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Comparison for the production of essential oil by conventional, novel and biotechnology methods

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ABSTRACT

Essential oils have many interesting applications in industry food, cosmetics, pharmaceutical, agriculture. Essential oils can be produced by various techniques, including conventional, novel and biotechnology methods. Novel extraction methods can be considered as a good alternative to conventional methods due to short extraction time, high efficiency and quality, non-decomposition of compounds due to heat and no pollution. Recently, due to the limitations of extraction methods, the attention of scientists has been focused on synthesizing aromatic compounds through biotechnological methods. In the biotechnology method, there is no concern about factors such as climate conditions, supply shortages, natural disasters, plant disease and a high-quality product is obtained. Biotechnology could provide an environmentally friendly alternative that does not require as much land and resources as traditional methods. This review covers up-to-date literature on extraction methods of essential oils, including conventional methods, novel methods and biotech methods, and a generally comparison between them.

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Essential oil; natural compounds; green extraction; conventional methods; novel methods; biotechnology

Introduction

Essential oils as colorless compounds are evaporated easily at normal temperatures and are known as secondary metabolisms (1–4). Produced compounds by plants in the nature can be classified into two main groups. The main or primary metabolites are the main elements of plant and animal life which are common to all, including carbohydrates, proteins, lipids and nucleic acids. In plants, there are other metabolic processes which the production of them by the organism is not fully understood. These compounds are referred to as secondary metabolites. Essential oils are secondary metabolites of plants (4–6) which can be extracted from various plant sources, for example flower (*Jasminum, Rose, Violet and Lavender*), leaves (*Thymes, Eucalyptus, Salvia*), bark (*Cinnamon*), buds (*Clove*), herbs, fruits (*Orange, Lemon*), twigs, seeds (*Cardamom*), wood (*Sandal*), rhizome and roots (*Ginger*) etc. (7–9).

Essential oils components are affected by factors such as genetics and the environment. Also, their compositions are dependent on the extraction methods and on how the plant grows (10,11). Some essential oils with their major constituents were randomly selected and are presented in Table 1 (12).

Two common and important techniques for the analysis of essential oils are chromatography and mass spectrometry. Gas chromatography – mass spectrometry (GC-MS) and high performance liquid chromatography (HPLC) are the most widely used (4,13,14). In general, gas chromatography (GC) for the analysis of volatile compounds and liquid chromatography (LC) for an analysis of non-volatile compounds in essential oils is used (15).

In addition to essential oils, other aromatic compounds are extracted from plants including concrete (is obtained by extraction with non-polar solvents), absolute (is obtained by washing concretes in ethanol or methanol followed by evaporation and distillation of alcohol), pomade (is obtained by a process known as enfleurage (will be described in later sections)), resinoids (are extracted from the natural resin material by hydrocarbon solvent. Resinoids are usually derived from dry material) (16,17).

Essential oils can be extracted from different plants by various extraction methods. The essential oil extraction technology is dependent on used plants. Another factor for essential oil extraction is state and form of material. One of the important factors that has a great impact on the quality of essential oil is the extraction method. Inappropriate choice of extraction methods can damage the chemical structure of the essential oil. In fact, the extraction method is one of the prime factors that determine the quality of essential oil (7). generally, extraction methods can be divided into two groups: conventional methods (Distillation, Cold Pressing,

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Table 1. Some essential oils with their major constituents.

Species	Popular Name	Major Components	The Main Organ Producing Oil
Cinnamomum verum	Cinnamon	Trans-cinnamaldehyde	Bark
Santalum album	Sandalwood	Santalol	Stem
Mentha × piperita	Peppermint	Menthone, Menthol, Isomenthone	Leaf
Salvia officinalis	Sage	Camphor, Thujone	Leaf
Mentha spicata	Spearmint	Carvone, Carveol	Leaf
Origanum majorana	Sweet marjoram	Terpenen-4-ol, Pinene	Leaf and flower
Ocimum basilicum	Common Basil	Chavicol, Linalool, Eugenol	Leaf
Lavandula angustifolia	Lavender	Geraniol, Linalool	Flower
Artemisia dracunculus	Wild Tarragon	Methyl chavicol	Leaf
Thymus vulgaris	Thyme	Thymol, Carvacrol, g-Terpinene, *p*-Cymene	Leaf
Syzygium aromaticum	Clove	Eugenol, Eugenyl acetate	Bud

Extraction Solvent, Enfleurage and Maceration Process) and novel methods (Supercritical Fluid, Ultrasound Assisted Extraction, Enzyme Assisted Extraction, Pulsed Electric Field Extraction, Pressurized Liquid Extraction, Microwave Assisted Extraction and High Voltage Electrical Discharge). Above-mentioned methods, such as distillation or supercritical fluid, can be useful in extracting volatile compounds and some technologies, such as solvent extraction, can be useful in extracting non-volatile compounds. In the last decades, investigation into novel technologies has led to more efficient extraction processes. Reduction of energy consumption and extraction time, high efficiency and improvement of essential oils quality are among the features of these methods.

Also, in addition to advantages, these methods include disadvantages, such as weather conditions, supply shortages, natural disasters, plant disease, etc. (18,19). So recently, scientists have been focused on biotechnological methods to produce a variety of plant compounds by microorganisms. In the new biotechnology method, which is a kind of green method, in addition to being environmentally friendly, there is no process pollution. In this method, scientists would not experience stress about problems, and a high-quality product is obtained. Biotechnology could provide an environmentally friendly alternative that does not require as much land and resources as traditional methods. Production of volatiles products by biotechnology can be an appropriate response to consumer demand in relation to the consumption of natural products. The aim of this review is to report production methods of essential oils, including conventional, novel and biotechnology methods, and a generally comparison between them.

Conventional methods

The conventional methods for the extraction include distillation, cold pressing, extraction solvent, enfleurage and maceration process.

Distillation

The most common method of essential oils extraction worldwide is distillation. During distillation, the essential oil of fragrant plants is released through evaporation. When the vapor pressure of liquids is equal to ambient pressure, it is converted to vapor (water + oil) followed by indirect cooling, vapor is condensed. Condensed mixture flows from the condenser to a separator, where oil is automatically separated from water (4,6,15,20). Types of distillation methods can be used, including hydro (water)-distillation, steam distillation, dry distillation and vacuum distillation.

Hydro-distillation

This method, as a standard method, is the simplest and cheapest method selected for essential oil extraction from plant material. In this method, the material is immersed in water and the mixture is boiled. The water and essential oil vapor are condensed to an aqueous fraction; the oil is separated from the water by a separator or decanter (Figure 1). Plant materials should always be immersed in water during the extraction process, so evaporated water should be replaced. This method is used to extract oil from dried flowers and powders. The main problem of this process is the loss of unstable and heat-sensitive compounds and their structural changes. Also, separation of water-soluble oils is difficult (4,7,21–23). Rose-scented geranium (*Pelargonium sp.*) (24), germander (*Teucrium orientale*)

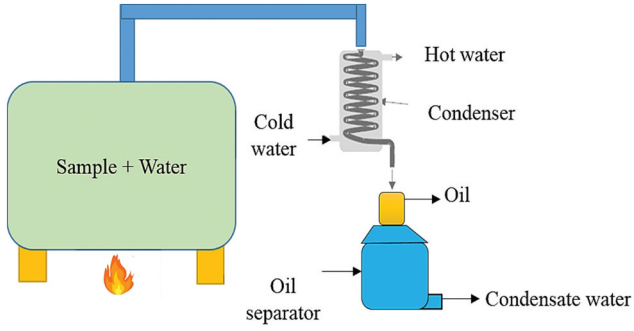

Figure 1. Hydro-distillation of essential oils (21).

(25) and thyme (*Thymus vulgaris L.)* (26) were extracted by hydro-distillation and their efficiency was compared.

The turbo distillation process is the same as water distillation, the only difference in this method is stirring. The mixture is stirred continuously with a stainless steel stirrer at an appropriate speed. This method is suitable for coarse raw materials and hard-to-extract (spices, woods). In Turbo distillation, times and energy consumption are reduced and the degradation of compounds compared to aqueous distillation is prevented. In fact, it is a kind of green extraction of water distillation (Figure 2) (23,28). Among the essential oils that were extracted by turbo hydro-distillation method, the extraction of essential oils from *Kaempferia galangal* can be mentioned (27).

Water-steam distillation

The water-steam distillation system is similar to the water distillation design (Figure 3). The plant material is packed into the steel pot sitting on a grill above the boiling water. Due to the heat, the essential oil with water is converted to vapor and condensed. After that, the oil and water are separated from each other by a mechanical separator or decanter (21). It is used for dried and fresh plants that are not destroyed due to boiling. In this method, at first, the crushed dried plant material is mixed with water, then the flow of steam is passed through the wet material (29).

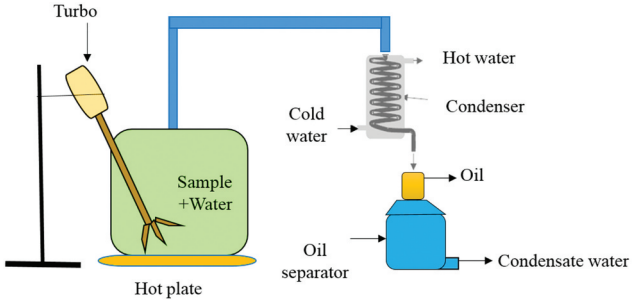

Figure 2. Turbo distillation of essential oils (27).

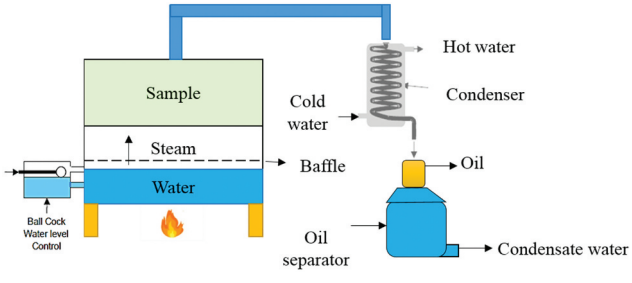

Figure 3. Water-steam distillation of essential oils (21).

Efficiency of essential oil extraction of *Cananga odorata* flowers by water-steam distillation was reported 43.25% (30). Also, production of citral oil from lemon grass (*Cymbopogon Cytratus*) was done by water-steam distillation with 40% efficiency (31).

Steam distillation

The most widely used method for extracting plant essential oil is steam distillation (7,32). Steam distillation is the process of distilling plant material with the generated steam in a boiler outside the still (Figure 4). As the steam-water distillation system, the plant material is placed on top of a perforated grid above the steam inlet (21). Either water and steam in this method are utilized, but the plant material is not in direct contact with water. Then generated steam in the boiler is flowed through a pipe into the bottom of the still. A mixture of water and oil is evaporated and condensed. Finally, the oil is separated by a separator. In this method, steam is always fully saturated, wet and never superheated (4,33). Also, the amount of steam is adjustable, and it is suitable for heat-sensitive compounds. Of course, this method is more expensive than the hydro-distillation and water-steam distillation. Extraction of *rosemary* essential oil by steam distillation was reported by Boutekedjiret (34). Also E. Cassel succeeded in extracting of *rosemary*, *basil* and *lavender* oils with 0.51%, 0.38% and 0.32% (w/w), respectively (35).

Hydro-diffusion extraction is a type of steam distillation where the only difference with the steam distillation is the inlet way of steam into the still. Steam is entered from the top of plant material, whereas in steam distillation, is entered from the bottom. This method is used when the plant material has been dried and is not damaged at boiling temperature (36). This process can be also worked under low pressure or vacuum and the steam temperature is reduced to below 100°C. This method is superior to steam distillation due to advantages such as shorter isolation times, higher efficiency and less used steam. Hydro-diffusion is also known as down hydro-diffusion or hydro-diffusion and gravity.

Dry distillation

Dry distillation is involved in heating in the absence of oxygen and heat is applied usually as a direct flame to the vessel. After releasing the essential oil at high temperature, the vapors of essential oil are condensed to produce essential oil. In extraction through dry distillation, many organic compounds may decompose and pyrolysis. This method is used to extract essential oils with a high boiling point from wood or coal.

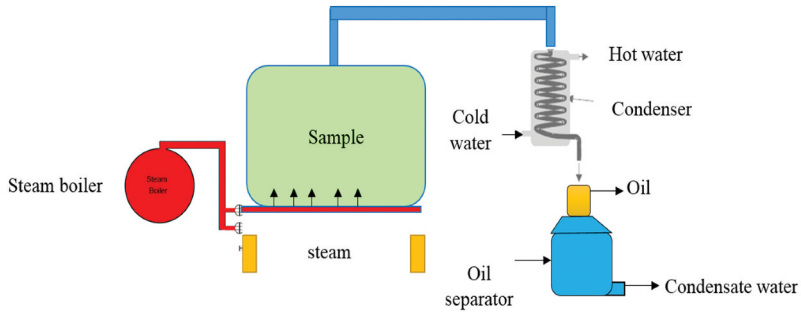

Figure 4. Steam Distillation of Essential Oils (21).

Birch tar and cade oils are produced by this method (20).

Vacuum distillation

The essential oil is obtained from plant materials under a vacuum varying in intensity depending on the material (37,38). The evaporation temperature of the material is lower under vacuum. As a result, materials can be separated by consuming less energy. Vacuum distillation is a suitable method for separating components with high boiling point and the destruction of plant tissue during extraction is prevented (16). This method is rarely used to distill oil directly from plant materials. For example, to extract volatile oil from oregano, the vacuum distillation method was used with an 8% increase in efficiency as compared to the conventional hydro-distillation (39).

Table 2 shows a generally comparison between conventional distillation methods (hydro-distillation, water-steam distillation, steam distillation). In this table, the construction, temperature, pressure, plant material suitability, use of Hydro-diffusion, hydrolysis condition and rate of distillation and yield are compared (16,21).

