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Review

Progressive innovations in essential oils extraction technologies and investigation of their phytochemical evidences

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Abstract

Ongoing advancements in essential oil extraction technologies have greatly improved the efficiency, environmental sustainability, and quality of phytochemical recovery from aromatic plants. Conventional extraction techniques, such as steam distillation and hydrodistillation, remain widely used but they often lead to the degradation of heat-sensitive compounds and produce relatively low yields. In contrast, modern approaches, including supercritical fluid extraction (SFE), microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), and subcritical water extraction (SWE), offer more efficient, selective, and environmentally friendly alternatives. These innovative methods improve extraction performance by preserving the structural integrity of bioactive compounds and improving the accuracy of phytochemical profiling. Detailed analyses of essential oils obtained using these advanced techniques have identified a broad spectrum of biologically active constituents, including monoterpenes, sesquiterpenes, and phenolics, essential for their therapeutic and industrial value. This review explores the evolution of essential oil extraction technologies, highlighting the link between extraction method and phytochemical yield, and emphasizing the crucial role of technological innovation in optimizing the potential of volatile plant compounds.

Keywords
Essential oil, extraction technologies, phytochemical recovery, biologically active constituents, therapeutic.

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1. Introduction

Essential oils are well known for their diverse therapeutic benefits, which make them highly valuable in medicine, cosmetics, and the food industry. They are concentrated plant extracts obtained from parts such as leaves, flowers, and roots, containing natural aromatic compounds that give each plant its distinctive fragrance [1].

Oily plant extracts, whether by direct or indirect steam distillation, dry distillation, or mechanical methods without heat, contain volatile aromatic compounds produced as secondary metabolites. Although most plants produce only small amounts of essential oils, clove, myrrh, nutmeg, and cardamom are notable exceptions. These oils are complex liquid mixtures that may undergo slight changes during extraction. They are separated from the aqueous phase by a physical process designed to preserve their chemical integrity, after which appropriate additional treatments may be applied [2].

Fresh essential oils are typically colorless and consist of hydrophobic molecules, yet they dissolve readily in alcohol, ether, and pentane. Over time, oxidation can cause them to darken, and they are highly sensitive to high temperatures, which accelerate their degradation. For this reason, they should be stored in a cool, dry environment, in tightly sealed amber glass containers to preserve their quality.

These compounds possess specific properties and applications, playing a key role in phytotherapy [3]. Their effectiveness is closely related to their aromatic concentration, most of which remain relatively stable and contain natural antioxidants and antimicrobial agents, particularly in citrus fruits [73].

Alongside many aromatic plants, the chemistry of perfume plants has gained increasing recognition, driven by growing consumer preference for natural herbal preparations. This is particularly true when the extraction of essential oils or oleoresins supports a thriving industry that requires consistent product quality, reliable year-round supply, and stable prices. It should be noted that the development of distillation equipment, from simple stills without cooling coils to those with long copper coils, was a gradual process, requiring large pipes to supply large quantities of cooling water. This advancement only became widespread when the industry began to provide the necessary pipes free of charge.

In these aromatic plants, essential oils contain volatile molecules that can be released at 100 °C. Some other molecules, though not volatile at either 40 °C or 100 °C, still possess aromatic, flavorful, or even medicinal properties. When discussing percolation, infusion, or decoction, we differentiate between consumption in fresh or raw form, such as parsley, or cooked form, like coriander leaves; and in dried form, such as bay leaf or thyme. All these molecules are extracted according to the method chosen by the pharmacist for later use.

It is important to note that some molecules transferred into the boiling liquid may deteriorate and be discarded, while others can undergo significant changes when exposed to heat. These molecules are valued not only for their pleasant aroma and flavor but also for their health benefits and therapeutic significance [4]. However, excessive purification may result in the loss of valuable compounds and essential nutrients.

When the herb is used fresh or dried, extraction occurs either in the mouth—through chewing, body temperature, and saliva, or during preparation, such as in culinary sauces or homemade liqueurs, following a meticulously observed protocol with precise ingredients. To ensure accuracy and control, the chemist carefully monitors each step and analyzes the various extracts. Rouzet (1993) identifies four standard procedures aiming to determine the non-volatile ethereal extract, the extract soluble in cold alcohol, the extract soluble in cold water and the essential oil content extractable by steam distillation. Richard and colleagues (1990) reported that essential oils contain various volatile compounds, ranging from α- and β-pinene to myristicin, while the spice itself includes flavorful components such as cinalpine and capsaicin [5].

