L.) Osbeck (pomelo) peel	Flavonoids	He et al. (2012)
Origanum vulgare, *Thymus zygis*, *Salvia officinalis*, *Rosmarinus officinalis*	Essential oil	Fornari et al. (2012b)
Tiger nut (*Cyperus esculentus* L.)	Oil	Lasekan and Abdulkarim (2012)
Cannabis sativa L. (hemp) seed	Seed oil, oxidative stability	Da Porto et al. (2012a)
Cannabis sativa L. (hemp) seed	Seed oil, oxidative stability	Da Porto et al. (2012b)
Grape	Seed oil, polyphenol co-extraction	Rombaut et al. (2014)
Moringa oleifera	Seed oil	Ruttarattanamongkol et al. (2014)
Prunus persica seeds	Oil, phytosterols	Ekinci and Gürü (2014)
Sasa palmata (bamboo) leaves	Phenolics	Zulkafli et al. (2014)
Tetraselmis sp. (green algae)	Lipids	Li et al. (2014)
Sasa palmata (bamboo) leaves	Phenolic compounds	Zulkafli et al. 2014
Artemisia sphaerocephala Krasch seeds	Polysaccharides	Chen et al. (2014)
Brazilian plants	Phenolics	Veggi et al. (2014a)
Hymenaea courbaril L. (jatoba)	Phenolic compounds	Veggi et al. (2014b)
Cannabis sativa L. (hemp)	Seed oil	Aladić et al. (2015)
Tiger nuts	Oil, phenolic compounds	Koubaa et al. (2015)
Euterpe oleracea (açaí)	Berry oil, fatty acids, phenolics, anthocyanins	De Cássia et al. (2016)
Dunaliella salina microalgae	Carotenoids	Mouahid et al. (2016)

(continued)

Table 7.3 (continued)

Primary source for biomolecule(s)	Target biomolecule(s)	References
Sunflower seed	Oil	Rai et al. (2016)
Diospyros kaki L. (persimmon)	Carotenoids	Zaghdoudi et al. (2016)
Artemisia annua L.	Artemisinin	Baldino et al. (2017)
Eremanthus erythroppapus (Candeia)	Oil	Santos et al. (2017)
Cannabis sativa L. (hemp)	Cannabinoids δ^9-Tetrahydrocannabinolic acid, δ^9-tetrahydrocannabinol	Rovetto and Aieta (2017)
Artemisia annua L. leaves	Bioactive extracts	Martinez-Correa et al. (2017)
Ocimum sanctum Linn.	Eugenol	Chatterjee et al. (2017)
Calendula officinalis	Oleoresin	López-Padilla et al. (2017)
Spinach by-products	Lutein and chlorophyll	Derrien et al. (2018)
Artemisia annua L.	Artemisinin	Ciftzi et al. (2018)
Phyllostachys heterocycle (bamboo)	Polysaccharide	Zou et al. (2018)
Oats	Phenolic acids, avenanthramides and antioxidant activity	Walters et al. (2018)
Craterellus tubaeformis (Finnish wild mushrooms)	Volatile compounds (aroma compounds)	Chen et al. (2018)
Algerian *Thymus munbyanus*	Essential oils	Bendif et al. (2018)
Avena sativa L. (oats)	Polyphenols	Escobedo-Flores et al. (2018)
Cacao pod husk	Phenolic compounds	Valadez-Carmona et al. (2018)
Garlic	Phenolic compounds	Liu et al. (2018)
Radish leaves	Bioactive compounds	Goyeneche et al. (2018)
Oenocarpus bacaba (bacaba)	Oil	Pinto et al. (2018)
Avena sativa L. (oats)	Oil, main fatty acids, polyphenols	Fernández-Acosta et al. (2019)
Soybean residue	Phytochemicals	Alvarez et al. (2019)
Parboiled rice bran	Rice bran oil	Juchen et al. (2019)
Solidago gigantea Ait.	Lipids	Wrona et al. (2019)
Euterpe oleracea Mart. (lyophilized açaí)	Pulp oil	Silva et al. (2019)
Artemisia annua L.	Artemisinin	Rodrigues et al. (2019)
Ginger rhizomes	Volatile oil and gingerols enriched oleoresin	Shukla et al. (2019)
Chrysopogon zizanioides	Vetiver essential oil	Santos et al. (2019)
"Horchata" by-products	Oils-phenolic profile	Roselló-Soto et al. (2019a)
"Horchata" by-products	Fatty acid profile, α-tocopherol, phenolic compounds and lipid oxidation parameters	Roselló-Soto et al. (2019b)
Punica granatum L. (pomegranate)	Seed oil	Natolino and Da Porto (2019)
Curcuma longa, *Curcuma amada*	Oleoresin	Nagavekar and Singhal (2019)
Origanum vulgare L.	Oil	García-Pérez et al. (2019)
Syzygium aromaticum (clove) leaves	Eugenol	Frohlich et al. (2019)
Oenocarpus distichus Mart. (bacaba-de-leque)	Oil	Cunha et al. (2019)
Virola surinamensis (ucuúba)	Seed oil	Cordeiro et al. (2019)

(Özkal et al. 2005). Huang et al. (2012) have described several models such as the "broken and intact cell" model (BIC), hot ball diffusion (HBD) model, shrinking core (SC) model, Tan-Liou model, partitioning coefficient model and the logistic model (LM) for different SC-CO_2 extraction systems (Fig. 7.1). The most widely used model for obtaining extracts via SC-CO_2 extraction from plant sources is the BIC model (Huang et al. 2012). The BIC model has been found suitable for the extraction of oleoresin from marigold (*Calendula officinalis*) plants (López-Padilla et al. 2017). Natolino and Da Porto (2019) have applied kinetic (BIC model) and solubility (Chrastil model) modelling for the SC-CO_2 extraction of pomegranate seed oil from *Punica granatum* L. The "shrinking core model" was applied for the isoflavone extraction (SC-CO_2 and methanol) from soybean meal by Kumhom et al. (2011) and investigated the axial dispersion coefficient, effective diffusivity, solubility and the film "mass transfer coefficient", of which the film "mass transfer coefficient" and the solubility were found to be the most significant. Sovová (2012, 2017), Sovová et al. (2016) and Sovová and Stateva (2019) have described the modelling of the SF extraction process for essential oils, lipids and carotenoids, which have been readily adapted to represent extraction curves.

Optimization targets (Fig. 7.1) are based on varying mainly the pressure, temperature and the flow rate of the SC-CO_2. Co-solvents such as water, methanol, diethyl ether, ethanol, acetone, acetonitrile or dichloromethane are added at varying concentrations to observe the effect on the extraction yield and the extract composition, as these improve the solvating power of the SC-CO_2 (Michalak et al. 2017; Rovetto and Aieta 2017). This is necessary for the extraction of polar compounds since SC-CO_2 is a non-polar solvent and its polarity can be influenced with the use of polar modifiers (Nagavekar and Singhal 2019). Additional parameters (Fig. 7.1) that are targeted for optimization are the sample's particle size, extraction time and solvent power (Ekinci and Gürü 2014). The effects of the solvent power of SC-CO_2 are critical during any extraction process, whereby the effects on solvent power and extraction selectivity are discussed by Ekinci and Gürü (2014). Solvent density is significantly affected by changes in pressure (Derrien et al. 2018). Rovetto and Aieta (2017) investigated the effect of different pressures, flow rates and co-solvent (ethanol) on the yield of cannabinoids from *Cannabis sativa* L., whereby pressure and plant material had notable effects on the extraction yield.

7.3 Lipids, Volatile Oils and Oleoresins

Lipids have been extracted from various macroalgae (MA) and microalgae (MI) species using SC-CO_2 such as *Chlorella vulgaris* (MI) (Mendes et al. 1995; Dejoye et al. 2011), *Tetraselmis* sp. (MI) (Li et al. 2014), *Chaetomorpha linum* (MA) (Aresta et al. 2005), *Sargassum hemiphyllum* (MA) (Cheung et al. 1998) and *Hypnea charoides* (MA) (Cheung 1999). Fatty acids from *Arthrospira maxima* (*Spirulina maxima*) (MI) have been extracted with SC-CO_2 and with 10% ethanol (Mendes et al. 2003). Michalak et al. (2017) reported a comparative summary of the