Cold pressing

Cold pressing is an extraction traditional method specific to citrus species (orange, bergamot, grapefruit, lemon, etc.) to produce essential oil. During extraction, oil glands are broken and volatile oils are released. The oil glands are located in the fruit rind or outside of the mezocarpe. Figure 5(a) shows a cross section of a citrus fruit (Figure 5). This method is also called 'Expression' (6,23,40). In this physical method primarily, fruit peels are crushed and pressed between two rotating cylinders to express the volatile oils in the peels. In this section, a mixture of water and oil is produced simultaneously. Finally, the mixture is allowed to settle. Then the collected oil is washed with water and followed by a centrifuge for separation (41). Figure 5(b) represents a schematic of the cold pressing (23). Today the systems of cold pressing can be classified into four categories: ''Sfumatrici' 'machines and ''Speciale Sfumatrici'', 'Pellatrici' 'machines', 'FMC whole fruit process'"mand' 'Brown oil extractors (BOEs)'" (6,42).

Soto et al. (43) used an enzymatic hydrolysis combined with cold pressing to obtain borage (*Borago officinalis*) seed oil for better yield. While, Anwar et al. (44) studied the effect of different enzymes on the yield of cold pressing and showed this system has higher yield in comparison to without the enzyme.

Extraction solvent

Solvent extraction method is used to extract non-volatile essential oils (45). The plant materials are placed in a fresh solvent and non-volatile essential oils of plants are removed. The solvent is more enriched with the oil compounds of plants during extraction, followed by filtration. Finally, the filtrate is concentrated by solvent evaporation and a thick residue that is called ''concentrate" is prepared. Then the concentrate is mixed with alcohol to extract the oil compounds. oily compounds are absorbed by alcohol. Followed by distillation of alcohol at low temperatures, the concentrated compound called "absolute" is obtained for use in perfumery. Used solvents in this method should have a low boiling point, be free of odors and impurities, and should also be inert to oil compositions (7,46,47). Different solvents are used in this method, such as acetone, hexane, petroleum ether, methanol, or ethanol (48–50).

The most important advantage of this method is the appropriate and low temperature (50°C). Solvent extraction methods have disadvantages such as solvent toxicity in some cases, high solvent consumption, flammability of solvents and the most important factor is the remaining solvent in the final product (23). Improved concentration of citrus essential oil by solvent

Table 2. Comparison of conventional distillation methods.

Method	Construction	Plant Material Suitability	Pressure	Temperature	Hydrolysis	Hydro-diffusion	Rate-Yield
Hydro Distillation	Simple, based on ancient designs	Not suitable for finely powdered materials. Not suitable for materials that contain acidic material which can saponify, water soluble, or high boiling constituents. Materials must be covered by water.	Atmosphere	100°C	High rate of ester hydrolysis	Excellent	Low, due to hydrolysis and loss of water soluble constituents into water, high boiling constituents often un-distilled.
Water-Steam Distillation	Plant materials are placed on a grill over boiling water.	Can be used for the most herbs and leaves. Materials must be packed in a uniform way to avoid channeling steam.	Atmosphere	Approximately 100°C	Usually low, although excessive wetting of material through prolong distillation can promote hydrolysis.	Good	Moderate rate, Good yield
Steam Distillation	Using an external source of steam.	Most materials except fine powders. Suitable for high boiling materials. Materials must be packed in a uniform way to avoid channeling steam.	Both high and reduced pressures.	Can be increased or reduced according to pressures used.	Slight hydrolysis	Steam should be slightly wet to promote diffusion. Superheated or high press steam can dry out the plant and inhibit diffusion	Fast tare, good yield

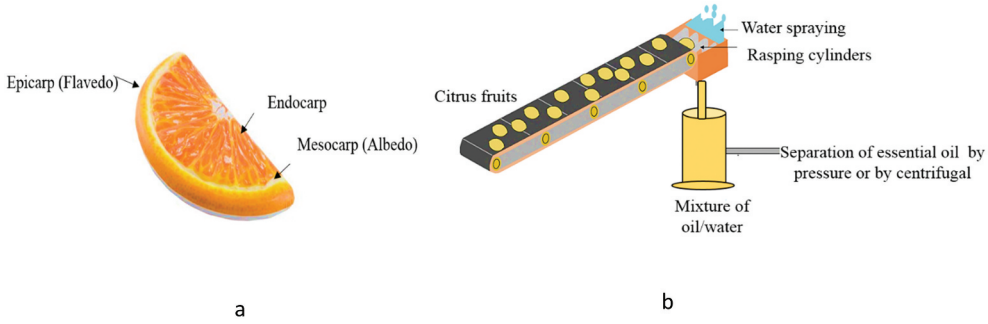

Figure 5. a) The parts of a citrus fruit (9), b) Schematic of cold pressing to obtain essential oil.

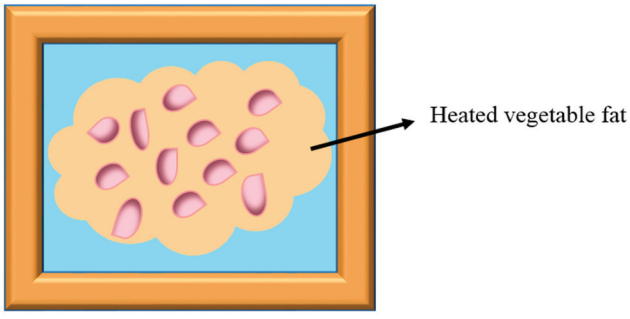

Figure 6. Hot enfleurage Process.

extraction with acetate ionic liquids was reported by Sara Lago (51). The results showed a great performance of these acetate-based ionic liquids. Extraction of essential oil from dried sage (*Salvia officinalis*) using ethanol – water mixtures was studied by Nicola E. Durling (52). The extract included 6.9% rosmarinic acid (55% recovery), 10.6% carnosic compounds (75% recovery) and 7.3% essential oil (42% recovery).

Enfleurage

This is an old method of extracting essential oils and is not commonly used today. Oil or animal fats (usually goat) are spread out over glass plates in a frame. Flowers or plant material are placed on top of the layer of fat and pressed in. This may take days or weeks, depending on the species. Followed the oil is filtered to leave a product called "Pomade". Then the absolute is obtained by mixing the pomade with alcohol and followed by distillation (16,53). The depleted material is then replaced by fresh ones until the fat is enriched with aromatic substances (54). The enfleurage process can be done either"hot"or"cold"way. The only difference is the heating of the fat during extraction in the hot process (Figure 6). Essential oil extraction from the double-flower variety of tuberose (*Polianthes tuberosaL*) by"hot"and"cold effleurage was investigated. The results showed extracts including 0.3137%, 6.5808%, respectively (55).

Maceration process

Maceration process is used as a traditional and common method (56). Macerated oils are referred to as infused oils (15). Macerated oil has an advantage over distilled oil because it is produced more essential oil due to the absorption of larger molecules and most of the plant's valuable compounds are preserved.

Maceration is a variation on enfleurage. In this method, plant material should be dried because any moisture can deteriorate the oil and lead to the growth of germs. In the maceration process, plant material is finely crushed, or ground into coarse powder and is placed in a closed vessel. Solvent (Menstruum) is added. The mixture is allowed to stand for 1 week and is shaken occasionally (depending on the plant species). Liquid is pressed and finally, is clarified through filtration or subsidence. Maceration method is useful for flowers whose physiological properties are lost rapidly after harvest. For example, lily of valley. In the 'hot maceration' process, the plant material is crushed or ground into coarse powder and is immersed in molten fat at 45–60°C for 1 to 2 h depending on the plant species. Therefore, due to heat and immersion in fat, the long enfleurage time is reduced. After each immersion, the fat is filtered and separated from the plant material. The fat is separated from waste flowers after 10 to 20 immersions. Finally, absolute maceration is obtained through the process of extraction and concentration under reduced pressure (15,16,54,56,57). Figure 7 shows a schematic of the maceration process (Figure 7). Such as extraction of flavonoids from the garden (*Salvia officinalis L.*) by a classical maceration method was examined with two types of

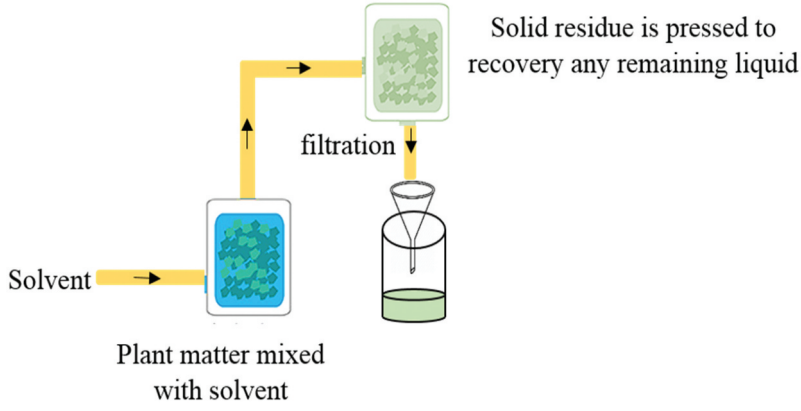

Figure 7. Schematic of maceration process.

polar and non-polar solvents. Higher yields of flavonoides were achieved using polar solvents (70% aqueous solution of ethanol and water) than the non-polar one (petroleum ether) (58).

Novel extraction methods

Novel extraction methods are also known as green methods. Green extraction can be defined as follows: Green extraction is based on extraction methods that reduce energy consumption, the use of alternative solvents and renewable natural products is allowed. Also, the process safety and product quality are ensured. In general, these types of extraction methods have the following characteristics (59).s

(1) Selection of varieties and renewable plant resources.
(2) The use of alternative solvent.
(3) Reducing energy consumption.
(4) Production of co-products instead of waste.
(5) Process control under safety aspects.
(6) Production of biodegradable extracts without contamination.

These green methods have been considered as new methods including supercritical fluid extraction (SFE), subcritical extraction liquids, enzyme-assisted extraction, ultrasound-assisted extraction (UAE), mcrowave-assisted extraction (MAE), (PEF) pulsed electric field (PEF), pressurized liquid extraction (PLE) and high voltage electrical discharge (HVED) for the extraction of essential oil.

Supercritical fluid extraction (SFE)

One of the alternative methods for extracting essential oils is supercritical fluids Extraction. SFE is based on the use of solvents in their supercritical state. A supercritical fluid is any substance at a temperature and pressure above its critical point (the critical point is the highest temperature and pressure at which a pure material can exist in vapor/liquid equilibrium). This means that the temperature and pressure above which this phase exists

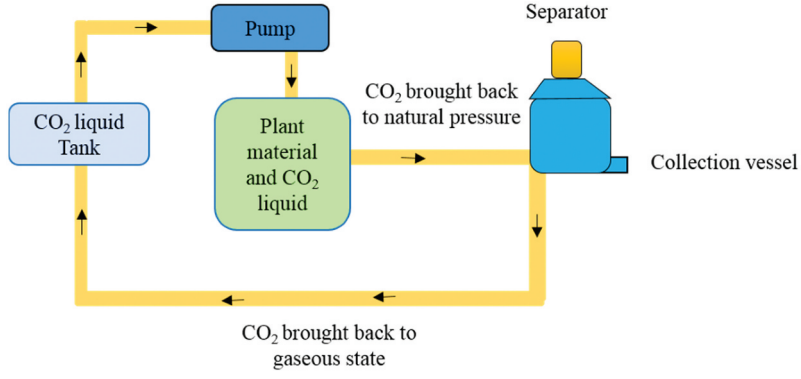

Figure 8. Supercritical fluid extraction (SFE).

is the critical point. SFE has a unique property. Supercritical fluid is between the liquid and gas phases depending on the pressure, temperature and composition of the liquids (7,9). In this method, the most widely used solvent is carbon dioxide, CO_2 (Figure 8). Due to moderate supercritical conditions (P_c: 72.9 atm, and T_c: 31.2 °C), it can be appropriate for heat-sensitive substances (60), it is not toxic and flammable; it is cheap and has high purity, it can be easily removed from the obtained extract (61), no solvent remains in the final product (62), etc.

SFE extracts show some properties of essential oils and absolutes. They have many beneficial therapeutic properties and, unlike absolutes; they are not extracted by chemical solvents; they are extracted using CO_2 gas under pressure and at room temperature.

Generally, extracts from SEF, have superior quality and better biological activities (63) compared to production of essential oil by hydro-distillation or liquid solvent (64,65). The high cost of capital and required skills in supercritical carbon dioxide extraction plant, also, the wide range of applications of the process, limits its use in industry. Rosemary, fennel and anise essential oils were obtained by supercritical fluid extraction. The results showed that extraction of supercritical fluids to obtain extracts is economically viable (66). Supercritical CO_2 extraction from *lavender* was performed by E. Reverchon (67). This compound showed 34.7% efficiency of the oil.

Subcritical extraction liquids (SEL)

Subcritical state is liquid under pressure at temperatures above usual boiling point. In fact, liquid is maintained in liquid form by applying pressure. Water and CO_2 are the most commonly used fluids in industrial applications. In the supercritical region, distinct liquid and gas phases do not exist. A supercritical fluid is similar to gas in terms of diffusion coefficient and is similar to liquid in terms of density (68,69). Process simplicity, low-cost and positive environmental impacts are advantages of this method. This technique has the advantages over other traditional extraction techniques including shorter extraction time, high-quality product, reducing extraction costs, an environmentally friendly method and low solvent consumption (60). When the temperature is between 31 and 55°C and the pressure is between 5.5 MPa and 4.7 MPa, the subcritical state of CO_2 is occurred. In this case, CO_2 behaves as a non-polar solvent (70). In the subcritical state of CO_2, the thermal degradation is prevented. K. Taraj reported extraction of essential oils of *chamomile* by subcritical CO_2 using high-pressure (65 bars). The extraction performed at 40°C and showed the high-yield (71).