It is hardly surprising that humans have long practiced heating and condensing vapors to obtain valuable substances. As Faure (1993) noted, this technique dates back to ancient times, long before the advent of the sophisticated distillation equipment found in modern laboratories [6]. The products of this process, known as aromatics, may be naturally secreted by plants or produced through various methods. Among them are oleoresins, natural mixtures of essential oils and resins, formed through the oxidation of these oils.

As an aromatic product, an oleoresin is obtained by macerating fresh or dried plant material, infused or not, in a pure volatile solvent such as acetone, dichloromethane, hexane, or methanol. The extract is then recovered through vacuum distillation at 40 °C. To isolate essential oils and other volatile compounds, steam distillation is employed, with the aromatic fraction collected alongside the essential oil, which separates mechanically by floating.

Distillation can also be carried out on an aqueous-alcoholic mixture. In this method, the aromatic substance is first macerated in alcohol at a temperature of 80 °C or macerated after cold maceration in pure alcohol. This process produces a mixture of water, alcohol and volatile compounds, which cannot be separated mechanically.

2. Occurrence and distribution of essential oils in aromatic plants

Essential oils from aromatic plants are found in numerous genera spread across roughly 60 families. Several plant families are particularly renowned for producing essential oils of medicinal and industrial importance, including alliaceae, apiaceae, asteraceae (compositae), lamiaceae (labiatae), myrtaceae, poaceae, cupressaceae, lauraceae, pinaceae, zingiberaceae, and rutaceae. Terpenoids are abundantly present in all these essential oil producing families. Moreover, certain families, such as apiaceae (umbelliferae), lamiaceae, myrtaceae, piperaceae, and rutaceae, tend to contain a higher proportion of phenylpropanoids [7] [8] [9]**.**

Superior aromatic plants possess abundant reserves of essential oils and aroma-bearing compounds, which they store in various anatomical parts: flowers (chamomile, ulmar, St. John's wort), leaves (mugwort, sage, melaleuca, lemongrass, eucalyptus), fruits (spices, star anise), seeds (khella, cardamom, flax, nutmeg), bark (cinnamon), wood (balsam, rosewood, sandalwood), roots (coleus, vetiver), and rhizomes (turmeric, ginger). These molecules are generally synthesized in the cytoplasm of secretory cells and accumulate in specialized glandular cells, often situated on or near the cell surface and covered by a cuticle [10].

3. Physicochemical properties of essential oils

With the exception of blue chamomile and green European valerian, essential oils are generally clear, mobile liquids at room temperature, though some, like orris, are solid, and others, such as guaiac wood, are semi-solid. Most essential oils are colorless or pale yellow, apart from the distinctive hues of blue chamomile and green European valerian.

The characteristic aroma of essential oils (EOs) depends on the plant organs, species, and sources from which they are derived. These volatile oils typically exhibit a high refractive index and optimal optical rotation due to the presence of numerous asymmetrical components. Their density is generally lower than that of water, though some exceptions exist. While essential oils are largely hydrophobic, they dissolve readily in fats, alcohols, and most organic solvents. They are also prone to oxidation and polymerization, which can lead to the formation of resinous compounds [11].

At high temperatures, essential oils vaporize, but at room temperature they condense into liquids, distinguishing them from fixed oils. They are soluble in certain organic and alcoholic solvents, as well as in fats, but have very limited solubility in water. To disperse them in water, a surfactant is required, as their density is lower than that of water and they possess a high refractive index [12].

4. Methods of extracting essential oils

Essential oils are complex mixes of low molecular weight, molecules that typically weighing less than 500 Daltons, the analytical processes used to extract essential oil from medicinal plants involve two independent steps : distillation or extraction, which normally takes several hours, and subsequent analysis which can be achieved after 15 minutes [13].

Different parts of aromatic plants can be used to obtain essential oils, which have wide-ranging applications in cosmetics, pharmaceuticals, and food safety. The choice of extraction method and technique depends on the specific properties and components sought in the botanical extract. The extraction process is crucial to maintaining essential oil quality, as unsuitable methods can cause degradation or alteration of the phytochemicals they contain. Such damage may lead to the loss of pharmacologically active compounds, unwanted discoloration, unpleasant flavors or odors, and other physical changes in the oils [14]. Selecting the appropriate production techniques is key to enhancing both the yield and quality of essential oils. These oils are extracted from plant raw materials using various methods [15] [16].