SF extraction methods and parameters used for the extraction of algae bioactives. Mainly, SC-CO_2 extraction alone has been applied with some reported to have added organic solvents, water or vegetable oils to the extraction process. Biomolecules that are oxidized easily and that are heat labile are suitably extracted with SC-CO_2 due to its non-oxidant nature (Michalak et al. 2017). SC-CO_2 has been identified as an appropriate method to extract lipids (Li et al. 2014). A low temperature of 30 °C and a pressure of 35 MPa were found to be optimum for the SC-CO_2 extraction of *Moringa oleifera* seed oil (75.27%) and in having the greatest solvation power (Ruttarattanamongkol et al. 2014). The solvent CO_2 showed higher selectivity at the low pressure of 15 MPa towards the extraction of sterols, tocopherols and fatty acids (Ruttarattanamongkol et al. 2014). At conditions of 15 MPa and 35 °C, biomolecules β-sitosterol, campesterol, γ-tocopherol and α-tocopherol were found to be at highest concentrations of 2310.9, 1179.2, 106.8 and 230.3 mg/kg, respectively (Ruttarattanamongkol et al. 2014). SC-CO_2 extraction of hemp seed oil from *Cannabis sativa* L. has been previously reported with oil yields of 21.50% w/w (40 °C, 300 bar, particle size of 0.71 mm) (Da Porto et al. 2012a) and 22% (300 bar and 40 °C and at 400 bar and 80 °C) obtained (Da Porto et al. 2012b). Hemp (*Cannabis sativa* L.) seed oil was extracted at varying temperature of 40 and 60 °C and at a constant pressure of 300 bar with a CO_2 flow rate of 1.94 kg/h (Aladić et al. 2015). The yield of seed oil was not affected by changes in temperature but increased with increasing pressure (Aladić et al. 2015). The fatty acid concentration was affected by pressure, whilst extraction time did not affect the content (Aladić et al. 2015). Temperature had a varying effect on the content of the fatty acids (Aladić et al. 2015). The common vegetable oil, sunflower oil (54.37 wt%), has been extracted with SC-CO_2 from the sunflower seed (particle size, 0.75 mm) with a flow rate of 10 g/min, 5% co-solvent at 400 bar and 80 °C (Rai et al. 2016). Oil from *Eremanthus erythropappus* (candeia wood) has been optimally extracted at 70 °C and 24 MPa with 2 ml/min flow rate and ethanol (1.3% v/v) and ethyl acetate (5% v/v) as co-solvents, yielding 2.35 wt% oil (Santos et al. 2017). The highest concentration of α-bisabolol (16.53 g/kg), a naturally occurring sesquiterpene alcohol, was obtained with 5% ethanol (Santos et al. 2017). A review on the properties (pharmacological), mechanisms of action and the applications of α-bisabolol and oils rich in α-bisabolol has been published by Kamatou and Viljoen (2010). The yield of total lipids extracted from *Solidago gigantea* Ait. (goldenrod) has been evaluated using a "Box-Behnken design with three variables" studied, temperature (40–80 °C), pressure (20–80 MPa) and the flow rate of CO_2 (3–7 kg/h) (Wrona et al. 2019). The optimum conditions reported are temperature at 313.95 K, pressure at 68.07 MPa and CO_2 flow rate of 3.18 kg/h yielding 203.32 mg stearic acid equivalent/g dry mass, with temperature having a negligible effect on the content of total lipids (Wrona et al. 2019).

Shukla et al. (2019) have applied SC-CO_2 (single-step) extraction and fractionation process to obtain oleoresin enriched with gingerols and essential oil from dried ginger rhizomes. Optimum conditions reported by Shukla et al. (2019) for obtaining 28.3 wt% volatile oil and 37.97 wt% major actives were pressure at 276 bar, temperature at 40 °C and flow rate of 30 g/min for 153 min. Shukla et al.

(2019) have presented a summary of reported literature on obtaining ginger extracts using SC-CO_2 extraction processes. Oregano oil (*Origanum vulgare* L.) extracted with SC-CO_2 (100 bar, 40 °C, 8 g/min ethanol) with a highest yield of 13.40% showed high antimicrobial and antioxidant activity (García-Pérez et al. 2019). The volatile compound, carvacrol (29.99%), and the fatty acids (70.9–76.8%), α-linolenic (C18:3ω3, 20.55–24.66%), palmitic (C16:0, 22.76–23.65%), oleic (C18:1ω9c, 15.19–16.63%) and linoleic acids (C18:2ω6c, 12.16–13.35%), were found at highest concentrations in the oil (García-Pérez et al. 2019). Oil has been extracted from parboiled rice bran with SC-CO_2 and ethanol, and the effects of varying pressures (100, 150, 200 bar) and temperatures (40, 60, 80 °C) and ethanol to rice bran (0:1, 0.5:1, 1:1, 2:1) were analysed (Juchen et al. 2019). Conditions for one experimental run for 250 min at 200 bar, 40 °C, 45.94 g CO_2/g bran and 1:1 ethanol to rice bran yielded 25.48 wt% of rice bran oil. Two sequential extractions at the same conditions yielded 26.32 wt% (Juchen et al. 2019). Roselló-Soto et al. (2019a) have compared the SC-CO_2 (10–40 MPa, 40 °C) extraction with the conventional extraction (modified Folch et al. 1957) of oil extracted from the "horchata" by-products with the SC-CO_2 extraction obtaining higher amounts of α-tocopherol and total phenolic compounds. The α-tocopherol concentration decreased, whilst total phenolic compounds increased with increasing pressure, respectively. The highest oil yield was obtained with conventional extraction (14.85%). Oil yield and pressure during the SC-CO_2 extraction were shown to have a linear relationship (10 MPa = 0.61%; 40 MPa = 7.36%), which has been reported by several other researchers (Lasekan and Abdulkarim (2012); Rombaut et al. 2014; Koubaa et al. 2015). Pinto et al. (2018) have obtained a yield of 60.39% after SC-CO_2 extraction of "bacaba oil" from *Oenocarpus bacaba* at temperature of 60 °C and pressure of 420 bar. A good quality bacaba-de-leque pulp oil from *Oenocarpus distichus* Mart. has been extracted using SC-CO_2 extraction with a yield of 46% at a pressure of 270 bar and temperature of 60 °C (Cunha et al. 2019). SC-CO_2 extraction (320 bar and 60 °C) has been used in the extraction of pomegranate (*Punica granatum* L.) seed oil that contained a higher punicic acid concentration and with a higher oxidation stability as compared to the Soxhlet extraction method (Natolino and Da Porto 2019). The extraction times with SC-CO_2 (2 h) were much shorter than the period needed for Soxhlet extraction (8 h) to reach the asymptotic yield. A CO_2 flow rate of 8.0 kg/h at 320 bar and 60 °C resulted in the highest yield of the seed oil (Natolino and Da Porto 2019). Fernández-Acosta et al. (2019) recently studied the effect of chemical pre-treatment, pressure, temperature, dynamic and static time and particle size on the SC-CO_2 extraction of oil *Avena sativa* L. (oats). The oat oil yield was significantly influenced by pressure and the size of particles. The pre-treatment, temperature and particle size significantly influenced the fatty acid composition and oxygen radical absorbance capacity (ORAC) antioxidant activity. Polyphenol concentration and total phenolic content were affected by pre-treatment and temperature (Fernández-Acosta et al. 2019). Cordeiro et al. (2019) recently investigated the SC-CO_2 extraction of ucuúba oil from the seeds of *Virola surinamensis*, a tree growing in the Amazon, with antimicrobial activity against *Staphylococcus aureus*. Extraction conditions applied were pressure (350 bar), temperature (40, 60 or 80 °C)

and a CO_2 mass flow of 7.9 × 10 kg/s (Cordeiro et al. 2019). De Cássia et al. (2016) have extracted the oil from the popular fruit (berries) açaí (*Euterpe oleracea* Mart.) obtained from Pará, Brazil, under varying temperature and pressure conditions. Highest oil yield was obtained at 70 °C and 490 bar. The fatty composition was affected by the varying operating conditions with significant effects reported on type and concentration of fatty acid detected (De Cássia et al. 2016). Silva et al. (2019) have evaluated the effects of pressure (350, 420, 490 bar), temperature (50, 60 or 70 °C) and geographical location on the extraction of the oil from açaí in lyophilized form. Oil yields between 49.28 (location, Anajás, 60 °C, 420 bar) and 57.06% (location, Chaves, 70 °C, 490 bar) were obtained (Silva et al. 2019) with the operating conditions not affecting the fatty acid composition within each study area. Operating conditions of 60 °C and 420 bar and 70 °C and 490 bar resulted in optimum results of antioxidant capacity, total anthocyanins and total phenolic compounds in the oil from Chaves (Silva et al. 2019). Kerrihard and Pegg (2015) reported on the suitability of the application of SC-CO_2 extraction of oils containing higher concentrations of γ-linolenic acid (GLA; 18:3*n*-6), which have as a result higher anti-inflammatory functionalities. Scale-up experiments and validation processes for the SC-CO_2 extraction of lipids and volatile oils have been investigated by several researchers with promising results of potential extraction at a commercial scale (Shukla et al. 2019; Wrona et al. 2019).