Subcritical water extraction (SWE), also known as "pressurized hot water", has dynamic conditions (under high-pressure to maintain the liquid state and temperature in the range of 100°C to 374°C) (4). Generally, the obtained extracts by subcritical carbon

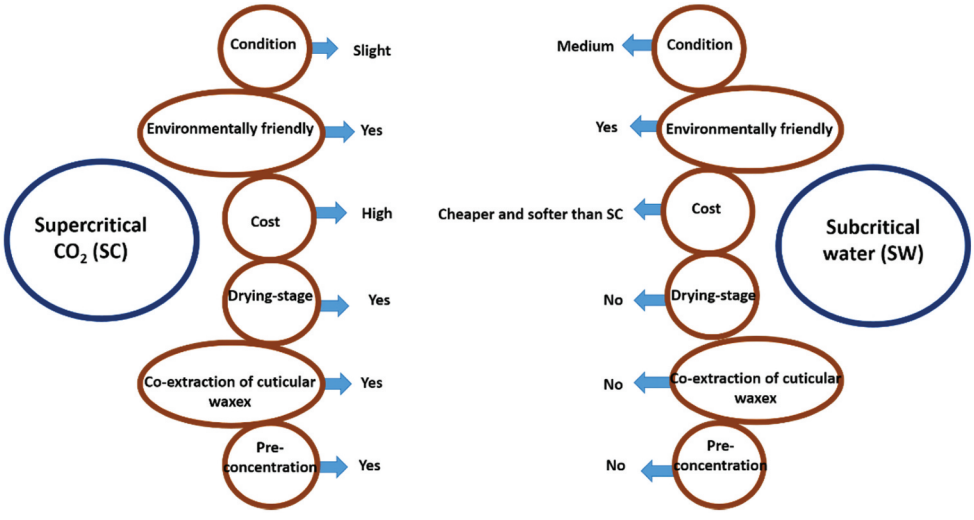

Figure 9. A comparison between supercritical CO_2 and subcritical.

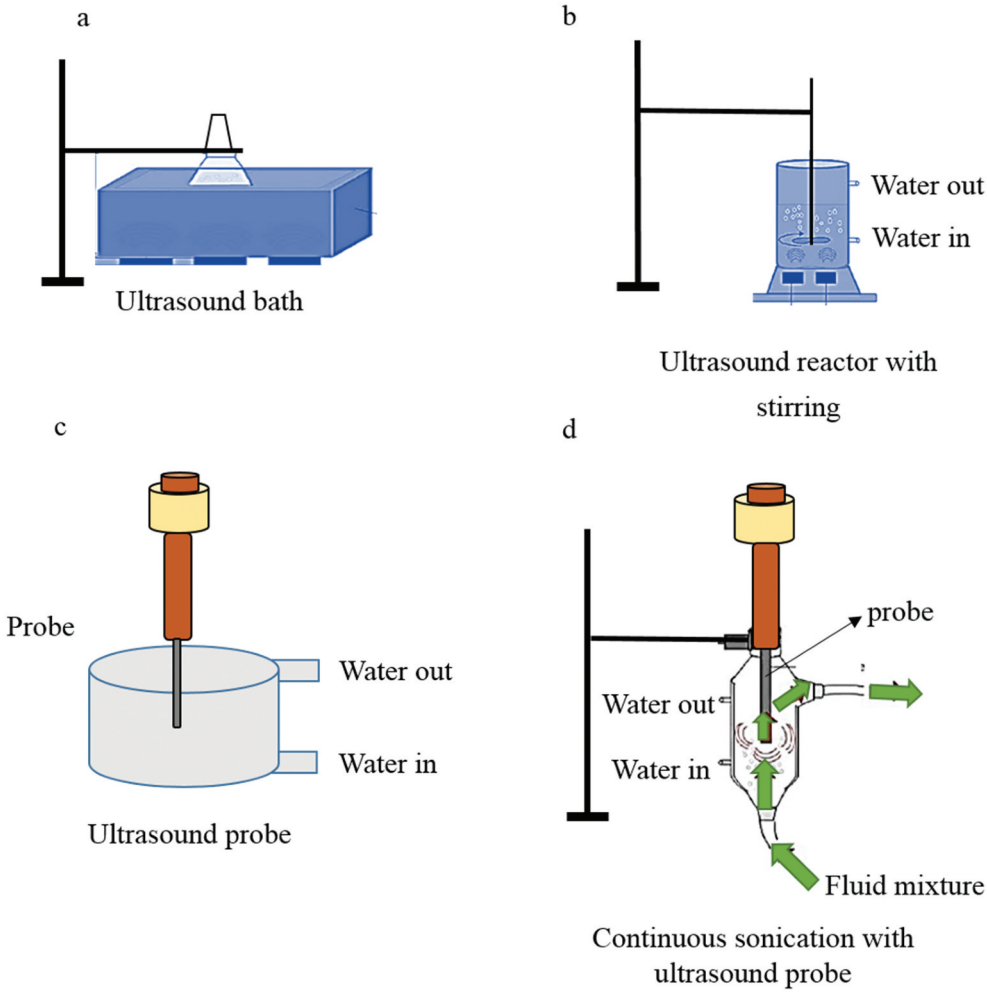

Figure 10. Ultrasonic systems (a: Ultrasound bath, b: Ultrasound reactor with stirring, c: Ultrasound probe, d: Continuous sonication with ultrasound probe) (78).

dioxide have high-quality and are better functional compared to SWE (72). According to studies, based on a comparison between supercritical CO_2 and SWE (73), it is concluded that although the SWE process is cheaper and softer than supercritical CO_2, but it is still expensive to operate due to the need for special equipment (74). The following schematic (Figure 9) compares supercritical CO_2 with subcritical water (60,74). For SWE, 130°C and 20 min extraction time were found optimal for obtaining high content of bioactive compounds. The results of this method were evaluated with other novel methods, such as microwave-assisted extraction, and showed lower efficiency (75). For example, Mustafa. Z. Ozel reported subcritical water extraction of essential oils from *Thymbra spiced* (76).

Ultrasound-assisted extraction (UAE)

In the ultrasound-assisted extraction (UAE) method, the plant material is immersed in water or solvent and exposed to ultrasound. The ultrasonic waves have a frequency of 20 kHz −1MH depending on plant species. In this method, the created mechanical vibration by ultrasonic waves causes plant cell walls to rupture. As a result, essential oil droplets are released. In other words, the cell walls are diffused, and once the walls are broken, the essential droplets are washed out (9,77). The size of the plant material is an important factor. In the small-size material, the more cells are exposed to the waves (9). Figure 10 shows commonly used ultrasonic systems (78).

Compared to traditional methods, in the UAE, extraction time and temperature are improved and the range of solvent selection is increased. Also, high-quality products with higher efficiency are produced. This method is useful for heat-sensitive substances. Compared to other new techniques, the equipment is relatively simple and inexpensive (9,79). For example, citrus (lemon) were extracted by the UAE. According to

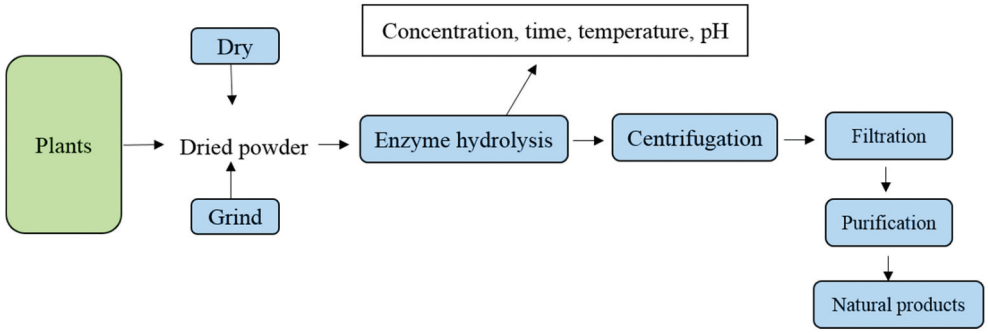

Figure 11. Enzyme-assisted extraction (81).

the result, the main component was Linalool with 11.3% efficiency (80).

Enzyme assisted extraction

Releasing essential oils from plant cells can be done by the green 'Enzyme Assisted Extraction' method. This method is based on the ability of enzymes to catalyze reactions under moderate conditions in aqueous solutions for releasing bioactive compounds. Enzyme-assisted extraction method is an environmentally friendly extraction technique (Figure 11). The used enzymes can be obtained from bacteria, fungi, animal organs and plant extracts. In this method, important factors such as efficiency, operating conditions such as time, temperature, pH, the ratio of enzyme to substrate and substrate particle size should be considered. The advantages of this method are: low solvent consumption, improving efficiency and quality. The limitations and problems of this method are: The relatively high-cost for large volume of raw materials, enzyme preparation and the problems of industrialization of process (due to the complex and different behavior of enzymes, it is depending on factors such as dissolved oxygen content, temperature and available materials) (81). There are two routes to enzyme-assisted extraction: enzyme-assisted aqueous extraction (EAAE) and enzyme-assisted cold pressing (EACP) (82). *Glycosidics* essential oils (bitter almond and mustard essential oil) were obtained by enzyme-assisted extraction (17).

Pulsed electric field extraction (PEF)

PEF is a new and green technology for extracting valuable compounds from wastes and food-agricultural by-products. The pulsed electric field is applied to the material between two electrodes with a pulsed amplitude. In this system, the pulse amplitude is changed from 100–300 V/cm to 20–80 kV/cm with low energy 10–20 Kj/Kg. The process is performed at ambient temperature or slightly higher than ambient temperature in less than 1 second (microseconds or milliseconds). In this process, by exposing plant cells to pulsed electric field, cell membranes are damaged and temporary or permanent cavities are formed. The process of damaging cells and forming cavities with electricity is called electroporation (82–84). E. Bozinou succeeded in application of the pulsed electric field (PEF) technique to the production of extracts from *Moringa oleifera* plant material (freeze-dried leaves) (85).

Pressurized liquid extraction (PLE)

This green method was proposed by Richter et al. for the first time (1996) (86) as an environment-friendly method. The technology is now known by various names: Pressurized liquid extraction (PLE),

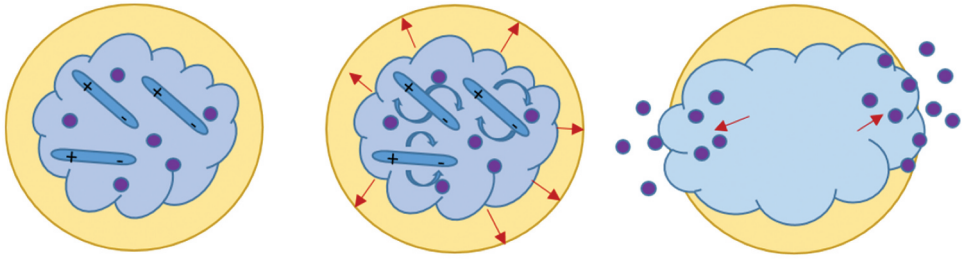

Figure 12. Mechanism of Microwave Extraction of Essential Oils Based on Dielectric Heating (23).

Accelerated solvent extraction (ASE), Enhanced solvent extraction, Subcritical water extraction (SWE) and Solvent extraction at high pressure (87,88). The use of high pressure (500–3000 psi) and temperature (50–200°C) results in a reduction of the extraction time and the solvent consumption, increase of extraction efficiency and process simplicity. This method is not suitable for heat-sensitive compounds to due to high temperature (23,88,89). Water is considered as one of the used solvents in this method that, if maintained in a liquid phase under pressure, could show a variety of behaviors such as methanol or ethanol. In general, this technology due to the technological challenges is not considered as a valuable method on an industrial scale (88,90,91). Safflower oil extraction process using pressurized ethanol was reported successfully (92).

Microwave assisted extraction (MAE)

This green method was first proposed in 1986 (93). Microwaves radiations including, X-ray and infrared rays, are characterized by frequencies between 300 MHz to 300 GHz. In this method, which is also called "dielectric heating" or "high-frequency heating", electromagnetic energy due to ionic conductivity and the molecular dipole rotation is converted to heat under the influence of the electric field (Figure 12). So, the only dielectric materials and solvents with permanent dipoles can be heated under a microwave.

In fact, electromagnetic waves lead to changes in cell structure, which, in turn, distinguishes MAE from other methods (94). In this method, due to the microwave energy, moisture inside the cells heats and evaporates, which, causes rupture of the cell wall. In fact, heat transfer occurs inversely from inside to outside in comparison with normal heating. The quality and efficiency of the final product is affected by parameters such as solvent, temperature and exposure time, pressure, sample viscosity, microwave power output and physicochemical properties of materials (4,95–97). The advantages of this method over other common methods include reduction of the extraction time and solvent consumption, low temperature, energy saving and increasing efficiency (4).

Recent Advances in the microwave extraction method have led to the development of other methods of microwave extraction including microwave assisted solvent extraction (98), vacuum microwave hydrodistillation (99) microwave hydro-distillation (100), solvent-free microwave extraction (101), microwave accelerated steam distillation (102), microwave hydrodiffusion and gravity (MHG) (36) and microwave-assisted simultaneous distillation-solvent extraction (103). Figure 13 gives a schematic description of microwave assisted extraction methods (20). Essential oil extraction by microwave steam diffusion (MSDF) was performed. 125 g raw material (*Lavandula Hybrida*) was soaked in water for 10 min, 500 W, t: 15 min, and the yield was obtained 5.4% (28). Essential oil of citrus *Camellia Sinensis* with yield of 5.43% was obtained by microwave steam distillation (MSD) (104).

High voltage electrical discharge (HVED)

HVED is a method of green extraction based on physical and chemical processes and interjects energy directly in an aqueous solution between immersed electrodes in water (105,106). In the HVED method, cellular tissues are disrupted and the valuable compounds are released. This extraction system can be divided into three different categories: discontinuous, continuous and eddy current systems. The basis of these systems is similar: discharge due to high intensity spatial electric field, cell destruction and increasing mass transfer due to various secondary phenomena. Their differences are related to the structure of the systems, especially the electrodes, and focus modes of the spatial electric field. The process of dielectric decomposition results from liquid ionization and occurs with high voltage (30–40 kV) and short pulse intensity approximately (10 kA) between two electrodes. The process mechanism is summarized by the following steps: electric pulse generation, electrostatic discharge, formation electric arc. Some major advantages of HVED technology over conventional methods are: higher extraction rate, reduction of processing time, higher mass transfer, lower temperature, reducing solvent consumption, reducing degradation of heat-sensitive compounds and environmental impacts, saving energy etc. (107). For example, extraction of bioactive compounds and aromas from Rosemary (*Salvia rosmarinus*) by means of high voltage electrical discharge (108).

The main difference between PEF and HVED is the geometry and composition of their electrodes (83).

Some essential oils with their major constituents were randomly selected and are presented in Table 3 with the different extraction technologies. Table 4 shows a generally comparison between bioactive compounds green extraction technologies, including flavors and fragrances (107,117).