Essential oils, also referred to as volatile oils, are commonly used in traditional medicine and aromatherapy and as natural additives due to their reported antimicrobial activities (Chávez-González et al. 2016) in the food and cosmetics industry (Fornari et al. 2012a). Grosso et al. (2010) have tested five mathematical models for the modelling of the extraction of aromatic plants, fennel, coriander, cotton lavender, savoury, winter savoury and thyme by which extraction was impacted by particle size, internal mass transfer coefficient, internal diffusion, and pressure and temperature changes.

Sovová (2012) has described various published mathematical models for the extraction of essential oils from plants for a 15-year period up to 2012. Tongnuanchan and Benjakul (2014) have discussed the extraction methods, including aspects of SC-CO_2 extraction among others, and the uses and bioactivities of essential oils. Yousefi et al. (2019) have compiled a review that investigates the SF extraction of essential oils from plants. The review describes conventional extraction methods as compared to the SF extraction, optimization and modelling techniques commonly applied and the effects of the various operating parameters on the supercritical extraction process (Yousefi et al. 2019). SC-CO_2 has been investigated for the extraction of the volatile oil from the flower heads of *Santolina chamaecyparissus* L. under different operating conditions. Notably, pressure increase to 9 MPa enriched the content of sesquiterpene in the extracted *Santolina chamaecyparissus* essential oil (Grosso et al. 2009a). The volatile oil from *Satureja montana* L. extracted by SC-CO_2 was reported by Grosso (2009b) to contain higher concentrations of thymoquinone (1.6–3.0%) as compared to the hydrodistillation, a conventional extraction method. Essential oils produced via SC-CO_2 extraction from various herbs and plants have been reported by Fornari et al. (2012a). A cooled mill

was used to crush the dried leaves (*O. vulgare*, *Thymus vulgaris*, *Salvia officinalis*, *Rosmarinus officinalis*, *Ocimum basilicum*, *Origanum majorana*) and petals (*Calendula officinalis*) and then sieved (200–600 μm). Essential oils were then extracted at 30 MPa and 40 °C with a flow rate of 60 g/min for 5 h (Fornari et al. 2012a). The economically important vetiver essential oil was extracted with SC-CO_2 among other methods ("pressurized liquid and ultrasound-assisted methods") from *Chrysopogon zizanioides* (L.) Roberty, syn. *Vetiveria zizanioides* (L.) Nash root with the highest yield (2.23% m/m) obtained at 20 MPa and 60 °C (Santos et al. 2019). A higher yield (2.66% (m/m)) was obtained after the addition of 5% (v/v) of the co-solvent, ethanol (Santos et al. 2019). The dominant compounds were isovalencenol (9.04% SC-CO_2; 8.70% SC-CO_2+ 5% EtOH 5%), khusimol (30.49% SC-CO_2; 31.33% SC-CO_2+ 5% EtOH 5%), zizanoic acid (8.33% SC-CO_2; 6.82% SC-CO_2+ 5% EtOH 5%) and α-vetivone (6.42% SC-CO_2; 6.61% SC-CO_2+ 5% EtOH 5%). Leaf powder (20 g, dp = 0.42 mm) of *Ocimum sanctum* Linn. has been used for the extraction of eugenol (2.96 mg/g dry leaves) with SC-CO_2 at a flow rate of 2.5 L/min, 200 bar and 50 °C for 90 min (Chatterjee et al. 2017). Eugenol yield was affected only by pressure changes, and the kinetics of the extraction were reported to be first-order kinetics (Higuchi model) (Chatterjee et al. 2017). Eugenol (29.84%) has been extracted from clove at 40 °C and 220 bar with highest antioxidant activity of the extract found after extraction at 40 °C and 150 bar (Frohlich et al. 2019). In comparison to the Soxhlet extraction, it was revealed that the SC-CO_2 was more efficient in terms of yield, antioxidant activity, sample clean-up, reaction time and temperature (Frohlich et al. 2019).

Oleoresin has been optimally extracted from *Curcuma longa* (conventional turmeric) and *Curcuma amada* (mango ginger) at 65 °C and 350 bar for 150 min and at 40 °C and 300 bar for 30 min, respectively (Nagavekar and Singhal 2019). Modifier (30% ethanol) and pre-treatment with Stargen®002 enzyme significantly improved the yield (Nagavekar and Singhal 2019).

7.4 Artemisinin

The active pharmaceutical ingredient, artemisinin, is extracted from the herbaceous plant *Artemisia annua* L. (sweet wormwood) and is used in pharmaceutical applications for the treatment of malaria and cancer (Rodrigues et al. 2019). Artemisinin is a sesquiterpene that is highly oxygenated with a 1,2,4-trioxane ring structure (Brown 2010). Faurant (2011) have provided a historic background on the discovery of artemisinin and market-related developments, with Brown (2010) having provided a review on the photochemistry of the plant *A. annua* L. and the biosynthesis of the compound artemisinin. The SC-CO_2 extraction has commonly been employed in the high yield extraction of artemisinin from *A. annua* L. yielding high purity and clean extracts (Kohler et al. 1997; Quispe-Condori et al. 2005; Lin et al. 2006; Tzeng et al. 2007; Baldino et al. 2017; Martinez-Correa et al. 2017; Ciftzi et al. 2018; Rodrigues et al. 2019). Lapkin et al. (2006) have published a comparative

analysis on existing conventional and green technologies such as SC-CO_2 for the extraction of artemisinin.

Pure, non-degraded extracts of artemisinin have been obtained with a flow rate of 2 ml/min of SC-CO_2/3% methanol at 50 °C and 15 MPa within 20 min (Kohler et al. 1997). Artemisinin yields of 0.62% and 0.70% have been achieved at conditions of 150 bar and 30 °C and 300 bar and 50 °C, respectively (Quispe-Condori et al. 2005). Artemisinin of high purity within a short reaction time was yielded at optimized conditions of 33 °C, 18.72 MPa, SC-CO_2/16.25 wt% of *n*-hexane after an extraction time of 1.5 h (Lin et al. 2006). The highest purity was obtained at 60 °C and 17.34 MPa and proved to be far better than when Soxhlet extraction (hexane) was applied (Lin et al. 2006). Martinez-Correa et al. (2017) reported the suitability of a two-step extraction procedure, starting with SC-CO_2 extraction (60 °C, 40 MPa), followed by further extractions with either ethanol (25 °C) or water (60 °C). Baldino et al. (2017) on the other hand reported the optimum procedure to be a one-step extraction at 40 °C and 100 bar for 600 min. Ciftzi et al. (2018) reported optimum conditions to be 33 °C and 30 MPa for yielding 1.09% (predicted yield). The cost-effectiveness of the SC-CO_2 extraction process of artemisinin as compared to the conventional extraction (ethanol) was evaluated by Rodrigues et al. (2019), which determined that this process is more attractive economically and viability could be achieved if reduced cost for the raw material could be achieved. An artemisinin content of 23.4% was reached at 50 °C and 200 bar for 60 min (Rodrigues et al. 2019). A reaction time of 180 min was needed to obtain 6% of artemisinin using conventional extraction with ethanol (Rodrigues et al. 2019).

7.5 Alkylamides

Alkylamides from the dried roots of *Echinacea angustifolia* were extracted by Sun et al. (2002) at highest concentration as compared to the fresh roots, by which the yield was positively affected by temperature and pressure.

7.6 Phenolics, Flavonoids, Chlorophylls and Carotenoids

Phenolics and flavonoids extracted from plants via the SC-CO_2 process have been reported by several researchers (Table 7.3). *Ampelopsis grossedentata* stems were used to optimally extract flavonoids and phenolics at 40 °C and 250 bar for 50 min with 1:3 v/v methanol/ethanol and 1:1 v/v methanol/ethanol, respectively (Wang et al. 2011). Pomelo peel was used for the extraction of flavonoids (2.37%) at 39 MPa, 80 °C, 85% ethanol for 49 min (He et al. 2012). SC-CO_2 extracted flavonoids had higher scavenging activities as compared to the conventional process (He et al. 2012). Increased concentration of total phenolic content and antioxidant activity were obtained with the addition of co-solvents (ethanol and ethyl acetate) to the

SC-CO_2 extraction process of the oil from *Eremanthus erythropappus* (candeia wood) (Santos et al. 2017). Total phenolics from radishes (*Raphanus sativus* L.) were reported at concentrations of 1375 mg GAE/100 g and 1455 mg GAE/100 g at operating conditions of 400 bar at 35 °C and 40 °C, respectively (Goyeneche et al. 2018). Escobedo-Flores et al. (2018) extracted polyphenols from *Avena sativa* L. (oats) obtaining maximum yields at 55 °C and 38 MPa. An optimum concentration of 1437.57 mg/g was predicted with the generated quadratic models (Escobedo-Flores et al. 2018). The effects of particle size on the concentrations of avenanthramides and phenolics extracted from medium oat bran, whole flour (WF), low bran and fine bran have been reported by Walters et al. (2018), with larger sizes presenting a limiting factor during SC-CO_2 extractions. Higher radical scavenging activities were observed with the extracts via the SC-CO_2 extraction of the defatted fraction of the fine particles (Walters et al. 2018). Avenanthramides have been reported to possess strong anti-inflammatory properties (Sur et al. 2008). The yield of total phenolics and total chlorophylls extracted from *Solidago gigantea* Ait. (goldenrod), a medicinal plant, has been evaluated using a "Box-Behnken design with three variables" studied, temperature (40–80 °C), pressure (20–80 MPa) and the flow rate of CO_2 (3–7 kg/h) (Wrona et al. 2019). The three variables studied had an effect on the yield of total phenolics and total chlorophylls with optimum conditions reported as temperature of 313.59 K and 352.22 K, pressure of 79.14 MPa and 74.59 MPa and CO_2 flow rate of 3.25 kg/h and 3.00 kg/h, respectively (Wrona et al. 2019). Increased temperature resulted in a decrease in the total phenolic content, but increased when pressure was increased (Wrona et al. 2019). Alvarez et al. (2019) determined that conditions of 40 MPa and 35 °C with the co-solvent ethanol were optimum or the extraction of polyphenols and flavonoids with highest antioxidant activity. Roselló-Soto et al. (2019a) affirmed the suitability of applying SC-CO_2 extraction of lipophilic phenolic compounds when compared to the conventional extraction. Isohydroxymatairesinol was extracted at highest concentrations at pressures of 30 MPa (756.22 ppb) and 40 MPa (1331.45 ppb). Increasing pressures improved the extraction of the phenolic compounds, including the antioxidant activity (Roselló-Soto et al. 2019a). A SC-CO_2 extraction process to obtain an extract rich in phenolic compounds from cacao (*Theobroma cacao*) pod husk was developed by Valadez-Carmona et al. (2018). The yield was influenced by pressure and co-solvent percentage, and a yield of 0.52% was obtained at optimum conditions of 299 bar, 60 °C and 13.7% ethanol with high selectivity towards antioxidants (Valadez-Carmona et al. 2018).

Carotenoids are pigments and the secondary metabolites of plants and some microorganisms (Zaghdoudi et al. 2016) and can be successfully extracted using SC-CO_2. Sovová et al. (2001) have published data on the effects of different temperatures and pressures with and without ethanol and vegetable oil on the solubility of β-carotene in SC-CO_2. Knowledge of the solubility of biomolecules such as the carotenoids in SC-CO_2 is necessary to develop appropriate SC-CO_2 extraction processes. De la Fuente et al. (2006) have determined the solubility of lycopene and

astaxanthin at different temperatures and pressures. Similar to the behaviour of β-carotene in SC-CO_2, lycopene and astaxanthin solubility was greater with increased temperature (313–333 K) and constant pressure (30 MPa) as compared to increased pressure (30–50 MPa) at constant temperature (313 K) (de la Fuente et al. 2006). A review on the extraction of carotenoids from pumpkin (*Cucurbita* spp.) via the SC-CO_2 process and the influence temperature and pressure, pre-treatment effects, entrainers (modifier or co-solvents) and co-matrices on total carotenoid yield and carotenoid composition has been published by Durante et al. (2014). Choudhari and Singhal (2008) have extracted lycopene, a red-coloured tetraterpenic C40 carotenoid, from *Blakeslea trispora*, a zygomycete, at optimized conditions of 349 bar and 52 °C for 1.1 h and using an entrainer such as acetone, yielding 92%. Astaxanthin has been extracted from the microalgae *Haematococcus pluvialis* with the use of olive oil and soybean oil as co-solvents achieving a yield of 51.03% and 36.36%, respectively (Krichnavaruk et al. 2008). The microalgae *Haematococcus pluvialis* has been reported to be one of the greatest sources of the natural occurring astaxanthin, a carotenoid with potent antioxidant activity (Shah et al. 2016).

Xanthophylls (all-*trans*-lutein (15.46 μg/g), all-*trans*-zeaxanthin (16.81 μg/g) and all-*trans*-β-cryptoxanthin (33.23 μg/g)) have been optimally extracted from persimmon fruits (*Diospyros kaki* L.) at a flow rate of 3 ml/min, 300 bars, 60 °C and 25% (w/w) ethanol for 30 min obtaining higher yields as compared to the Soxhlet extraction method (Zaghdoudi et al. 2016). Conditions of flow rate of 1 ml/min, 100 bars, 40 °C and 25% (w/w) ethanol for 30 min were better suited for the extraction of 11.19 μg/g all-*trans*-β-carotene (Zaghdoudi et al. 2016). Spinach by-products have been used by Derrien et al. (2018) for the optimization of SC-CO_2 extraction of chlorophyll and lutein. Optimized conditions that resulted in a 72% and 50% yield of lutein and chlorophyll, respectively, were reported to be 39 MPa, 56 °C with a co-solvent of 10% ethanol for 3.6 h (Derrien et al. 2018). The SC-CO_2 extraction process of carotenoids from microalgae with the use of published data was described and modelled by Sovová and Stateva (2019). The model confirmed that higher temperatures and pressures increased yield of carotenoid in oil and extraction rate due to increased solubility of carotenoid in the supercritical fluid and the reduced capacity of adsorption of the microalga (Sovová and Stateva 2019). The phase equilibrium was found to be responsible in controlling the extraction process (Sovová and Stateva 2019).

7.7 Polysaccharides

Polysaccharides have been extracted via the SC-CO_2 process from the seeds of *Artemisia sphaerocephala* Krasch. at optimum conditions of temperature (extraction, 45 °C; separation, 56 °C), pressure (extraction, 45 MPa; separation, 10 MPa), a flow rate of 20 L/h for 2 h resulted in a yield of 18.59% (w/w) (Chen et al. 2014).

The 551.3 kDa polysaccharide was composed of the monosaccharides, mannose (10.8 mg/g), rhamnose (8.78 mg/g), galactose (9.86 mg/g), glucose (16.2 mg/g), arabinose (8.48 mg/g), xylose (38.48 mg/g) and fucose (10.09 mg/g) (Chen et al. 2014). The polysaccharide extracted from *Artemisia sphaerocephala* Krasch. has been reported to have medicinal applications (Xing et al. 2009). A polysaccharide (2.47%) from the leaves of bamboo (*Phyllostachys heterocycla*) has been extracted with SC-CO_2/ethanol modifier (30 ml) at optimized parameters of 50 °C and 40 MPa with a 2-h reaction time (Zou et al. 2018).

7.8 Tocopherols and Sterols

Plant cells synthesize α-, β-, γ- and δ-tocopherol, which are then stored in their seeds and leaves (Bendif et al. 2018). Tocopherols have strong antioxidant properties (Bendif et al. 2018). The content of tocopherols in extracted *Cannabis sativa* L. seed oil is significantly affected by temperature and pressure with higher temperatures and pressures resulting in a negative response (Aladić et al. 2015). Potential sources of tocopherol were reported by Bendif et al. (2018) to be contained in the SC-CO_2 extracts obtained from *Thymus munbyanus* subsp. *coloratus* (α-tocopherol [1580 μg/g], β-tocopherol [170 μg/g], γ-tocopherol [220 μg/g], δ-tocopherol [160 μg/g]) and *Thymus munbyanus* subsp. *munbyanus* (α-tocopherol [780 μg/g], β-tocopherol [140 μg/g], γ-tocopherol [120 μg/g], δ-tocopherol [130 μg/g]). The *Thymus* extracts were obtained with SC-CO_2 extraction with a flow rate of 2 L/min at 70 °C and 45 MPa for 210 min (Bendif et al. 2018). Sitosterol (1220 mg/kg seed) has been found to be contained in peach oil (extracted yield, 35.3 g/100 g seed) after SC-CO_2 extraction from the *Prunus persica* seeds (0.3 mm) at optimum conditions of 200 bar, flow rate of 7 ml/min and at 40 °C after 3 h (Ekinci and Gürü 2014).

7.9 Conclusions

A wide variety of biomolecules can be efficiently extracted with the SC-CO_2 extraction process. Optimization strategies are targeting to achieve parameters that can achieve high yield products with high purity and quality at less costs and environmental impacts. Research on the cost-effectiveness, economics and possible facility designs for the scaling up of the SC-CO_2 extraction process is underway with some successful examples already in place. The advent of the Green Chemistry era has made it possible to explore more opportunities in the development of innovative extraction and processing technologies.