Cohobation system

In the distillation method, distilled water (hydrosol (118)) after separation from the oil can be recycled and reused for another distillation process. This process

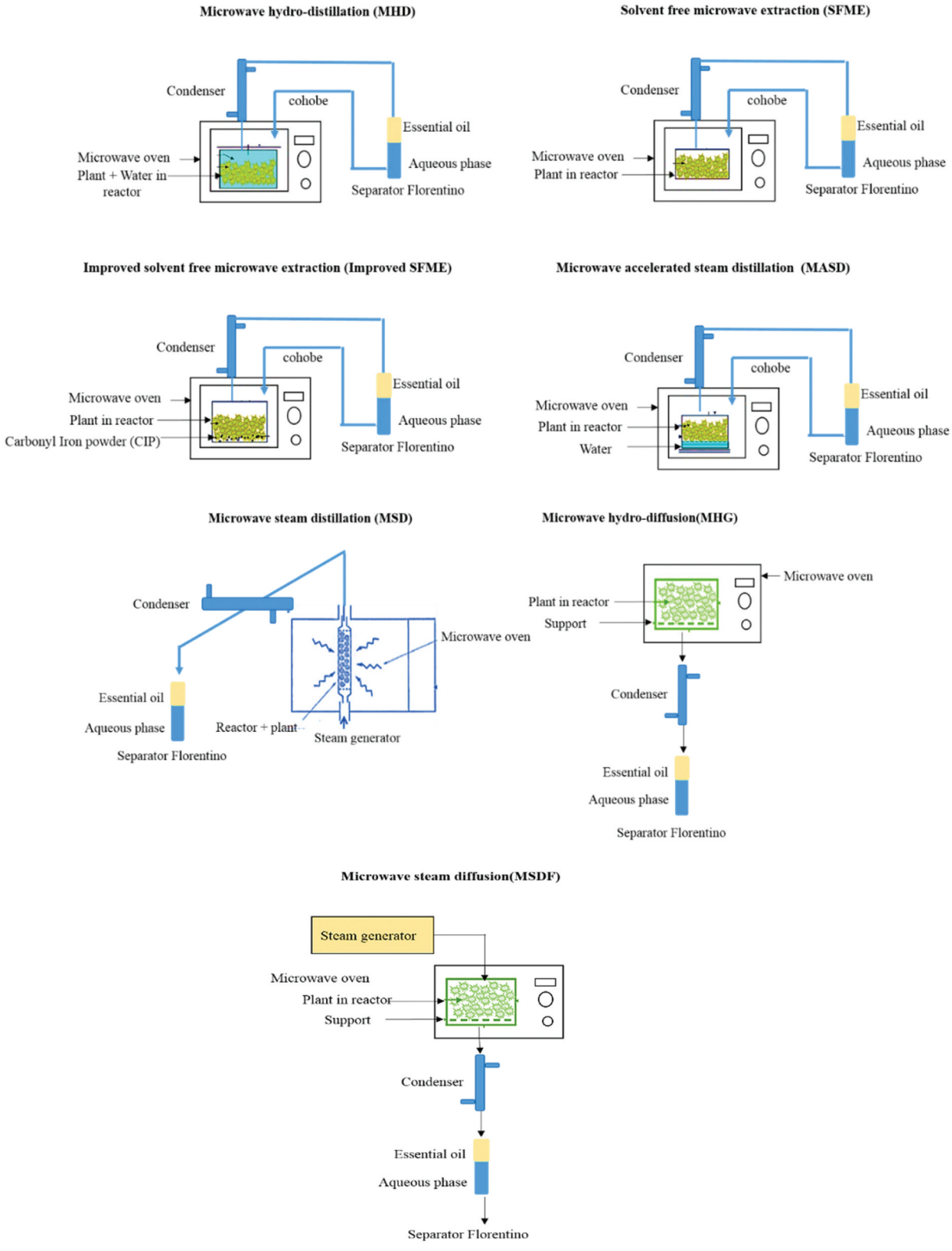

Figure 13. A schematic of microwave assisted extraction methods (20).

Table 3. Different extraction technologies of some essential oils and their major constituents.

Species	plant	Major Components	Technique Extraction	Ref
Boswellia serrata	Indian frankincense	(3E,5E)-2,6-Dimethy l-1,3,5,7-octatetraene	hydro-distillation	(109)
Protium aracouchini	Breu	*p*-Cymene	hydro-distillation	(110)
Satureja hortensis	savory	Carvacrol	microwave-assisted hydro-distillation	(111)
Salvia rosmarinus	Rosemary	1,8-Cineol	steam distillation hydro-distillation	(34)
Ocimum basilicurn	Basil	Linalool	steam distillation hydro-distillation Solvent extraction	(112)
Citrus latifolia	Tahiti lime	Limonene	supercritical fluid hydro-distillation	(113)
Salvia officinalis	sage	Linalyl acetate 1,8-cineol	supercritical fluid hydro-distillan	(114)
Syzygium aromaticum	Clove	Eugenol	supercritical fluid steam distillation hydro-distillation	(115)
Aerva javanica	Kapok bush	Heptacosane	hydro-distillation	(116)
Citrus limon	lemon (lemon peel)	Linalool	ultrasound Assisted Extraction	(80)

is called 'Cohobation' (Figure 14 (119)). It is believed that will be controlled the loss of water-soluble oxygen compounds in hydrosol. This is due to the saturation of water with dissolved components which prevents further extraction. It is worth noting that the cohobation method is not recommended for high temperatures (above 100 °C), because in the case of continuous and direct contact of an oxygenated element with heat, the possibility of degradation and hydrolysis will be promoted (56,57,120). This type of system is a kind of continuous system and reduces extraction time and costs.

There are other types of continuous systems known as continuous systems. In the late twentieth century, essential oil producers had to load and unload still after each process regularly. So they tried to create a process that could produce essential oils continuously. In such a way, plant materials are slowly loaded into the upper still and are removed from the bottom of the still. This method is not suitable for inflorescences, fruits and roots (9).

Biotechnology for the production of essential oil

As mentioned in the previous sections, natural and volatile compounds have become commercially popular due to flavor and aroma properties. The concentration of the most desirable volatiles in essential oils is very low, about less than 10% (sometimes even less than 1%) (121). Essential oils are usually obtained through extraction of intact plants (18) such as distillation, solvents, carbon dioxide, etc. or by the methods of chemical synthesis. Each of them has drawbacks. Chemical synthesis often leads to the production of a mixture of products with approximation quality. Also, this method is not the environmentally friendly method (121). Common extraction methods, in addition to being costly, have problems such as weather conditions including monsoon, drought, or even by volcano, supply shortages, natural disasters, plant diseases, low efficiency, etc (18,19). Therefore, due to the limitations and disadvantages of methods of extraction from intact plants or chemical synthesis, the attention of scientists has been focused on biotechnology methods that a wide variety of plant compounds are produced by microorganisms. In the new biotechnology green method, in addition to being environmentally friendly and no contamination of the process, there are no more problems mentioned, and a high-quality product with good efficiency is obtained. Production of natural and volatile products by biotechnology can be an appropriate response to consumer demand in relation to the consumption of natural products. One of the major applications of biotransformation is the production of biotechnology products that are usually synthesized by chemical methods. Bio-methods include volatile production through tissue and cell cultures, hairy roots cultures, culture of microorganisms, biotransformation, metabolic engineering. Various biotechnological methods for the production of volatiles are discussed below:

De novo production of volatile compounds through tissue and cell cultures

One of the most important techniques in the industrial production of volatile compounds is plant cultivation. The used techniques in this field are mainly: cell cultures, tissue cultures, hairy roots cultures, microorganism cultures.

Table 4. Comparison of green technologies in the extraction of natural compounds.

Disadvantages	Advantages	Technique
It is not suitable for the most medicines and herbal. Polar molecules are not soluble. Expensive	Compared to liquid extraction: Less viscosity, more penetration, better mass transfer, environmentally friendly, saving time, no solvent residue in product, better functional, room temperature, useful for compounds sensitive to heat.	SFE
Ultrasonic frequency, factors, nominal power, input power, system geometry and size of the plant materials are effective in increasing performance.	Reducing energy consumption,more extraction efficiency, saving time Reducing Consumption of chemical materials, useful for compounds sensitive to heat.	UAE
Relatively high cost for large volume. Not suitable for industrial scale due to complex conditions of the enzyme. Particle size, moisture, hydrolysis time, operating conditions should be controlled.	Environmentally friendly, Suitable for extracting bonded compounds, High extraction rate, low solvent consumption, More extraction efficiency and quality.	Enzyme Extraction
Process parameters are input energies, process temperature, field resistance.	Short extraction time and better efficiency. The refining processes are easy. Reducing environmental impacts. Reducing energy consumption. Ambient temperature or slightly higher than ambient temperature.	PEF
High equipment costs and is not suitable for samples weighing more than 100 grams. Not considered as a valuable method on an industrial scale due to the technological challenges	Suitable for solid samples. It is more suitable for polar compounds than SFE, Reducing extraction time and solvent consumption and increases extraction yield. Not suitable for compounds sensitive to heat	PLE
Equipment is expensive. Operation is more difficult than UAE. They are less environmentally friendly due to the use of organic solvents. Less extraction efficiency for non-polar compounds. Not suitable for compounds sensitive to heat. Parameters such as solvent, temperature and exposure time, pressure, viscosity, microwave output power and physicochemical properties of materials are important.	Better quality and higher selectivity, higher extraction efficiency, less extraction time and volume of solvent, energy saving. Compared to SFE, the operation is simpler and more economical.	MAE
Less selectivity than PEF, Their feasibility for industrial scale or pilot has not been studied yet.	Reducing energy consumption than new methods such as MAE and UAE. Saving time. Reducing solvent consumption and less penetration temperature	HVED

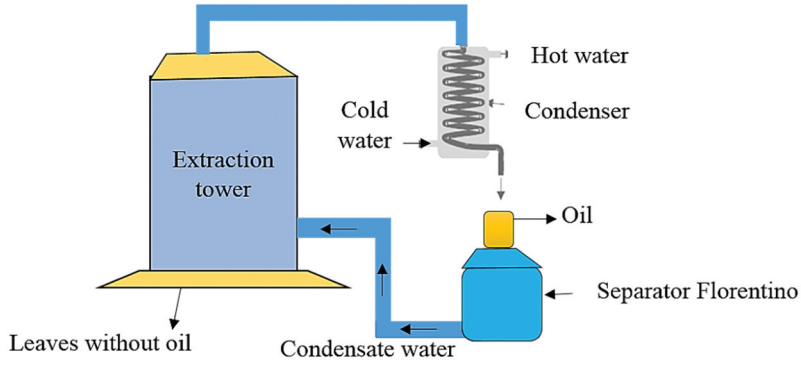

Figure 14. The water-steam distillation method by cohobation for extraction essential oil (119).

Cell cultures

It seems that each cultured cell has all the genetic information of the parent plant and, therefore; it is capable of producing chemicals in the plant (5). Through this culture, the desired volatile compound can be prepared. For reasons such as scarcity, the slow-growth plants, it is expected the vitro under controlled conditions will be accelerated biomass propagation to produce essential oil (122). The yield of this method is affected by the factors of nutrients and growth regulators of the culture medium such as sugar, nitrogen, phosphate, growth regulators, precursors and suitable culture medium (123). But the yield of the obtained compounds is low (0.01–0/1 g/l day) (122), for reasons that are not yet clear (121). So generally, this method does not seem to be a promising method, even with effective agents.

Tissue cultures

Due to the secondary metabolites synthesis in the differentiated tissues, volatile compounds production through cultures and differentiated organs such as root stems, etc. is preferred (124) Production of volatile compounds by hairy roots culture described below.

Hairy roots culture

Hairy root culture is a type of plant tissue culture for the production of volatile compounds (125). The formation of hairy roots in plants or hair-like root structures is

Table 5. A list of produced volatile compounds by the cell, hairy roots, and microorganism.

	Plant	Microorganism	Substrate	Product	Ref
Cell Culture	*Vanilla planifolia*	-	-	Vanillin	(129)
	Smyrnium perfoliatum	-	-	α-Pinene	(130)
	Coleonema album	-	-	Monoterpenes	(131)
	Artemisia dracunculus	-	-	phenylpropenes of the essential oil	(132)
	Mentha piperita	-	-	Mint oil components	(133)
Hairy Root Culture	*Cucumis melo*	-	-	2-Hexenal as main ingredient	(134)
	Pimpinella anisum	-	-	Yield of essential oil was comparable to that of normal plant.	(135)
	Ambrosia trifida	-	-	Essential oil of roots was similar to that of the normal roots.	(136)
	Anethum graveolens	-	-	Essent ial oil yield was only 0.02%, compared to 0.06%, 0.3% and 2% of normal plant root, leaf and fruits, respectively.	(137)
Microorganisms Culture	-	*Aspergillus oryzae*	castor oil	g-Decalactone, 0.86 g/l	(138)
	-	*Aspergillus nige*	Rice bran oil (4 g/l ferulic acid)	2.8 g/l Vanillin	(139)
	-	*Kluyveromyces marxianus*	Grape must + Phe	2 phenylethanol, 0.4 g/l	(127)
	-	*Sporobolomyces odorous*	Hydrolysed castor oil	y-Decalactone, 5.5 g/l	(140)
	-	*Stigmatella aurantiaca*	Agar cultures	C_{10} volatile ketones	(141)

Table 6. Produced volatile compounds by biotransformation of plants or microorganisms.

	Plant/Microorganism	Substrate	Product	Ref
Plants orMicroorganisms	*Capsicum annuum*	Ferulic acid, 2.5 mM	Vanillin, 10 mg/l	(142)
	Rosa (roses)	Geraniol	Nerol, citronellol	(151)
	Lasiodiplodia theobromae	(+)-Valencene (sesquiterpene), 0.4 g/l	Nootkatone	(152)
	Rhodococcus opacus	Limonene	Carveol, carvone	(153)
	Fungi and algae	β-Ionone	Hydroxyl and oxo derivatives	(154)
	Fragaria (strawberry)	α-Ketovalerat	Butanal, butanol	(155)

actually the result of a plant disease caused by a gram-negative bacterium called "*Agrobacterium rhizogenes*". This roots are used as a source for the production of aromatic and volatile substances (126). Basically, the importance of hair roots is due to their rapid growth without the need for an external auxin (5) compared to conventional roots. They are produced volatile compounds at levels and patterns similar to natural roots, but secondary metabolites or volatile compounds are also produced in the aerial parts of plants. The efficiency of this method is higher than cell culture and, by the ingress of abiotic or biotic elicitors in the culture medium, efficiency can be increased (121).