References

Aladić K, Jarni K, Barbir T, Vidović S, Vladić J, Bilić M, Jokić S (2015) Supercritical CO_2 extraction of hemp (*Cannabis sativa* L.) seed oil. Ind Crops Prod 76:472–478. https://doi.org/10.1016/j.indcrop.2015.07.016

Alvarez MV, Cabred S, Ramirez CL, Fanovich MA (2019) Valorization of an agroindustrial soybean residue by supercritical fluid extraction of phytochemical compounds. J Supercrit Fluids 143:90–96. https://doi.org/10.1016/j.supflu.2018.07.012

Andrich G, Nesti U, Venturi F, Zinnai A, Fiorentini R (2005) Supercritical fluid extraction of bioactive lipids from the microalga *Nannochloropsis* sp. Eur J Lipid Sci Technol 107:381–386. https://doi.org/10.1002/ejlt.200501130

Aresta M, Dibenedetto A, Carone M, Colonna T, Fragale C (2005) Production of biodiesel from macroalgae by supercritical CO_2 extraction and thermochemical liquefaction. Environ Chem Lett 3(3):136–139. https://doi.org/10.1007/s10311-005-0020-3

Armenta S, Garrigues S, Esteve-Turrillas FA, de la Guardia M (2019) Green extraction techniques in green analytical chemistry. Trends Anal Chem 116:248–253. https://doi.org/10.1016/j.trac.2019.03.016

Baldino L, Reverchon E, Della Porta G (2017) An optimized process for SC-CO_2 extraction of antimalarial compounds from *Artemisia annua* L. J Supercrit Fluids 128:89–93. https://doi.org/10.1016/j.supflu.2017.05.018

Bendif H, Adouni K, Miara MD, Baranauskienė R, Kraujalis P, Venskutonis PR, Nabavi SM, Maggi F (2018) Essential oils (EOs), pressurized liquid extracts (PLE) and carbon dioxide supercritical fluid extracts (SFE-CO_2) from Algerian *Thymus munbyanus* as valuable sources of antioxidants to be used on an industrial level. Food Chem 260:289–298. https://doi.org/10.1016/j.foodchem.2018.03.108

Brown GD (2010) The biosynthesis of artemisinin (Qinghaosu) and the phytochemistry of *Artemisia annua* L. (Qinghao). Molecules (Basel, Switzerland) 15(11):7603–7698. https://doi.org/10.3390/molecules15117603

Certik M, Horenitzky R (1999) Supercritical CO_2 extraction of fungal oil containing γ-linolenic acid. Biotechnol Tech 13(1):11–15. https://doi.org/10.1023/A:1008853214591

Chatterjee D, Ghosh PK, Ghosh S, Bhattacharjee P (2017) Supercritical carbon dioxide extraction of eugenol from tulsi leaves: process optimization and packed bed characterization. Chem Eng Res Des 118:94–102. https://doi.org/10.1016/j.cherd.2016.11.025

Chávez-González ML, Rodríguez-Herrera R, Aguilar CN (2016) Essential oils: A natural alternative to combat antibiotics resistance. In: Kon K, Rai M (eds) Antibiotic resistance. Academic, Cambridge, pp 227–237. https://doi.org/10.1016/B978-0-12-803642-6.00011-3

Chemat F, Abert-Vian A, Cravotto G (2012) Green extraction of natural products: concept and principles. Int J Mol Sci 13:8615–8627. https://doi.org/10.3390/ijms13078615

Chemat F, Abert-Vian M, Fabiano-Tixier AS, Strube J, Uhlenbrock L, Gunjevic V, Cravotto G (2019) Green extraction of natural products. Origins, current status, and future challenges. Trends Anal Chem 118:248–263. https://doi.org/10.1016/j.trac.2019.05.037

Chen J, Li J, Sun AD, Zhang B-L, Qin S-G, Zhang Y-Q (2014) Supercritical CO_2 extraction and pre-column derivatization of polysaccharides from *Artemisia sphaerocephala* Krasch. Seeds via gas chromatography. Ind Crop Prod 60:138–143. https://doi.org/10.1016/j.indcrop.2014.06.013

Chen X, Huynh N, Cui H, Zhou P, Zhang X, Yang B (2018) Correlating supercritical fluid extraction parameters with volatile compounds from Finnish wild mushrooms (*Craterellus tubaeformis*) and yield prediction by partial least squares regression analysis. RSC Adv 8:5233. https://doi.org/10.1039/c7ra12472d

Cheung PCK (1999) Temperature and pressure effects on supercritical carbon dioxide extraction of n-3 fatty acids from red seaweed. Food Chem 65(3):399–403. https://doi.org/10.1016/S0308-8146(98)00210-6

Cheung PCK, Leung AYH, Ang PO Jr (1998) Comparison of supercritical carbon dioxide and Soxhlet extraction of lipids from a brown seaweed, *Sargassum hemiphyllum* (Turn.) C. Ag. J. Agric Food Chem 46:4228–4232. https://doi.org/10.1021/jf980346h

Choudhari SM, Singhal RS (2008) Supercritical carbon dioxide extraction of lycopene from mated cultures of *Blakeslea trispora* NRRL 2895 and 2896. J Food Eng 89(3):349–354. https://doi.org/10.1016/j.jfoodeng.2008.05.016

Ciftzi ON, Cahyadi J, Guigard SE, Saldaña MDA (2018) Optimization of artemisinin extraction from *Artemisia annua* L. with supercritical carbon dioxide + ethanol using response surface methodology. Electrophoresis 39:926–1933. https://doi.org/10.1002/elps.201800084

Cikoš A-M, Jokić S, Šubarić D, Jerković I (2018) Overview on the application of modern methods for the extraction of bioactive compounds from marine macroalgae. Mar Drugs 16:348. https://doi.org/10.3390/md16100348

Coelho JAP, Pereira AP, Mendes RL, Palavra AMF (2003) Supercritical carbon dioxide extraction of *Foeniculum vulgare* volatile oil. Flavour Fragr J 18:316–319. https://doi.org/10.1002/ffj.1223

Cordeiro RM, de S e Silva AP, RHH P, da Costa WA, da Silva SHM, de Souza Pinheiro WB, MSP A, Carvalho RN Jr (2019) Supercritical CO_2 extraction of ucuúba (*Virola surinamensis*) seed oil: global yield, kinetic data, fatty acid profile, and antimicrobial activities. Chem Eng Commun 206(1):86–97. https://doi.org/10.1080/00986445.2018.1474741

Cunha VMB, da Silva MP, de Sousa SHB, do Nascimento Bezerra P, EGO M, da Silva NJN, da Silva Banna DAD, Araújo ME, de Carvalho RN Jr (2019) Bacaba-de-leque (*Oenocarpus distichus* Mart.) oil extraction using supercritical CO_2 and bioactive compounds determination in the residual pulp. J Supercrit Fluids 144:81–90. https://doi.org/10.1016/j.supflu.2018.10.010

Da Porto C, Voinovich D, Decorti D, Natolino A (2012a) Response surface optimization of hemp seed (*Cannabis sativa* L.) oil yield and oxidation stability by supercritical carbon dioxide extraction. J Supercrit Fluids 68:45–51. https://doi.org/10.1016/j.supflu.2012.04.008

Da Porto C, Decorti D, Tubaro F (2012b) Fatty acid composition and oxidation stability of hemp (*Cannabis sativa* L.) seed oil extracted by supercritical carbon dioxide. Ind Crop Prod 36:401–404. https://doi.org/10.1016/j.indcrop.2011.09.015

Da Silva RPFF, Rocha-Santos TAP, Duarte AC (2016) Supercritical fluid extraction of bioactive compounds. Trends Analyt Chem 76:40–51. https://doi.org/10.1016/j.trac.2015.11.013

De Cássia C, Batista R, de Oliveira MS, Araújo ME, Rodrigues AMC, Botelho JRS, da Silva Souza Filho AP, Machado NT, Carvalho RN Jr (2016) Supercritical CO_2 extraction of açaí (*Euterpe oleracea*) berry oil: global yield, fatty acids, allelopathic activities, and determination of phenolic and anthocyanins total compounds in the residual pulp. J Supercrit Fluids 107:364–369. https://doi.org/10.1016/j.supflu.2015.10.006

De la Fuente JC, Oyarzún B, Quezada N, del Valle JM (2006) Solubility of carotenoid pigments (lycopene and astaxanthin) in supercritical carbon dioxide. Fluid Phase Equilib 247(1–2):90–95. https://doi.org/10.1016/j.fluid.2006.05.031

De Melo MMR, Silvestre AJD, Silva CM (2014) Supercritical fluid extraction of vegetable matrices: applications, trends and future perspectives of a convincing green technology. J Supercrit Fluids 92:115–176. https://doi.org/10.1016/j.supflu.2014.04.007

Dejoye C, Abert Vian M, Lumia G, Bouscarle C, Charton F, Chemat F (2011) Combined extraction processes of lipid from *Chlorella vulgaris* microalgae: microwave prior to supercritical carbon dioxide extraction. Int J Mol Sci 12:9332–9341. https://doi.org/10.3390/ijms12129332