Microorganisms culture

The culture of micrograms is another method of biotechnology. Microorganisms (such as bacteria, fungi, algae . . .) are more potent than plant cells in bioreactor conditions (121). Also, the use of immediate precursor, increases the efficiency. In this case, the method is similar to biotransformation, which will be explained in the next section. For example, 0.4 g/l 2-phenylethanol with rose-like aroma can be produced by *Kluyveromyces marxianus* (127). Also, 2.8 g/l vanillin was achieved by cultured *Aspergillus Niger* (128). Table 5 presents a list of produced volatile compounds by cell, hairy roots, and microorganism cultures.

Biotransformation

Biotransformation is a chemical modification and is performed by an organism on a chemical compound. In other words, microorganisms, through specific chemical reactions, can cause special changes in some compounds. This process is called 'biotransformation'. In this method, either the whole-cell of the microorganism or the isolated enzymes of the microorganism are used. The advantages of biotransformation such as high purity product, minimal side reactions and balanced process, high efficiency, economical, environmentally friendly and production of compounds that cannot be produced by traditional methods have caused this method to be superior to other methods.

The used techniques in this field are mainly: biotransformation by plant cultures and microorganisms, biotransformation by isolated enzymes. Each of which is briefly explained in the next section:

Table 7. Produced volatile compounds by biotransformation of isolated enzymes.

	Isolated Enzyme	Source	Product	Ref
Isolated Enzymes	*Lipoxygenase/hydroperoxide lyase*	Apple pomace, crude mixture	Production of hexanal and 2,4-decadienal from unsaturated fatty acids.	(156)
	100 kDa cut-off extract	Tomato fruits	5 µg/min hexanal from 16 mM linoleic acid	(157)
	Enzyme mix	Citrus poonensis fruit peel	30% of limonene was converted to terpineol, linalool, and linalool oxide	(158)
	Amine oxidase	Aspergillus niger	Production of vanillin from vanillamine	(159)
	Germacrene A hydroxylase	Cichorium intybus	Production of nootkatone from valencene	(160)

Biotransformation by plant cultures and microorganisms

Biotransformation by plant cultures and microorganisms is a good method based on biotechnology for the preparation of volatile compounds. In biotransformation, an intermediate precursor is incorporated into the culture medium, which is bio-transformed or bio-converted to volatile compounds by enzymatic activities. The efficiency of this method is much higher than the methods in which no precursor is used. But it should be noted that cheap precursors should be searched and used to produce valuable products (121). For example, 10 mg/l vanillin was obtained on ferulic acid substrate by cultured *Capsicum annuum* (142). Citronellol can be obtained by biotransformation of citronellal by the *Peganum harmala* (143). Also, the biotransformation of ricinoleic acid by *Candida sorbophila* can be produced up to 40 g/l ɣ-decalactone (144).

This method, in addition to the positive aspects, also has the negative aspects. For example, volatiles are not dissolved easily in an aqueous medium. Dissolution facilitating agents can be used to solve this problem (cell growth is inhibited above a threshold concentration.). Even a high concentrations of the product itself can be toxic and an inhibitor of cell growth. As a result, continuous addition of substrate at non-harmful concentrations and removal of the product was developed. Among these methods, the pervaporation method (145) and inserting a volatile binder compound are most commonly used. The issue of trapping and isolating produced volatile compounds in the culture medium were discussed by Georgiev et al. (146); and Ramachandra and Ravishankar (5). For example, β-cyclodextrins have an amphiphilic structure, which is composed of a hydrophilic exterior and a hydrophobic cavity that, with proper modification, the product can be trapped in the cavities.

Biotransformation by isolated enzymes

Isolated enzymes typically have higher biotransformation rates than cell culture-based methods. But the cost of enzyme separation is played a major role in using that enzyme to produce volatiles (147). Enzymes have a high selectivity and reduce the production of undesirable by-products (148). However, most studies have been done by whole-cells systems rather than isolated enzymes (7%) (139), although this method has been significant (149), but only in cases of biological transmission, volatile compounds are presented. The use of isolated enzymes for biotransformation is depended on the availability of the enzyme, pH, optimum temperature conditions, solvent and substrate. The nature of the enzyme, the type of biotransformation reaction and the need for a cofactor are some influencing factors in the method. In order to facilitate the separation of the product and the recycling catalyst, the use of immobilizing the enzyme is preferred (150).

Table 8. A generally comparison of conventional, novel and biotechnology methods.

Aspect	Conventional	Novel	Biotechnology
Environmentally Friendly	In Some methods such as solvent extraction: No	Yes	Yes
Quality and Yields	Low	More than conventional	In some method: Excellent
Thermal Decomposition	In some methods: Yes	No	No
Processing Time	Long	Short	Short
Energy Consumption	High	Low	Low
Harmful and Expensive Solvents	Some methods such as solvent extraction, Yes	No	No
Need to Raw Material	Yes	Yes	No
Affected by Environmental Conditions	Yes	Yes	No
Cost	Low	High	Low

Table 9. Extraction technologies some material from agricultural products.

Material	Extract	Extraction Techniques	Ref
Rapeseed	Pesticides	Pressurized Liquid Extraction	(169)
Paprika Powder	Pigments	Microwave Assisted Extraction	(169)
Capsicum Fruit	Capsaicinoids	Microwave Assisted Extraction	(169)
Oilseed Such as Almond	Oil	Solvent Extraction	(170)
Palm Fruit	Oil	Enzymatic Extraction Method (Pectinase/Cellulase/Tannase	(170)
Industrial Tobacco Waste	Solanesol	Supercritical Fluid Extraction (CO_2)	(171)
Kalahari Melon and Roselle Seeds	Tocopherol	Supercritical Fluid Extraction (CO_2)	(170)
Potato Peel	Carbohydrates and Phenolic	Subcritical Water	(171)

The Tables 6 and 7 present a list of produced volatile compounds by biotransformation of plant cultures, microorganisms and isolated enzymes.

Metabolic engineering

Metabolic engineering is the most promising and the newest path for volatile production. Metabolic engineering is the use of genetic engineering to modify the metabolism of an organism to increase the cells' production by a certain substance (121,161). Large amounts of the fragrance and flavors can be produced by metabolic engineering without need for the rare plants (18). The use of genetically engineered strains was first reported in 2010 when oil extraction from Pogostemon cablin (*Patchouli*) was severely deficient. Because it has reported that the rainy weather in Indonesia is caused the destruction of medicinal shrubs. Also, other natural problems, such as volcanic eruptions and earthquakes, are exacerbated supply problems. As a result, in order to solve these problems and supply shortages, scientists have been focused on engineering the genetics of the strains to produce the fragrances of the *Patchouli* plant. In addition, fragrances of bitter orange, grapefruit, rose and sandalwood were produced using genetically modified (19).

Genetic engineering of microorganisms

Microorganisms, such as bacteria and yeasts that are not normally unable to synthesize a particular compound, are genetically engineered to improve the synthesis of volatiles or to produce new compounds. The production of volatile substances in commercially valuable quantities by genetically modified microorganisms would be a major success in biotechnology. For example, using metabolic engineering, the scientists succeeded in producing a synthetic banana smell using the bacterium *E. coli* (18). By *Yarrowia Lipolytica* microorganism, Acyl-CoA oxidase genes pox1, pox3 were disrupted, and ɣ-decalactone, 0.35 g/l from methyl ricinoleate was observed (162). Vanillin can be produced at 5 g/l by *E. coli* carrying the 3-deoxyarabino-heptulosonic acid 7-phosphate synthase gene (163).

Genetically engineered plants

In the genetically modified plant, the DNA has been modified using genetic engineering methods. Genetically modified plants have been engineered for scientific research to produce of special compounds, improvement of plant resistance, increase of plant production and advanced products creation (164). For example, Antisense suppression, 10–100-fold more methyl benzoate was observed by Dianthus Caryophyllus (*carnation*) with Flavanone-3-hydroxylase gene (165). *Arabidopsis thaliana* was genetically engineered by β-Farnesene synthase gene for Synthesis of (E)-β-farnesene (166).

Extraction of bioactive compounds in agriculture products

Some scientists have been focused on the transmutation of process conditions and development of capable models to explain observed phenomena during extraction (167), on the other hand, food production and processing in developing countries generate high levels of waste and by-products, causing a negative environmental impact and economics. But at the same time, many of these by-products are a source of valuable compounds such as proteins, starch, lipids, micronutrients, bioactive compounds and dietary fibers. As a result, by extracting bioactive compounds, they can be used in various innovative processes to produce beneficial products (168).

A generally comparison of conventional, novel and biotechnology methods ae mentioned in Table 8. Modern extraction techniques of agriculture products are extraction solvent, supercritical fluid extraction, pressurized liquid extraction, pressurized hot water extraction, microwave assisted extraction, etc (169). Extraction technologies some material from agricultural products are mentioned in Table 9.

Conclusion

Plant essential oils are natural and aromatic compounds that are found in small amounts in plants with many

interesting applications as flavors and fragrances in perfumery, cosmetics, pharmaceutical, food, agriculture, industry, etc. Research on the methods of extracting essential oils has attracted the attention of many scientists. As is evidenced in this review, essential oils can be produced by various techniques, including conventional, novel and biotechnology methods. Novel or green methods can be a good alternative to conventional methods due to their advantages, such as good efficiency and quality, short extraction time, non-decomposition of compounds by heat, no pollution, etc. But due to the problems of the traditional technologies and green methods such as climate conditions, supply shortages, natural disasters, plant diseases, etc., recently scientists have chosen biotechnology methods for the production of natural compounds which, does not have the mentioned problems and a high-quality product is obtained. Production of natural and volatile products by a biotechnology green method can be an appropriate response to consumer demand in relation to the consumption of natural products.

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References

1. L.B. Bullerman, F.Y. Lieu and A.S. Sally, *Inhibition of growth and aflatoxin production by cinnamon and clove oils. Cinnamic aldehyde and eugenol*. Journal of Food Science, **42**(4), 1107–1109 (1977). doi:10.1111/j.1365-2621.1977.tb12677.x.
2. E.R.A. Salim and E.M. Salim-Eisa, *Method for modification of evaporation test (British Pharmacopeia) by Sudanese essential oils*. Journal of Applied Biotechnology & Bioengineering, **3**(2), 315–319 (2017).
3. S. Burt, *Essential oils: their antibacterial properties and potential applications in foods—a review*. International Journal of Food Microbiology, **94**(3), 223–253 (2004). doi:10.1016/j.ijfoodmicro.2004.03.022.
4. F. Reyes-Jurado, A. Franco-Vega, N. Ramírez-Corona, E. Palou and A. López-Malo, *Essential oils: antimicrobial activities, extraction methods, and their modeling*. Food Engineering Reviews, **7**(3), 275–297 (2015). doi:10.1007/s12393-014-9099-2.
5. S. Ramachandra Rao and G.A. Ravishankar, *Plant cell cultures: chemical factories of secondary metabolites*. Biotechnology Advances, **20**(2), 101–153 (2002). doi:10.1016/S0734-9750(02)00007-1.
6. K.H.C. Baser and G. Buchbauer, Handbook of Essential Oils: Science, Technology, and Applications. CRC Press. Boca Raton, Florida (2009).
7. P. Tongnuanchan and S. Benjakul, *Essential oils: extraction,bioactivities, and their uses for food preservation*. Journal of Food Science, **79**(7), R1231–R49 (2014). doi:10.1111/1750-3841.12492.
8. K.P. Svoboda and R.I. Greenaway, *Investigation of volatile oil glands of Satureja hortensis L.(summer savory) and phytochemical comparison of different varieties*. The International Journal of Aromatherapy, **4**(13), 196–202 (2003). doi:10.1016/S0962-4562(03)00038-9.
9. A. El Asbahani, K. Miladi, W. Badri, M. Sala, E.H. Aït Addi, H. Casabianca, A. El Mousadik, D. Hartmann, A. Jilale, F.N.R. Renaud and A. Elaissari, *Essential oils: from extraction to encapsulation*. International Journal of Pharmaceutics, **483**(1–2), 220–243 (2015). doi:10.1016/j.ijpharm.2014.12.069.
10. C.E. Talanda. The Design, Construction and Testing of a Mobile Essential Oil Distillation Unit. Ph.D. Diss(2005).
11. A.C. Figueiredo, J.G. Barroso, L.G. Pedro and J. J. Scheffer, *Factors affecting secondary metabolite production in plants: volatile components and essential oils*. Flavour and Fragrance Journal, **23**(4), 213–226 (2008). doi:10.1002/ffj.1875.
12. D.A. Nagegowda and N. Dudareva, *Plant biochemistry and biotechnology of flavor compounds and essential oils*. Med Plants Biotechnol from Basic Res Ind Applications **2**, 469–492 (2007).
13. R. Teranishi, E.L. Wick and I. Hornstein, Flavor Chemistry: Thirty Years of Progress. Springer Science & Business Media. North America (1999).
14. T. Cserháti, Chromatography of Aroma Compounds and Fragrances. Springer Science & Business Media. London New York (2010).
15. S. Mali, Essential Oil Research: Trends in Biosynthesis, Analytics, Industrial Applications and Biotechnological Production. Springer. New York (2019).
16. M. Hunter, Essential Oils: Art, Agriculture, Science, Industry and Entrepreneurship. Nova Science Publishers, Incorporated. Rawalpindi, Pakistan (2010).
17. K. Jaymand and M. Rezai, *Essential oil and essential oil extractors*. Iranian Journal of Medicinal and Aromatic Plants Research, **1**(9), 1–161 (2001).
18. C. Gupta, D. Prakash and S. Gupta, *A biotechnological approach to microbial based perfumes and flavours*. Journal of Microbiology & Experimentation, **3**(1) (2015).
19. M. Carlquist, B. Gibson, Y. Karagul Yuceer, A. Paraskevopoulou, M. Sandell, A.I. Angelov, V. Gotcheva, A.D. Angelov, M. Etschmann, G.M. de Billerbeck and G. Lidén, *Process engineering for bioflavour production with metabolically active yeasts–a mini-review*. Yeast, **32**(1), 123–143 (2015). doi:10.1002/yea.3058.
20. F. Chemat and C. Boutekedjiret, *Extraction//steam distillation*. In: *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering*, pp. 1–12, Elsevier,

Amsterdam, The Netherlands (2015). doi:10.1016/B978-0-12-409547-2.11557-4.
21. M. Douglas, J. Heyes and B. Smallfield, *Herbs, spices and essential oils: post-harvest operations in developing countries*. UNIDO and FAO, **61** (2005).
22. H. Noori and M. Khajenoori, *Subcritical water extraction of essential oils from Matricaria chamomilla L.* International Journal of Engineering, **26**(5), 489–494 (2013).
23. P. Burger, H. Plainfossé, X. Brochet, F. Chemat and X. Fernandez, *Extraction of natural fragrance ingredients: history overview and future trends*. Chemistry & Biodiversity, **16**(10), e1900424 (2019). doi:10.1002/cbdv.201900424.
24. K.G.D. Babu and V.K. Kaul, *Variation in essential oil composition of rose-scented geranium (Pelargonium sp.) distilled by different distillation techniques*. Flavour and Fragrance Journal, **20**(2), 222–231 (2005). doi:10.1002/ffj.1414.
25. A. Yildirim, A. Cakir, A. Mavi, M. Yalcin, G. Fauler and Y. Taskesenligil, *The variation of antioxidant activities and chemical composition of essential oils of Teucrium orientale L. var. orientale during harvesting stages*. Flavour and Fragrance Journal, **19**(5), 367–372 (2004). doi:10.1002/ffj.1343.
26. M. Gavahian, A. Farahnaky, K. Javidnia and M. Majzoobi, *Comparison of ohmic-assisted hydrodistillation with traditional hydrodistillation for the extraction of essential oils from Thymus vulgaris L*. Innovative Food Science & Emerging Technologies, **14**, 85–91 (2012). doi:10.1016/j.ifset.2012.01.002.
27. L. Cao, L. Yin, S. Chen, F. Yun, L.Q. Guo and J.F. Lin, *Study on techniques of turbo-hydrodistillation extraction of essential oil from Kaempferia galangal with response surface methodology*. China Food Additives, **11**, 9 (2015).
28. S. Périno-Issartier, C. Ginies, G. Cravotto and F. Chemat, *A comparison of essential oils obtained from lavandin via different extraction processes: ultrasound, microwave, turbohydrodistillation, steam and hydrodistillation*. Journal of Chromatography: A, **1305**, 41–47 (2013). doi:10.1016/j.chroma.2013.07.024.
29. K. Jaimand and M.B. Rezaee, *Investigation extraction by two different apparatus and effects of essential oils on content and constituents of Tripleurospermum disciforme (CA Mey) Schultz-Bip*. Natural Sciences, **16**, 2–7 (2003).
30. I. Oktavianawati. Essential oil extraction of cananga odorata flowers using hydrodistillation and steam-water distillation processes. Paper presented at the IOP Conference Series: Materials Science and Engineering, Indonesia (2020).
31. P.N. Alam, H. Husin and T.M. Asnawi. Extraction of citral oil from lemongrass (Cymbopogon citratus) by steam-water distillation technique. Paper presented at the Materials Science and Engineering Conference Series, Indonesia (2018).
32. E. Reverchon and F. Senatore, *Isolation of rosemary oil: comparison between hydrodistillation and supercritical CO_2extraction*. Flavour and Fragrance Journal, **7**(4), 227–230 (1992). doi:10.1002/ffj.2730070411.
33. C.S. Sell and D. Pybus, *Perfumery materials of natural origin*. In: *The Chemistry of Fragrances* (, pp. 24–51). Cambridge 2006).
34. C. Boutekedjiret, F. Bentahar, R. Belabbes and J. M. Bessiere, *Extraction of rosemary essential oil by steam distillation and hydrodistillation*. Flavour and Fragrance Journal, **18**(6), 481–484 (2003). doi:10.1002/ffj.1226.
35. E. Cassel, R.M.F. Vargas, N. Martinez, D. Lorenzo and E. Dellacassa, *Steam distillation modeling for essential oil extraction process*. Industrial Crops and Products, **29** (1), 171–176 (2009). doi:10.1016/j.indcrop.2008.04.017.
36. M.A. Vian, X. Fernandez, F. Visinoni and F. Chemat, *Microwave hydrodiffusion and gravity, a new technique for extraction of essential oils*. Journal of Chromatography: A, **1190**(1–2), 14–17 (2008). doi:10.1016/j.chroma.2008.02.086.
37. C.E. Talanda, The Design, Construction and Testing of a Mobile Essential Oil Distillation Unit.
38. E.A. Weiss, Essential oil crops: cab International (2005) (1997).
39. Z. Wu, L. Xie, Y. Li, Y. Wang, X. Wang, N. Wan, X. Huang, X. Zhang and M. Yang, *A novel application of the vacuum distillation technology in extracting Origanum vulgare L. essential oils*. Industrial Crops and Products, **139**, 111516 (2019). doi:10.1016/j.indcrop.2019.111516.
40. M.A. Ferhat, B.Y. Meklati and F. Chemat, *Comparison of different isolation methods of essential oil from Citrus fruits: cold pressing, hydrodistillation and microwave 'dry'distillation*. Flavour and Fragrance Journal, **22**(6), 494–504 (2007). doi:10.1002/ffj.1829.
41. A. Velluti, *Ecofisiología de Especies de Fusarium Productoras de Fumonisinas, Zearalenona Y Deoxinivalenol En Maíz: Aceites Esenciales Como Inhibidores Fúngicos*. Universitat de Lleida (2002).
42. J.F. Arnodou. The taste of nature; industrial methods of natural products extraction. Paper presented at the a Conference Organized by the Royal Society of Chemistry in Canterbury, Canterbury (1991).
43. C. Soto, R. Chamy and M.E. Zuniga, *Enzymatic hydrolysis and pressing conditions effect on borage oil extraction by cold pressing*. Food Chemistry, **102**(3), 834–840 (2007). doi:10.1016/j.foodchem.2006.06.014.
44. F. Anwar, Z. Zreen, B. Sultana and A. Jamil, *Enzyme-Aided cold pressing of flaxseed (Linum usitatissimum L.): enhancement in yield, quality and phenolics of the oil*. Grasas Y Aceites, **64**(5), 463–471 (2013). doi:10.3989/gya.132212.
45. A.J. Burbott and W.D. Loomis, *Effects of light and temperature on the monoterpenes of peppermint*. Plant Physiology, **42**(1), 20–28 (1967). doi:10.1104/pp.42.1.20.
46. B.M. Lawrence, *The isolation of aromatic materials from natural plant products*. THE THIRD UNIDO WORKSHOP ON ESSENTIAL OIL AND AROMA CHEMICAL INDUSTRIES HELD, ANADOLU UNIVERSITY, TURKEY, 7–154 (1995).
47. X.M. Li, S.L. Tian, Z.C. Pang, J.Y. Shi, Z.S. Feng and Y. M. Zhang, *Extraction of Cuminum cyminum essential oil by combination technology of organic solvent with low boiling point and steam distillation*. Food Chemistry, **115**(3), 1114–1119 (2009). doi:10.1016/j.foodchem.2008.12.091.

48. F. Areias, P. Valentão, P.B. Andrade, F. Ferreres and R. M. Seabra, *Flavonoids and phenolic acids of sage: influence of some agricultural factors*. Journal of Agricultural and Food Chemistry, **48**(12), 6081–6084 (2000).
49. L. Pizzale, R. Bortolomeazzi, S. Vichi, E. Überegger and L.S. Conte, *Antioxidant activity of sage (Salvia officinalis and S fruticosa) and oregano (Origanum onites and O indercedens) extracts related to their phenolic compound content*. Journal of the Science of Food and Agriculture, **82**(14), 1645–1651 (2002). doi:10.1002/jsfa.1240.
50. M. Koşar, H.J.D. Dorman and R. Hiltunen, *Effect of an acid treatment on the phytochemical and antioxidant characteristics of extracts from selected Lamiaceae species*. Food Chemistry, **91**(3), 525–533 (2005). doi:10.1016/j.foodchem.2004.06.029.
51. S. Lago, H. Rodríguez, A. Arce and A. Soto, *Improved concentration of citrus essential oil by solvent extraction with acetate ionic liquids*. Fluid Phase Equilibria, **361**, 37–44 (2014). doi:10.1016/j.fluid.2013.10.036.
52. N.E. Durling, O.J. Catchpole, J.B. Grey, R.F. Webby, K. A. Mitchell, L.Y. Foo and N.B. Perry, *Extraction of phenolics and essential oil from dried sage (Salvia officinalis) using ethanol–water mixtures*. Food Chemistry, **101**(4), 1417–1424 (2007). doi:10.1016/j.foodchem.2006.03.050.
53. L. Manniche, Sacred Luxuries: Fragrance, Aromatherapy, and Cosmetics in Ancient. Cornell University Press, Egypt (1999).
54. N.B. Engineers, The Complete Technology Book on Flavours, Fragrances and Perfumes. Niir Project Consultancy Services, India (2007).
55. P. Rakthaworn, U. Dilokkunanant, U. Sukkatta, S. Vajrodaya, V. Haruethaitanasan, P. Pitpiangchan and P. Punjee, *Extraction methods for tuberose oil and their chemical components*. Agriculture and Natural Resources, **43**(5), 204–211 (2009).
56. S.S. Handa, *An overview of extraction techniques for medicinal and aromatic plants*. Extraction Technologies for Medicinal and Aromatic Plants, **1**, 21–40 (2008).
57. T. De Silva, A manual on the essential oil industry/ editor, K. Tuley De Silva. In: UNIDO Workshop on Essential Oil and Aroma Chemical Industries" (3rd: 1995: Anadolu Universitesi) TBAM-ICS/UNIDO Training Course on Quality Improvement of Essential Oils, Eskis, Ehir, Turkey, United Nations Industrial Development Organization (1999).
58. J.B. Stojanovi, V.B. Veljkovi, S. Ivancheva, J. Stojanovic and V. Veljkovic, *Extraction of flavonoids from garden (Salvia officinalis L.) and glutinous (Salvia glutinosa L.) sage by ultrasonic and classical maceration*. Journal of the Serbian Chemical Society, **72**(1), 73–80 (2007). doi:10.2298/JSC0701073V.
59. F. Chemat, M.A. Vian and G. Cravotto, *Green extraction of natural products: concept and principles*. International Journal of Molecular Sciences, **13**(7), 8615–8627 (2012). doi:10.3390/ijms13078615.
60. M. Herrero, A. Cifuentes and E. Ibañez, *Sub-And supercritical fluid extraction of functional ingredients from different natural sources: plants, food-by-products, algae and microalgae: a review*. Food Chemistry, **98**(1), 136–148 (2006). doi:10.1016/j.foodchem.2005.05.058.
61. S.M. Pourmortazavi and S.M. Hajimirsadeghi, *Supercritical fluid extraction in plant essential and volatile oil analysis*. Journal of Chromatography: A, **1163**(1–2), 2–24 (2007). doi:10.1016/j.chroma.2007.06.021.
62. S.B. Hawthorne, M.L. Rickkola, K. Screnius, Y. Holm, R. Hiltunen and K. Hartonen, *Comparison of hydrodistillation and supercritical fluid extraction for the determination of essential oils in aromatic plants*. Journal of Chromatography: A, **634**(2), 297–308 (1993). doi:10.1016/0021-9673(93)83017-M.
63. A. Capuzzo, M.E. Maffei and A. Occhipinti, *Supercritical fluid extraction of plant flavors and fragrances*. Molecules, **18**(6), 7194–7238 (2013). doi:10.3390/molecules18067194.
64. E. Vági, B. Simándi, A. Suhajda and E. Hethelyi, *Essential oil composition and antimicrobial activity of Origanum majorana L. extracts obtained with ethyl alcohol and supercritical carbon dioxide*. Food Research International, **38**(1), 51–57 (2005). doi:10.1016/j.foodres.2004.07.006.
65. O. Lasekan, S. Azeez, J. Beckstead, R. Titus and R. Ryan, *Effect of amphotericin B nanodisks on Leishmania major infected mice*. Pharmaceutica Analytica Acta, **5**(306), 2 (2014). doi:10.4172/2153-2435.1000311.
66. C.G. Pereira and M.A.A. Meireles, *Economic analysis of rosemary, fennel and anise essential oils obtained by supercritical fluid extraction*. Flavour and Fragrance Journal, **22**(5), 407–413 (2007). doi:10.1002/ffj.1813.
67. E. Reverchon, G.D. Porta and F. Senatore, *Supercritical CO_2 extraction and fractionation of lavender essential oil and waxes*. Journal of Agricultural and Food Chemistry, **43**(6), 1654–1658 (1995). doi:10.1021/jf00054a045.
68. R.S. Ayala and M.D.L. De Castro, *Continuous subcritical water extraction as a useful tool for isolation of edible essential oils*. Food Chemistry, **75**(1), 109–113 (2001). doi:10.1016/S0308-8146(01)00212-6.
69. S. Rovio, K. Hartonen, Y. Holm, R. Hiltunen and M. L. Riekkola, *Extraction of clove using pressurized hot water*. Flavour and Fragrance Journal, **14**(6), 399–404 (1999). doi:10.1002/(SICI)1099-1026(199911/12)14:6<399:AID-FFJ851>3.0.CO;2-A.
70. D.A. Moyler, *Extraction of essential oils with carbon dioxide*. Flavour and Fragrance Ournal, **8**(5), 235–247 (1993). doi:10.1002/ffj.2730080502.
71. K. Taraj, A. Delibashi, A. Andoni, P. Lazo, E. Kokalari, A. Lame, K. Xhaxhiu and A. Çomo, *Extraction of chamomile essential oil by subcritical CO2 and its analysis by UV-VIS spectrophotometer*. Asian Journal of Chemistry, **25**(13), 7361 (2013). doi:10.14233/ajchem.2013.14642.
72. C.C. Chen, M.C. Kuo, C.M. Wu and C.T. Ho, *Pungent compounds of ginger (Zingiber officinale Roscoe) extracted by liquid carbon dioxide*. Journal of Agricultural and Food Chemistry, **34**(3), 477–480 (1986). doi:10.1021/jf00069a027.
73. M.D.L. De Castro, M.M. Jiménez-Carmona and V. Fernandez-Perez, *Towards more rational techniques for the isolation of valuable essential oils from plants*. TrAc Trends in Analytical Chemistry, **18**(11), 708–716 (1999). doi:10.1016/S0165-9936(99)00177-6.
74. M.H. Eikani, F. Golmohammad and S. Rowshanzamir, *Subcritical water extraction of essential oils from*