Derrien M, Aghabararnejad M, Gosselin A, Desjardins Y, Angers P, Boumghar Y (2018) Optimization of supercritical carbon dioxide extraction of lutein and chlorophyll from spinach by-products using response surface methodology. LWT Food Sci Technol 93:79–87. https://doi.org/10.1016/j.lwt.2018.03.016

Durante M, Salvatore Lenucci M, Mita G (2014) Supercritical carbon dioxide extraction of carotenoids from pumpkin (*Cucurbita* spp.): a review. Int J Mol Sci 15:6725–6740. https://doi.org/10.3390/ijms15046725

Ekinci MS, Gürü M (2014) Extraction of oil and β-sitosterol from peach (*Prunus persica*) seeds using supercritical carbon dioxide. J Supercrit Fluids 92:319–323. https://doi.org/10.1016/j.supflu.2014.06.004

Escobedo-Flores Y, Chavez-Flores D, Salmeron I, Molina-Guerrero C, Perez-Vega S (2018) Optimization of supercritical fluid extraction of polyphenols from oats (*Avena sativa* L.) and their antioxidant activities. J Cereal Sci 80:198–204. https://doi.org/10.1016/j.jcs.2018.03.002

Faurant C (2011) From bark to weed: the history of artemisinin. Parasite (Paris, France) 18(3):215–218. https://doi.org/10.1051/parasite/2011183215

Fernández-Acosta K, Salmeron I, Chavez-Flores D, Perez-Reyes I, Ramos V, Ngadi M, Kwofie EM, Perez-Vega S (2019) Evaluation of different variables on the supercritical CO_2 extraction of oat (*Avena sativa* L.) oil; main fatty acids, polyphenols, and antioxidant content. J Cereal Sci 88:118–124. https://doi.org/10.1016/j.jcs.2019.05.017

Folch J, Lees M, Sloane Stanley GH (1957) A simple method for the isolation and purification of total lipides from animal tissues. J Biol Chem 226(1):497–509. http://www.jbc.org/content/226/1/497.long

Fornari T, Vicente G, Vázquez E, García-Risco MR, Reglero G (2012a) Isolation of essential oil from different plants and herbs by supercritical fluid extraction. J Chromatogr A 1250:34–48. https://doi.org/10.1016/j.chroma.2012.04.051

Fornari T, Ruiz-Rodriguez A, Vicente G, Vázquez E, García-Risco MR, Reglero G (2012b) Kinetic study of the supercritical CO_2 extraction of different plants from the *Lamiaceae* family. J Supercrit Fluids 64:1–8. https://doi.org/10.1016/j.supflu.2012.01.006

Frohlich PC, Santos KA, Palu F, Cardozo-Filho L, da Silva C, da Silva EA (2019) Evaluation of the effects of temperature and pressure on the extraction of eugenol from clove (*Syzygium aromaticum*) leaves using supercritical CO_2. J Supercrit Fluids 143:313–320. https://doi.org/10.1016/j.supflu.2018.09.009

Gallego R, Bueno M, Herrero M (2019) Sub- and supercritical fluid extraction of bioactive compounds from plants, food-by-products, seaweeds and microalgae-an update. Trends Anal Chem 116:198–213. https://doi.org/10.1016/j.trac.2019.04.030

García-Pérez JS, Cuéllar-Bermúdez SP, de la Cruz-Quiroz R, Arévalo-Gallegos A, Esquivel-Hernandez DA, Rodríguez-Rodríguez J, García-García R, Iqbal HMN, Parra-Saldivar R (2019) Supercritical CO_2-based tailor made valorization of *Origanum vulgare* L. extracts: a green approach to extract high-value compounds with applied perspectives. J Environ Manag 232:796–802. https://doi.org/10.1016/j.jenvman.2018.11.117

Goyeneche R, Fanovichc A, Rodrigues CR, Nicolao MC, Di Scala K (2018) Supercritical CO_2 extraction of bioactive compounds from radish leaves: yield, antioxidant capacity and cytotoxicity. J Supercrit Fluids 135:78–83. https://doi.org/10.1016/j.supflu.2018.01.004

Grosso C, Ferraro V, Figueiredo AC, Barroso JG, Coelho JA, Palavra AM (2008) Supercritical carbon dioxide extraction of volatile oil from Italian coriander seeds. Food Chem 111:197–203. https://doi.org/10.1016/j.foodchem.2008.03.031

Grosso C, Figueiredo AC, Burillo J, Mainar AM, Urieta JS, Barroso JG, Coelho JA, Palavra AM (2009a) Supercritical fluid extraction of the volatile oil from *Santolina chamaecyparissus*. J Sep Sci 32:3215–3222. (errata in J Separat Sci 32:3365–3366). https://doi.org/10.1002/jssc.200900350

Grosso C, Figueiredo AC, Burillo J, Mainar AM, Urieta JS, Barroso JG, Coelho JA, Palavra AMF (2009b) Enrichment of the thymoquinone content in volatile oil from *Satureja montana* using supercritical fluid extraction. J Sep Sci 32:328–334. https://doi.org/10.1002/jssc.200800490

Grosso C, Coelho JP, Pessoa FLP, Fareleira JMNA, Barroso JG, Urieta JS, Palavra AF, Sovova H (2010) Mathematical modelling of supercritical CO_2 extraction of volatile oils from aromatic plants. Chem Eng Sci 65:3579–3590. https://doi.org/10.1016/j.ces.2010.02.046

He J-Z, Shao P, Liu J-H, Ru Q-M (2012) Supercritical carbon dioxide extraction of flavonoids from pomelo (*Citrus grandis* (L.) Osbeck) peel and their antioxidant activity. Int J Mol Sci 13:13065–13078. https://doi.org/10.3390/ijms131013065

Herrero M, del Pilar S-CA, Cifuentes A, Ibáñez E (2015) Plants, seaweeds, microalgae and food by-products as natural sources of functional ingredients obtained using pressurized liquid extraction and supercritical fluid extraction. Trends Anal Chem 71:26–38. https://doi.org/10.1016/j.trac.2015.01.018

Huang Z, Shi X-H, Jiang W-J (2012) Theoretical models for supercritical fluid extraction. J Chromatogr A 1250:2–26. https://doi.org/10.1016/j.chroma.2012.04.032

Juchen PT, Araujo MN, Hamerski F, Corazza ML, Voll FAP (2019) Extraction of parboiled rice bran oil with supercritical CO_2 and ethanol as CO-solvent: kinetics and characterization. Ind Crops Prod 139:111506. https://doi.org/10.1016/j.indcrop.2019.111506

Kamatou GPP, Viljoen AM (2010) Review of the application and pharmacological properties of α-bisabolol and α-bisabolol-rich oils. J Am Oil Chem Soc 87(1):1–7. https://doi.org/10.1007/s11746-009-1483-3

Kerrihard AL, Pegg RB (2015) Utilizing the bioactive contents of specialty oils and fats. In: Talbot G (ed) Food science, technology and nutrition, specialty oils and fats in food and nutrition. Woodhead Publishing, Sawston, pp 317–348. https://doi.org/10.1016/B978-1-78242-376-8.00013-2

Khaw K-Y, Parat M-O, Shaw PN, Falconer JR (2017) Solvent supercritical fluid technologies to extract bioactive compounds from natural sources: a review. Molec 22:1186. https://doi.org/10.3390/molecules22071186

Knez Ž, Škerget M, KnezHrnčič M (2013) Principles of supercritical fluid extraction and applications in the food, beverage and nutraceutical industries. In: Rizvi SSH (ed) Food science, technology and nutrition, separation, extraction and concentration processes in the food, beverage and nutraceutical industries. Woodhead Publishing, Sawston, pp 3–38. https://doi.org/10.1533/9780857090751.1.3

Knez Z, Pantić M, Cör D, Novak Z, Knez Hrnčič M (2019) Are supercritical fluids solvents for the future? Chem Eng Process Process Intensification 141:107532. https://doi.org/10.1016/j.cep.2019.107532

Kohler M, Haerdi W, Christen P, Veuthey J-L (1997) Extraction of artemisinin and artemisinic acid from *Artemisia annua* L. using supercritical carbon dioxide. J Chromatogr A 785(1–2):353–360. https://doi.org/10.1016/S0021-9673(97)00403-2

Koubaa M, Barba FJ, Mhemdi H, Grimi N, Koubaa W, Vorobiev E (2015) Gas assisted mechanical expression (GAME) as a promising technology for oil and phenolic compound recovery from tiger nuts. Innov Food Sci Emerg Technol 32:172–180. https://doi.org/10.1016/j.ifset.2015.09.019

Krichnavaruk S, Shotipruk A, Goto M, Pavasant P (2008) Supercritical carbon dioxide extraction of astaxanthin from *Haematococcus pluvialis* with vegetable oils as cosolvent. Bioresour Technol 99(13):5556–5560. https://doi.org/10.1016/j.biortech.2007.10.049