coriander seeds (Coriandrum sativum L.). Journal of Food Engineering, **80**(2), 735–740 (2007). doi:10.1016/j.jfoodeng.2006.05.015.
75. J. Vladić, T. Janković, J. Živković, M. Tomić, G. Zdunić, K. Šavikin and S. Vidović, *Effects of cocoa-derived polyphenols on cognitive function in humans. systematic review and analysis of methodological aspects*. Plant Foods for Human Nutrition, **75**(1), 1–8 (2020). doi:10.1007/s11130-019-00779-x.
76. M.Z. Ozel, F. Gogus and A.C. Lewis, *Subcritical water extraction of essential oils from Thymbra spicata*. Food Chemistry, **82**(3), 381–386 (2003). doi:10.1016/S0308-8146(02)00558-7.
77. M. Vinatoru, *An overview of the ultrasonically assisted extraction of bioactive principles from herbs*. Ultrasonics Onochemistry, **8**(3), 303–313 (2001). doi:10.1016/S1350-4177(01)00071-2.
78. F. Chemat, N. Rombaut, A.G. Sicaire, A. Meullemiestre, A.S. Fabiano-Tixier and M. Abert-Vian, *Ultrasound assisted extraction of food and natural products. Mechanisms, techniques, combinations, protocols and applications. A review*. Ultrasonics Sonochemistry, **34**, 540–560 (2017). doi:10.1016/j.ultsonch.2016.06.035.
79. G. Romanik, E. Gilgenast, A. Przyjazny and M. Kamiński, *Techniques of preparing plant material for chromatographic separation and analysis*. Journal of Biochemical and Biophysical Methods, **70**(2), 253–261 (2007). doi:10.1016/j.jbbm.2006.09.012.
80. E. Alissandrakis, D. Daferera, P.A. Tarantilis, M. Polissiou and P.C. Harizanis, *Ultrasound-Assisted extraction of volatile compounds from citrus flowers and citrus honey*. Food Chemistry, **82**(4), 575–582 (2003). doi:10.1016/S0308-8146(03)00013-X.
81. M. Selvamuthukumaran and J. Shi, *Recent advances in extraction of antioxidants from plant by-products processing industries*. Food Quality and Safety, **1**(1), 61–81 (2017). doi:10.1093/fqs/fyx004.
82. E. Sarlaki, M. Abu Najmi, E. Marzban and H. R. Bakhshi, *Green technologies: an innovative and sustainable approaches in the extraction of bioactive compounds from agro-food wastes*. Iranian Journal of Green Chemistry and Sustainable Technology, **1**(1), 13–32 (2019).
83. E. Puértolas, M. Koubaa and F.J. Barba, *An overview of the impact of electrotechnologies for the recovery of oil and high-value compounds from vegetable oil industry: energy and economic cost implications*. Food Research International, **80**, 19–26 (2016). doi:10.1016/j.foodres.2015.12.009.
84. F.J. Barba, Z. Zhu, M. Koubaa, A.S. Sant'Ana and V. Orlien, *Green alternative methods for the extraction of antioxidant bioactive compounds from winery wastes and by-products: a review*. Trends in Food Science & Technology, **49**, 96–109 (2016). doi:10.1016/j.tifs.2016.01.006.
85. E. Bozinou, I. Karageorgou, G. Batra, V.G. Dourtoglou and I.S. Lalas, *Pulsed electric field extraction and antioxidant activity determination of Moringa oleifera dry leaves: a comparative study with other extraction techniques*. Beverages, **5**(1), 8 (2019). doi:10.3390/beverages5010008.
86. B.E. Richter, B.A. Jones, J.L. Ezzell, N.L. Porter, N. Avdalovic and C. Pohl, *Accelerated solvent extraction: a technique for sample preparation*. Analytical Chemistry, **68**(6), 1033–1039 (1996). doi:10.1021/ac9508199.
87. F. Barba, S. Brianceau, M. Turk, N. Boussetta and E. Vorobiev, *Effect of alternative physical treatments (ultrasounds, pulsed electric fields, and high-voltage electrical discharges) on selective recovery of bio-compounds from fermented grape pomace*. Food and Bioprocess Technology, **8**(5), 1139–1148 (2015). doi:10.1007/s11947-015-1482-3.
88. C. Pronyk and G. Mazza, *Design and scale-up of pressurized fluid extractors for food and bioproducts*. Journal of Food Engineering, **95**(2), 215–226 (2009). doi:10.1016/j.jfoodeng.2009.06.002.
89. F.J. Barba, V. Orlien, M.J. Mota, R.P. Lopes, S.A. Pereira and J.A. Saraiva, *Implementation of emerging technologies*. In: *Innovation Strategies in the Food Industry*, pp. 117–148, Academic Press. Cambridge, Massachusetts (2016).
90. J.E. Cacace and G. Mazza, *Pressurized low polarity water extraction of lignans from whole flaxseed*. Journal of Food Engineering, **77**(4), 1087–1095 (2006). doi:10.1016/j.jfoodeng.2005.08.039.
91. M. Hayes, Marine Bioactive Compounds: Sources, Characterization and Applications. Springer Science & Business Media. Heidelberg London (2011).
92. R. Conte, L.M. Gullich, D. Bilibio, O. Zanella, J. P. Bender, N. Carniel and W.L. Priamo, *Pressurized liquid extraction and chemical characterization of safflower oil: a comparison between methods*. Food Chemistry, **213**, 425–430 (2016). doi:10.1016/j.foodchem.2016.06.111.
93. K. Ganzler, A. Salgó and K. Valkó, *Microwave extraction: a novel sample preparation method for chromatography*. Journal of Chromatography: A, **371**, 299–306 (1986). doi:10.1016/S0021-9673(01)94714-4.
94. S. Périno-Issartier, F. Abert-Vian, M. Chemat and F. Chemat, *Solvent free microwave-assisted extraction of antioxidants from sea buckthorn (Hippophae rhamnoides) food by-products*. Food and Bioprocess Technology, **4**(6), 1020–1028 (2011). doi:10.1007/s11947-010-0438-x.
95. K. Ameer, H.M. Shahbaz and J.H. Kwon, *Green extraction methods for polyphenols from plant matrices and their byproducts: a review*. Comprehensive Reviews in Food Science and Food Safety, **16**(2), 295–315 (2017). doi:10.1111/1541-4337.12253.
96. F. Chémat and X. Fernandez, *La Chimie des Huiles Essentielles: Tradition Et Innovation*, Vuibert, Paris, France (2012).
97. A.A. Craveiro, F.J.A. Matos, J.W. Alencar and M. M. Plumel, *Microwave oven extraction of an essential oil*. Flavour and Fragrance Journal, **4**(1), 43–44 (1989). doi:10.1002/ffj.2730040110.
98. M. Tomaniova, J. Hajšlová, J. PavelkasJr., V. Kocourek, K. Holadova and I. Klımova, *Microwave-Assisted solvent extraction—a new method for isolation of polynuclear aromatic hydrocarbons from plants*. Journal of Chromatography: A, **827**(1), 21–29 (1998). doi:10.1016/S0021-9673(98)00754-7.

99. F. Elmaataoui, M. Abert-Vian, M. Chemat and F. Chemat, *A novel idea in food extraction field: study of vacuum microwave hydrodiffusion technique for by-products extraction*. Journal of Food Engineering, **105**(2), 351–360 (2011). doi:10.1016/j.jfoodeng.2011.02.045.
100. M.T. Golmakan and K. Rezaei, *Microwave-assisted hydrodistillation of essential oil from Zataria multiflora Boiss*. European Journal of Lipid Science and Technology, **110**(5), 448–454 (2008). doi:10.1002/ejlt.200700239.
101. M.A. Bendahou, A. Muselli, M. Grignon-Dubois, M. Benyoucef, J.M. Desjobert, A.F. Bernardini and J. Costa, *Antimicrobial activity and chemical composition of Origanum glandulosum Desf. essential oil and extract obtained by microwave extraction: comparison with hydrodistillation*. Food Chemistry, **106**(1), 132–139 (2008). doi:10.1016/j.foodchem.2007.05.050.
102. F. Chemat, M.E. Lucchesi, J. Smadja, L. Favretto, G. Colnaghi and F. Visinoni, *Microwave accelerated steam distillation of essential oil from lavender: a rapid, clean and environmentally friendly approach*. Analytica Chimica Acta, **555**(1), 157–160 (2006). doi:10.1016/j.aca.2005.08.071.
103. M.A. Ferhat, N. Tigrine-Kordjani, S. Chemat, B. Y. Meklati and F. Chemat, *Rapid extraction of volatile compounds using a new simultaneous microwave distillation: solvent extraction device*. Chromatographia, **65**(3–4), 217–222 (2007). doi:10.1365/s10337-006-0130-5.
104. N. Sahraoui, M.A. Vian, M. El, C.B. Maataoui and F. Chemat, *Valorization of citrus by-products using microwave steam distillation (MSD)*. Innovative Food Science & Emerging Technologies, **12**(2), 163–170 (2011). doi:10.1016/j.ifset.2011.02.002.
105. V. Barišić, I. Flanjak, M. Kopjar, M. Benšić, A. Jozinović, J. Babić, D. Šubarić, B. Miličević, K. Doko and M. Jašić, *Does high voltage electrical discharge treatment induce changes in tannin and fiber properties of cocoa shell?*. Foods, **9**(6), 810 (2020).
106. E. Roselló-Soto, F.J. Barba, O. Parniakov, M.G. Ch, N. Lebovka, N. Grimi and E. Vorobiev, *High voltage electrical discharges, pulsed electric field, and ultrasound assisted extraction of protein and phenolic compounds from olive kernel*. Food and Bioprocess Technology, **8**(4), 885–894 (2015). doi:10.1007/s11947-014-1456-x.
107. Z. Li, Y. Fa and J. Xi, *Recent advances in high voltage electric discharge extraction of bioactive ingredients from plant materials*. Food Chemistry, **277**, 246–260 (2019). doi:10.1016/j.foodchem.2018.10.119.
108. M. Nutrizio, J. Gajdoš Kljusurić, Z. Marijanović, I. Dubrović, M. Viskić, E. Mikolaj, F. Chemat and A. Režek Jambrak, *The potential of high voltage discharges for green solvent extraction of bioactive compounds and aromas from rosemary (Rosmarinus officinalis L.)—computational simulation and experimental methods*. Molecules, **25**(16), 3711 (2020). doi:10.3390/molecules25163711.
109. N.A.A. Ali, N. Wurster, N. Arnold, A. Teichert, J. Schmidt, U. Lindequist and L. Wessjohann, *Chemical composition and biological activities of essential oils from the oleogum resins of three endemic Soqotraen Boswellia species*. Records of Natural Products, **2**(1), 6 (2008).
110. E.R. da Silva, D.R. Oliveira, S.G. Leitão, I.M. Assis, V. F. Veiga-Junior, M.C. Lourenço, D.S. Alviano, C. S. Alviano and H.R. Bizzo, *Essential oils of Protium spp. samples from Amazonian popular markets: chemical composition, physicochemical parameters and antimicrobial activity*. Journal of Essential Oil Research, **25**(3), 171–178 (2013). doi:10.1080/10412905.2012.751055.
111. G. Figueredo, A. Ünver, J.C. Chalchat, D. Arslan and M. M. Özcan, *A research on the composition of essential oil isolated from some aromatic plants by microwave and hydrodistillation*. Journal of Food Biochemistry, **36**(3), 334–343 (2012). doi:10.1111/j.1745-4514.2011.00542.x.
112. D.J. Charles and J.E. Simon, *Comparison of extraction methods for the rapid determination of essential oil content and composition of basil*. Journal of the American Society for Horticultural Science, **115**(3), 458–462 (1990). doi:10.21273/JASHS.115.3.458.
113. A.C. Atti-Santos, M. Rossato, L.A. Serafini, E. Cassel and P. Moyna, *Extraction of essential oils from lime (Citrus latifolia Tanaka) by hydrodistillation and supercritical carbon dioxide*. Brazilian Archives of Biology and Technology, **48**(1), 155–160 (2005). doi:10.1590/S1516-89132005000100020.
114. Y. Yamini, M. Khajeh, E. Ghasemi, M. Mirza and K. Javidnia, *Comparison of essential oil compositions of Salvia mirzayanii obtained by supercritical carbon dioxide extraction and hydrodistillation methods*. Food Chemistry, **108**(1), 341–346 (2008). doi:10.1016/j.foodchem.2007.10.036.
115. W. Guan, S. Li, R. Yan, S. Tang and C. Quan, *Comparison of essential oils of clove buds extracted with supercritical carbon dioxide and other three traditional extraction methods*. Food Chemistry, **101**(4), 1558–1564 (2007). doi:10.1016/j.foodchem.2006.04.009.
116. M.Q. Samejo, S. Memon, M.I. Bhanger and K.M. Khan, *Comparison of chemical composition of Aerva javanica seed essential oils obtained by different extraction methods*. Pakistan Journal of Pharmaceutical Sciences, **26**(4), 757–760 (2013).
117. S.A. Moreira, E.M. Alexandre, M. Pintado and J. A. Saraiva, *Effect of emergent non-thermal extraction technologies on bioactive individual compounds profile from different plant materials*. Food Research International, **115**, 177–190 (2019). doi:10.1016/j.foodres.2018.08.046.
118. A. Wollinger, E. Perrin, J. Chahboun, V. Jeannot, D. Touraud and W. Kunz, *Antioxidant activity of hydro distillation water residues from Rosmarinus officinalis L. leaves determined by DPPH assays*. Comptes Rendus Chimie, **19**(6), 754–756 (2016). doi:10.1016/j.crci.2015.12.014.
119. W.F. Quezada-Moreno, W.D. Quezada-Torres, I. Gallardo-Aguilar, E. Cevallos-Carvajal, G. Arias-Palma, A. Trávez-Castellano, Z. Zambrano-Ochoa and O. Rojas-Molina, *Extraction and chemical characterization of the essential oil of Tagetes pusilla, in fresh and stored samples*. Afinidad, **76**(588), 307–313 (2019).
120. F. Perineau, L. Ganou and G. Vilarem, *Studying production of lovage essential oils in a hydrodistillation pilot unit equipped with a cohobation system*. Journal of

Chemical Technology & Biotechnology, **53**(2), 165–171 (1992). doi:10.1002/jctb.280530210.
121. Y. Gounaris, *Biotechnology for the production of essential oils, flavours and volatile isolates. A review*. Flavour and Fragrance Journal, **25**(5), 367–386 (2010). doi:10.1002/ffj.1996.
122. P.R.H. Moreno, R. van der Heijden and R. Verpoorte, *Cell and tissue cultures of Catharanthus roseus: a literature survey*. Plant Cell, Tissue and Organ Culture, **42**(1), 1–25 (1995). doi:10.1007/BF00037677.
123. B. Habibi Khaniani, A. Moeini and M.R. Abdollahi, Production of Secondary Metabolites and drugs through Tissue and Plant Cells Culture. PhD diss., (in Persian) (2005).
124. G. Roja, Biotechnology of Indigenous Medicinal Plants. PhD diss., Ph. D Thesis, Bombay University. Bombay (1994).
125. N. Sevón and K. M, *Oksman-Caldentey."agrobacterium rhizogenes-mediated transformation: root cultures as a source of alkaloids*. Planta Medica, **68**(10), 859–868 (2002). doi:10.1055/s-2002-34924.
126. H.E. Flores, J.M. Vivanco and V.M. Loyola-Vargas, *Radicle'biochemistry: the biology of root-specific metabolism*. Trends in Plant Science, **4**(6), 220–226 (1999). doi:10.1016/S1360-1385(99)01411-9.
127. J. Garavaglia, S.H. Flôres, T.M. Pizzolato, M. Do Carmo Peralba and M.A.Z. Ayub, *Bioconversion of L-phenylalanine into 2-phenylethanol by Kluyveromyces marxianus in grape must cultures*. World Journal of Microbiology & Biotechnology, **23**(9), 1273–1279 (2007). doi:10.1007/s11274-007-9361-3.
128. L. Zheng, P. Zheng, Z. Sun, Y. Bai, J. Wang and X. Guo, *Production of vanillin from waste residue of rice bran oil by Aspergillus niger and Pycnoporus cinnabarinus*. Bioresource Technology, **98**(5), 1115–1119 (2007). doi:10.1016/j.biortech.2006.03.028.
129. H. Dornenburg and D. Knorr, *Production of phenolic flavor compounds with cultured cells and tissues of vanilla species*. Food Biotechnology, **10**(1), 75–92 (1996). doi:10.1080/08905439609549902.
130. B. Tirillini and B. Tosi, *Presence of α-pinene in plant callus cultures of Smyrnium perfoliatum L*. Journal of Essential Oil Research, **4**(4), 431–432 (1992). doi:10.1080/10412905.1992.9698100.
131. G. Reil and R.G. Berge, *Variation of chlorophyll and essential oils in photomixotrophic cell cultures of Coleonema album (Thunb.)*. Journal of Plant Physiology, **150**(1–2), 160–166 (1997). doi:10.1016/S0176-1617(97)80196-4.
132. C.M. Cotton, J.W. Gramshaw and L.V. Evans, *The effect of α-naphthalene acetic acid (NAA) and benzylaminopurine (BAP) on the accumulation of volatile oil components in cell cultures of tarragon (Artemisia dracunculus)*. Journal of Experimental Botany, **42**(3), 377–386 (1991). doi:10.1093/jxb/42.3.377.
133. I.S. Chung, Y.M. Kang, J.H. Oh, T. Kim, H.J. Lee and Y. A. Chae, *Continuous suspended cell culture of Mentha piperita in cell-recycled air-lift bioreactor*. Biotechnology Techniques, **8**(11), 789–792 (1994). doi:10.1007/BF00152885.
134. Y. Matsuda, H. Toyoda, A. Sawabe, K. Maeda, N. Shimizu, N. Fujita, T. Fujita, T. Nonomura and S. Ouchi, *A hairy root culture of melon produces aroma compounds*. Journal of Agricultural and Food Chemistry, **48**(4), 1417–1420 (2000). doi:10.1021/jf9906580.
135. P.M. Santos, A.C. Figueiredo, M.M. Oliveira, J. Barroso, L.G. Pedro, S.G. Deans, A.K.M. Younus and J. J. Scheffer, *Essential oils from hairy root cultures and from fruits and roots of Pimpinella anisum*. Phytochemistry, **48**(3), 455–460 (1998). doi:10.1016/S0031-9422(98)00022-3.
136. L. Tiansheng, F.J. Parodi, D. Vargas, L. Quijano, E. R. Mertooetomo, M.A. Hjortso and N.H. Fischer, *Sesquiterpenes and thiarubrines from Ambrosia trifida and its transformed roots*. Phytochemistry, **33**(1), 113–116 (1993). doi:10.1016/0031-9422(93)85405-G.
137. P.A. Santos, A.C. Figueiredo, P.M. Lourenço, J. G. Barroso, L.G. Pedro, M.M. Oliveira, J. Schripsema, S.G. Deans and J.J. Scheffer, *Hairy root cultures of Anethum graveolens (dill): establishment, growth, time-course study of their essential oil and its comparison with parent plant oils*. Biotechnology Letters, **24**(12), 1031–1036 (2002). doi:10.1023/A:1015653701265.
138. M.I. Farbood and B.J. Willis, *Production of γ-decalactone*. Google Patents, US4560656A (1985).
139. C.C.C.R. De Carvalho and M.M.R. Da Fonseca, *Biotransformation of terpenes*. Biotechnology Advances, **24**(2), 134–142 (2006). doi:10.1016/j.biotechadv.2005.08.004.
140. S.J. Lin, S.L. Lee and C.C. Chou, *Effects of various fatty acid components of castor oil on the growth and production of γ-decalactone by Sporobolomyces odorus*. Journal of Fermentation and Bioengineering, **82**(1), 42–45 (1996). doi:10.1016/0922-338X(96)89452-9.
141. J.S. Dickschat, H.B. Bode, S.C. Wenzel, R. Müller and S. Schulz, *Biosynthesis and identification of volatiles released by the myxobacterium Stigmatella aurantiaca*. Chem Biochem, **6**(11), 2023–2033 (2005). doi:10.1002/cbic.200500174.
142. S.M. Kang, H.Y. Jung, Y.M. Kang, J.Y. Min, C. S. Karigar, J.K. Yang, S.W. Kim, Y.R. Ha, S.-H. Lee and M.S. Choi, *Biotransformation and impact of ferulic acid on phenylpropanoid and capsaicin levels in Capsicum annuum L. cv. P1482 cell suspension cultures*. Journal of Agricultural and Food Chemistry, **53**(9), 3449–3453 (2005). doi:10.1021/jf048675z.
143. W. Zhu, G. Asghari and G.B. Lockwood, *Factors affecting volatile terpene and non-terpene biotransformation products in plant cell cultures*. Fitoterapia, **71**(5), 501–506 (2000). doi:10.1016/S0367-326X(00)00160-X.
144. K. Mitsuhashi and M. Iimori, *Method for producing lactone*. U.S. Patent 7,129,067 (2006).
145. L.M. Vane, *A review of pervaporation for product recovery from biomass fermentation processes*. Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology, **80**(6), 603–629 (2005). doi:10.1002/jctb.1265.
146. M.I. Georgiev, A.I. Pavlov and T. Bley, *Hairy root type plant in vitro systems as sources of bioactive substances*. Applied Microbiology and Biotechnology, **74**(6), 1175 (2007). doi:10.1007/s00253-007-0856-5.

147. Z. Liu, R. Weis and A. Glieder, *Enzymes from higher eukaryotes for industrial biocatalysis*. Food Technology and Biotechnology, **42**(4), 237–249 (2004).
148. M. Menzel and P. Schreier (editor), *Enzymes and flavour biotechnology*. In: *Flavours and Fragrances*, pp. 489–505, Springer. Berlin, Heidelberg (2007).
149. A. Giri, V. Dhingra, C.C. Giri, A. Singh, O.P. Ward and M.L. Narasu, *Biotransformations using plant cells, organ cultures and enzyme systems: current trends and future prospects*. Biotechnology Advances, **19**(3), 175–199 (2001). doi:10.1016/S0734-9750(01)00054-4.
150. K.T. Elvers and H.M. Lappin-Scott, Encyclopedia of Microbiology. Academic Press, San Diego, CA (2000).
151. T.H. Mulder-Krieger, R. Verpoorte, A.B. Svendsen and J.J.C. Scheffer, *Production of essential oils and flavours in plant cell and tissue cultures. A review*. Plant Cell, Tissue and Organ Culture, **13**(2), 85–154 (1988). doi:10.1007/BF00034451.
152. A. Hausler, *Microbial production of natural flavors*. ASM News, 551–559 (1977).
153. C.C.C.R. de Carvalho and M.M.R. da Fonseca, *Towards the bio-production of trans-carveol and carvone from limonene: induction after cell growth on limonene and toluene*. Tetrahedron, Asymmetry, **14**(24), 3925–3931 (2003). doi:10.1016/j.tetasy.2003.09.039.
154. C. Larroche, C. Cruely and J.B. Gros, *Fed-batch biotransformation of β-ionone by Aspergillus niger*. Applied Microbiology and Biotechnology, **43**(2), 222–227 (1995). doi:10.1007/BF00172816.
155. Y.C.A. Hong, C.H. Li, G.A. Reineccius, S.K. Harlander and T.P. Labuza, *Production of aroma compounds from strawberry cell suspension cultures by addition of precursors*. Plant Cell, Tissue and Organ Culture, **21**(3), 245–251 (1990). doi:10.1007/BF00047617.
156. A.M. Almosnino, M. Bensoussan and J.M. Belin, *Unsaturated fatty acid bioconversion by apple pomace enzyme system. Factors influencing the production of aroma compounds*. Food Chemistry, **55**(4), 327–332 (1996). doi:10.1016/0308-8146(95)00100-X.
157. B.J. Cass, F. Schade, C.W. Robinson, J.E. Thompson and R.L. Legge, *Production of tomato flavor volatiles from a crude enzyme preparation using a hollow-fiber reactor*. Biotechnology and Bioengineering, **67**(3), 372–377 (2000). doi:10.1002/(SICI)1097-0290(20000205)67:3<372:AID-BIT14>3.0.CO;2-N.
158. M.H. Lee, H. Liu, N.W. Su, K.L. Ku and Y.M. Choong, *Bioconversion of d-Limonene to oxygenated compounds by endogenous enzymes of the citrus peel*. Journal-Chinese Agricultural Chemical Society, **37**, 1–19 (1999).
159. A. Yoshida, Y. Takenaka, H. Tamaki, I. Frébort, O. Adachi and H. Kumagai, *Vanillin formation by microbial amine oxidases from vanillylamine*. Journal of Fermentation and Bioengineering, **84**(6), 603–605 (1997). doi:10.1016/S0922-338X(97)81920-4.
160. J.W. de Kraker, M. Schurink, M.C.R. Franssen, W. A. König, A. de Groot and H.J. Bouwmeester, *Hydroxylation of sesquiterpenes by enzymes from chicory (Cichorium intybus L.) roots*. Tetrahedron, **59**(3), 409–418 (2003). doi:10.1016/S0040-4020(02)01479-5.
161. Y.T. Yang, G.N. Bennett and K.Y. San, *Genetic and metabolic engineering*. Electronic Journal of Biotechnology, **1**(3), 20–21 (1998). doi:10.2225/vol1-issue3-fulltext-3.
162. Y. Waché, M. Aguedo, A. Choquet, I.L. Gatfield, J. M. Nicaud and J.M. Belin, *Role of β-oxidation enzymes in γ-decalactone production by the yeast Yarrowia lipolytica*. Applied and Environmental Microbiology, **67**(12), 5700–5704 (2001). doi:10.1128/AEM.67.12.5700-5704.2001.
163. C.C. de Guzmán and R.R. Zara Vanilla, Handbook of Herbs and Spices. Woodhead Publishing Limited. Boca Raton, Florida (2012).
164. B. Alberts, A. Johnson, J. Lewis, M. Raff, K. Roberts and P. Walter (editors), *Studying gene expression and function*. In: *Molecular Biology of the Cell*, 4th, Garland Science. New York (2002).
165. A. Zuker, T. Tzfira, H. Ben-Meir, M. Ovadis, E. Shklarman, H. Itzhaki, G. Forkmann, S. Martens, I. Neta-Sharir, D. Weiss and A. Vainstein, *Modification of flower color and fragrance by antisense suppression of the flavanone 3-hydroxylase gene*. Molecular Breeding, **9**(1), 33–41 (2002). doi:10.1023/A:1019204531262.
166. M.H. Beale, M.A. Birkett, T.J. Bruce, K. Chamberlain, L. M. Field, A.K. Huttly, J.L. Martin, R. Parker, A. L. Phillips, J.A. Pickett, I.M. Prosser, P.R. Shewry, L. E. Smart, L.J. Wadhams, C.M. Woodcock and Y. Zhang, *Aphid alarm pheromone produced by transgenic plants affects aphid and parasitoid behavior*. Proceedings of the National Academy of Sciences, **103**(27), 10509–10513 (2006). doi:10.1073/pnas.0603998103.
167. A.F. Alonge and N.I. Jackson. Extraction of vegetable oils from agricultural materials: a review. In Nigeria: Proceedings of the 12th CIGR Section VI International Symposium, held at the International Institute of Tropical Agriculture, Ibadan, Oyo State, Nigeria (2018).
168. S. Rawdkuen and S. Ketnawa, *Extraction, characterization, and application of agricultural and food processing by-products. Food preservation and waste exploitation*. IntechOpen, 1–32 (2019).
169. C. Turner, *Overview of modern extraction techniques for food and agricultural samples*, 3–19 (2006).
170. S.J. Kumar, S.R. Prasad, R. Banerjee, D.K. Agarwal, K. S. Kulkarni and V.K. Ramesh, *Green solvents and technologies for oil extraction from oilseeds*. Chemistry Central Journal, **11**(1), 1–7 (2017). doi:10.1186/s13065-017-0238-8.
171. L.S. Torres-Valenzuela, A. Ballesteros-Gómez and S. Rubio, *Green solvents for the extraction of high added-value compounds from agri-food waste*. Food Engineering Reviews, **12**(1), 83–100 (2020). doi:10.1007/s12393-019-09206-y.