Kumhom T, Elkame A, Douglas PL, Douglas S, Pongamphai S, Teppaitoon W (2011) Prediction of isoflavone extraction from soybean meal using supercritical carbon dioxide with cosolvents. Chem Eng J 172:1023–1032. https://doi.org/10.1016/j.cej.2011.07.019

Lang Q, Wai CM (2001) Supercritical fluid extraction in herbal and natural product studies-a practical review. Talanta 53:771–782. https://doi.org/10.1016/s0039-9140(00)00557-9

Lapkin AA, Plucinski PK, Cutler M (2006) Comparative assessment of technologies for extraction of artemisinin. J Nat Prod 69:1653–1664. https://doi.org/10.1021/np060375j

Lasekan O, Abdulkarim SM (2012) Extraction of oil from tiger nut (*Cyperus esculentus* L.) with supercritical carbon dioxide (SC-CO_2). LWT Food Sci Technol 47(2):287–292. https://doi.org/10.1016/j.lwt.2012.01.021

Li Y, Naghdi FG, Garg S, Adarme-Vega TC, Thurecht KJ, Ghafor WA, Tannock S, Schenk PM (2014) A comparative study: the impact of different lipid extraction methods on current microalgal lipid research microbial cell factories. Microb Cell Factories 13:1–9. https://doi.org/10.1186/1475-2859-13-14

Lin YL, Yang CC, Hsu HK, Hsu SL, Chang CMJ (2006) Response surface methodology to supercritical fluids extraction of artemisinin and the effects on rat hepatic stellate cell in vitro. J Supercrit Fluids 39:48–53. https://doi.org/10.1016/j.supflu.2006.02.012

Liu J, Ji F, Chen F, Guo W, Yang M, Huang S, Zhang F, Liu Y (2018) Determination of garlic phenolic compounds using supercritical fluid extraction coupled to supercritical fluid chromatography/tandem mass spectrometry. J Pharm Biomed Anal 159:513–523. https://doi.org/10.1016/j.jpba.2018.07.020

López-Padilla A, Ruiz-Rodriguez A, Reglero G, Fornari T (2017) Supercritical carbon dioxide extraction of *Calendula officinalis*: kinetic modeling and scaling up study. J Supercrit Fluids 130:292–300. https://doi.org/10.1016/j.supflu.2017.03.033

Martínez J, de Aguiar AC (2014) Extraction of triacylglycerols and fatty acids using supercritical fluids - review. Curr Anal Chem 10:67–77. https://doi.org/10.2174/1573411011410010006

Martinez-Correa HA, Bitencourt RG, Kayano ACAV, Magalhães PM, Costa FTM, Cabral FA (2017) Integrated extraction process to obtain bioactive extracts of *Artemisia annua* L. leaves using supercritical CO_2, ethanol and water. Ind Crop Prod 95:535–542. https://doi.org/10.1016/j.indcrop.2016.11.007

Meireles MAA (2003) Supercritical extraction from solid: process design data (2001–2003). Curr Opin Solid State Mater Sci 7(4–5):321–330. https://doi.org/10.1016/j.cossms.2003.10.008

Mendes RL, Fernandes HL, Coelho JP, Reis EC, Cabral JMS, Novais JM, Palavra AF (1995) Supercritical CO_2 extraction of carotenoids and other lipids from *Chlorella vulgaris*. Food Chem 53:99–103. https://doi.org/10.1016/0308-8146(95)95794-7

Mendes RL, Nobre BP, Cardoso MT, Pereira AP, Palavra AF (2003) Supercritical carbon dioxide extraction of compounds with pharmaceutical importance from microalgae. Inorg Chim Acta 356:328–334. https://doi.org/10.1016/S0020-1693(03)00363-3

Michalak I, Chojnacka K, Saeid A (2017) Plant growth biostimulants, dietary feed supplements and cosmetics formulated with supercritical CO_2 algal extracts. Molecules 22:66. https://doi.org/10.3390/molecules22010066

Modey WK, Mulholland DA, Raynor MW (1996) Analytical supercritical fluid extraction of natural products. Phytochem Anal 7:1–15. https://doi.org/10.1002/(SICI)1099-1565(199601)7:1<1::AID-PCA275>3.0.CO;2-U

Mouahid A, Crampon C, Toudji S-A A, Badens E (2016) Effects of high water content and drying pre-treatment on supercritical CO_2 extraction from *Dunaliella salina* microalgae: experiments and modelling. J Supercrit Fluids 116:271–280. https://doi.org/10.1016/j.supflu.2016.06.007

Mukhopadhyay M (2000) Natural extracts using supercritical carbon dioxide. CRC Press, Boca Raton. https://doi.org/10.1201/9781420041699

Nagavekar N, Singhal RS (2019) Supercritical fluid extraction of *Curcuma longa* and *Curcuma amada* oleoresin: optimization of extraction conditions, extract profiling, and comparison of bioactivities. Ind Crops Prod 134:134–145. https://doi.org/10.1016/j.indcrop.2019.03.061

Natolino A, Da Porto C (2019) Supercritical carbon dioxide extraction of pomegranate (*Punica granatum* L.) seed oil: kinetic modelling and solubility evaluation. J Supercrit Fluids 151:30–39. https://doi.org/10.1016/j.supflu.2019.05.002

Özkal SG, Yener ME, Bayindirli L (2005) Mass transfer modelling of apricot kernel oil extraction with supercritical carbon dioxide. J Supercrit Fluids 35:119–127. https://doi.org/10.1016/j.supflu.2004.12.011

Pereira CG, Meireles MAA (2010) Supercritical fluid extraction of bioactive compounds: fundamentals, applications and economic perspectives. Food Bioprocess Technol 3:340–372. https://doi.org/10.1007/s11947-009-0263-2

Perrut M, Clavier JY, Poletto M, Reverchon E (1997) Mathematical modeling of sunflower seed extraction by supercritical CO_2. Ind Eng Chem Res 36:430–435. https://doi.org/10.1021/ie960354s

Pinto RHH, Sena C, Santos OV, Costa WA, Rodrigues AMC, Carvalho RN Jr (2018) Extraction of bacaba (*Oenocarpus bacaba*) oil with supercritical CO_2: global yield isotherms, fatty acid composition, functional quality, oxidative stability, spectroscopic profile and antioxidant activity. Grasas Aceites 69(2):1–8. https://doi.org/10.3989/gya.0883171

Pourmortazavi SM, Hajimirsadeghi SS (2007) Supercritical fluid extraction in plant essential and volatile oil analysis. J Chromatogr A 1163(2):2–24. https://doi.org/10.1016/j.chroma.2007.06.021

Quispe-Condori S, Sánchez D, Foglio MA, Rosa PTV, Zetzl C, Brunner G, Meireles MAA (2005) Global yield isotherms and kinetic of artemisinin extraction from *Artemisia annua* L. leaves using supercritical carbon dioxide. J Supercrit Fluids 36:40–48. https://doi.org/10.1016/j.supflu.2005.03.003

Rai A, Mohanty B, Bhargava R (2016) Supercritical extraction of sunflower oil: a central composite design for extraction variables. Food Chem 192:647–659. https://doi.org/10.1016/j.foodchem.2015.07.070

Reverchon E, De Marco I (2006) Supercritical fluid extraction and fractionation of natural matter. J Supercrit Fluids 38:146–166. https://doi.org/10.1016/j.supflu.2006.03.020

Rodrigues MFF, Sousa IMO, Vardanega R, Nogueira GC, Meireles MAA, Foglio MA, Marchese JA (2019) Techno-economic evaluation of artemisinin extraction from *Artemisia annua* L. using supercritical carbon dioxide. Ind Crops Prod 132:336–343. https://doi.org/10.1016/j.indcrop.2019.02.049

Rombaut N, Savoire R, Thomasset B, Bélliard T, Castello J, Van Hecke É, Lanoisellé J-L (2014) Grape seed oil extraction: interest of supercritical fluid extraction and gas-assisted mechanical extraction for enhancing polyphenol co-extraction in oil. C R Chim 17(3):284–292. https://doi.org/10.1016/j.crci.2013.11.014

Roselló-Soto E, Barba FJ, Lorenzo JM, Dominguez R, Pateiro M, Mañes J, Moltó JC (2019a) Evaluating the impact of supercritical-CO_2 pressure on the recovery and quality of oil from "horchata" by-products: fatty acid profile, α-tocopherol, phenolic compounds and lipid oxidation parameters. Food Res Int 120:888–894. https://doi.org/10.1016/j.foodres.2018.11.054

Roselló-Soto E, Barba FJ, Lorenzo JM, Munekata PES, Gómez B, Moltó JC (2019b) Phenolic profile of oils obtained from "horchata" by-products assisted by supercritical-CO_2 and its relationship with antioxidant and lipid oxidation parameters: triple TOF-LC-MS-MS characterization. Food Chem 274:865–871. https://doi.org/10.1016/j.foodchem.2018.09.055

Rovetto LJ, Aieta NV (2017) Supercritical carbon dioxide extraction of cannabinoids from *Cannabis sativa* L. J Supercrit Fluids 129:16–27. https://doi.org/10.1016/j.supflu.2017.03.014

Ruttarattanamongkol K, Siebenhandl-Ehn S, Schreiner M, Petrasch AM (2014) Pilot-scale supercritical carbon dioxide extraction, physico-chemical properties and profile characterization of *Moringa oleifera* seed oil in comparison with conventional extraction methods. Ind Crops Prod 58:68–77. https://doi.org/10.1016/j.indcrop.2014.03.020

Sánchez-Camargo AP, Parada-Alonso F, Ibáñez E, Cifuentes A (2019) Recent applications of online supercritical fluid extraction coupled to advanced analytical techniques for compounds extraction and identification. J Sep Sci 42:243–257. https://doi.org/10.1002/jssc.201800729

Santos KA, Frohlich PC, Hoscheid J, Tiuman TS, Gonçalves JE, Cardozo-Filho L, da Silva EA (2017) Candeia (*Eremanthus erythroppapus*) oil extraction using supercritical CO_2 with ethanol and ethyl acetate cosolvents. J Supercrit Fluids 128:323–330. https://doi.org/10.1016/j.supflu.2017.03.029

Santos KA, Klein EJ, da Silva C, da Silva EA, Cardozo-Filho L (2019) Extraction of vetiver (*Chrysopogon zizanioides*) root oil by supercritical CO_2, pressurized-liquid, and ultrasound-assisted methods and modelling of supercritical extraction kinetics. J Supercrit Fluids 150:30–39. https://doi.org/10.1016/j.supflu.2019.04.005

Shah MM, Liang Y, Cheng JJ, Daroch M (2016) Astaxanthin-producing green microalga *Haematococcus pluvialis*: from single cell to high value commercial products. Front Plant Sci 7:531. https://doi.org/10.3389/fpls.2016.00531

Shukla A, Naik SN, Goud VV, Das C (2019) Supercritical CO_2 extraction and online fractionation of dry ginger for production of high-quality volatile oil and gingerols enriched oleoresin. Ind Crops Prod 130:352–362. https://doi.org/10.1016/j.indcrop.2019.01.005

Silva MP, Cunha VMB, Sousa SHB, Menezes EGO, do Nascimento Bezerra P, de Farias Neto JT, GNR F, Araújo ME, de Carvalho RN Jr (2019) Supercritical CO_2 extraction of lyophilized Açaí

(*Euterpe oleracea* Mart.) pulp oil from three municipalities in the state of Pará, Brazil. J CO2 Utilization 31:226–234. https://doi.org/10.1016/j.jcou.2019.03.019

Sovová H (2012) Modeling the supercritical fluid extraction of essential oils from plant materials. J Chromatogr A 1250:27–33. https://doi.org/10.1016/j.chroma.2012.05.014

Sovová H (2017) Broken-and-intact cell model for supercritical fluid extraction: its origin and limits. J Supercrit Fluids 129:3–8. https://doi.org/10.1016/j.supflu.2017.02.014

Sovová H, Stateva RP (2019) New developments in the modelling of carotenoids extraction from microalgae with supercritical CO_2. J Supercrit Fluids 148:93–103. https://doi.org/10.1016/j.supflu.2019.03.002

Sovová H, Stateva RP, Galushko AA (2001) Solubility of beta-carotene in supercritical CO_2 and the effect of entrainers. J Supercrit Fluids 21(3):195–203. https://doi.org/10.1016/S0896-8446(01)00101-2

Sovová H, Nobre BP, Palavra A (2016) Modeling of the kinetics of supercritical fluid extraction of lipids from microalgae with emphasis on extract desorption. Materials 9(6):423–441. https://doi.org/10.3390/ma9060423

Stuart IA, MacLachlan J, McNaughtan A (1996) Compounds of agricultural significance using environmental analytical supercritical fluid extraction. A review. Analyst 121 (IIR-28R):11R. https://doi.org/10.1039/AN996210011R

Sun L, Rezaei KA, Temelli F, Ooraikul B (2002) Supercritical fluid extraction of alkylamides from *Echinacea angustifolia*. J Agric Food Chem 50:3947–3953. https://doi.org/10.1021/jf0200265

Sur R, Nigam A, Grote D, Liebel F, Southall MD (2008) Avenanthramides, polyphenols from oats, exhibit anti-inflammatory and anti-itch activity. Arch Dermatol Res 300(10):569–574. https://doi.org/10.1007/s00403-008-0858-x

Tongnuanchan P, Benjakul S (2014) Essential oils: extraction, bioactivities, and their uses for food preservation. J Food Sci 79(7):R1231–R1249. https://doi.org/10.1111/1750-3841.12492

Tzeng TC, Lin YL, Jong TT, Chang CMJ (2007) Ethanol modified supercritical fluids extraction of scopoletin and artemisinin from *Artemisia annua* L. Sep Purif Technol 56:18–24. https://doi.org/10.1016/j.seppur.2007.01.010

Valadez-Carmona L, Ortiz-Moreno A, Ceballos-Reyes G, Mendiola JA, Ibáñez E (2018) Valorization of cacao pod husk through supercritical fluid extraction of phenolic compounds. J Supercrit Fluids 131:99–105. https://doi.org/10.1016/j.supflu.2017.09.011

Veggi PC, Cavalcanti RN, Meireles MAA (2014a) Production of phenolic-rich extracts from Brazilian plants using supercritical and subcritical fluid extraction: experimental data and economic evaluation. J Food Eng 131:96–109. https://doi.org/10.1016/j.jfoodeng.2014.01.027

Veggi PC, Prado JM, Bataglion GA, Eberlin MN, Meireles MAA (2014b) Obtaining phenolic compounds from jatoba (*Hymenaea courbaril* L.) bark by supercritical fluid extraction. J Supercrit Fluid 89:68–77. https://doi.org/10.1016/j.supflu.2014.02.016

Walters M, Ribeiro APL, Hosseinian F, Tsopmo A (2018) Phenolic acids, avenanthramides, and antioxidant activity of oats defatted with hexane or supercritical fluid. J Cereal Sci 79:21–26. https://doi.org/10.1016/j.jcs.2017.09.010

Wang Y, Ying L, Sun D, Zhang S, Zhu Y, Xu P (2011) Supercritical carbon dioxide extraction of bioactive compounds from *Ampelopsis grossedentata* stems: process optimization and antioxidant activity. Int J Mol Sci 12:6856–6870. https://doi.org/10.3390/ijms12106856

Wrona O, Rafińska K, Możeński C, Buszewski B (2017) Supercritical fluid extraction of bioactive compounds from plant materials. J AOAC Int 100:1624–1635. https://doi.org/10.5740/jaoacint.17.0232

Wrona O, Rafińska K, Możeński C, Buszewski B (2019) Supercritical carbon dioxide extraction of *Solidago gigantea* Ait.: optimization at quarter technical scale and scale up the process to half technical plant. Ind Crops Prod 130:316–324. https://doi.org/10.1016/j.indcrop.2018.12.050

Xing XH, Zhang ZM, Hu XZ, Wu RQ, Xu C (2009) Antidiabetic effects of *Artemisia sphaerocephala* Krasch gum, a novel food additive in China, on streptozotocin-induced type 2 diabetic rats. J Ethnopharmacol 125(3):410–416. https://doi.org/10.1016/j.jep.2009.07.021

Yousefi M, Rahimi-Nasrabadi M, Pourmortazavi SM, Wysokowski M, Jesionowski T, Ehrlich H, Mirsadeghi S (2019) Supercritical fluid extraction of essential oils. Trends Anal Chem 118:182–193. https://doi.org/10.1016/j.trac.2019.05.038

Zaghdoudi K, Framboisier X, Frochot C, Vanderesse R, Barth D, Kalthoum-Cherif J, Blanchard F, Guiavarćh Y (2016) Response surface methodology applied to supercritical fluid extraction (SFE) of carotenoids from persimmon (*Diospyros kaki* L.). Food Chem 208:209–219. https://doi.org/10.1016/j.foodchem.2016.03.104

Zou X, Liu Y, Tao C, Liu Y, Liu M, Wu J, Lv Z (2018) CO_2 supercritical fluid extraction and characterization of polysaccharide from bamboo (*Phyllostachys heterocycla*) leaves. J Food Meas Charact 12(1):35–44. https://doi.org/10.1007/s11694-017-9614-2

Zulkafli ZD, Wang H, Miyashita F, Utsumi N, Tamura K (2014) Cosolvent-modified supercritical carbon dioxide extraction of phenolic compounds from bamboo leaves (*Sasa palmata*). J Supercrit Fluids 94:123–129. https://doi.org/10.1016/j.supflu.2014.07.008