Essential oils can be extracted using a variety of methods, including steam distillation, hydrodistillation, organic solvent extraction, expression, enfleurage, microwave-assisted distillation, microwave hydrodiffusion and gravity, high-pressure solvent extraction, supercritical carbon dioxide extraction, ultrasonic extraction, solvent-free microwave extraction, and the phytonic process [17]. These extraction methods can be classified into two main groups: conventional techniques and innovative approaches. The adoption of innovative methods has enhanced extraction efficiency by reducing isolation time and energy consumption, while also increasing production yield and improving the quality of the essential oils [18].

4.1. Classical methods (conventional methods)

Conventional techniques for extracting essential plant oils rely on water distillation through heating. Numerous extraction methods are employed, and they hold significant importance given their widespread and intensive use around the world.

4.1.1. Hydrodistillation (HD)

Hydrodistillation is the oldest and simplest method of oil extraction, first developed by Avicenna, who pioneered the use of the alembic [19]**.** In this process, plant materials are immersed directly in the alembic (vessel) filled with water, which is then brought to a boil. The apparatus includes a heat source, an alembic vessel, a condenser to transform the vapor into liquid, and a decanter to collect the condensate and separate the valuable oils from the water.

The extraction principle relies on azeotropic distillation. Under atmospheric pressure, and during the heating of oil-containing plant material in water or other solvents, hydrodistillation (HD) functions as a variant of steam distillation. It was established by the French Pharmacopoeia for extracting essential oils from dried plants and for laboratory quality control. There are three main types of hydrodistillation: water immersion, direct steam injection, and a combination of water immersion with steam injection. This versatile method can be applied in both large-scale and small-scale industries. The distillation time varies depending on the plant material, and prolonged processing yields only minimal additional essential oil while also producing undesirable compounds and high-boiling oxidation products. This method is widely used for extracting hydrophobic natural plant materials, particularly suited for components such as wood or flowers. By keeping the oils submerged in water during boiling, it enables extraction without excessive heating, thus preserving their quality. Its main advantage lies in the ability to separate plant constituents at temperatures below 100 °C [18]**.** Some researchers have introduced new technologies to enhance the conventional hydrodistillation process. Microwave-Assisted Hydrodistillation (MAHD), developed by Golmakani and Rezaei, has demonstrated clear advantages, reducing isolation time to 75 minutes compared to 4 hours for traditional HD, while also lowering energy consumption [20]. Additionally, Gavahian and colleagues developed Ohmic-Assisted Hydrodistillation (OAHD), another improved extraction method, which allows thyme essential oil to be obtained in about 25 minutes. Notably, the chemical composition of thyme extracted using OAHD remained unchanged compared to that obtained by conventional HD [21]**.**

4.1.2. Steam-Entrained Distillation (SD)

Steam distillation is used to extract natural aromatic compounds from heat-sensitive plants. Once commonly employed in laboratories for purifying organic compounds, it has largely been replaced by vacuum distillation. In this method, plant material placed in the still is exposed to steam without prior maceration in water. The injected steam penetrates the plant's molecular pores, releasing the essential oil as it moves upward through the material. This process produces a mixture of condensed steam and essential oil, which is then collected [22]. The principle of this method is that the combined vapor pressure equals the ambient pressure at 100 °C, allowing volatile compounds with boiling points between 150 °C and 300 °C to evaporate at a temperature close to that of water. Moreover, the process can be carried out under pressure when extracting essential oils that are more difficult to obtain.

This method recovers about 93% of the essential oils, while the remaining 7% can be obtained using alternative extraction techniques [23]**.** The process essentially starts by heating the plant material with steam from a steam generator. Heat plays a crucial role in breaking down the plant's structure and facilitating the release of its aromatic components, or essential oils [24]**.**

Masango developed an advanced steam distillation method aimed at reducing wastewater production and increasing essential oil yield. In this system, a packed bed of plant material is placed above the steam source, allowing only steam, not boiling water, to pass through the plants. This approach reduces the water content of the distillate and lowers the amount of steam needed for the process.

4.1.3. Solvent Extraction

This method uses common solvents such as acetone, petroleum ether, hexane, methanol, or ethanol to extract delicate or fragile flower components that cannot tolerate heat or steam. In this process, the plant material is mixed with the solvent, gently heated, filtered, and the solvent allowed to evaporate. The resulting filter contains resin or synthetic resin, a mixture of aromatic compounds, essential oils, and waxes. The essential oil is separated by mixing the filter with alcohol and then distilling it at a low temperature. During distillation, the alcohol absorbs the scent and evaporates, while the absolute essential oil remains in the residue. Although this method is effective, it is more complex, costly, and time-consuming than other techniques [25]**.** This method is also known as liquid-liquid extraction, and it separates oils based on the solubility of their components, using two immiscible liquids, such as water and an organic solvent. In this process, the extraction unit is filled with perforated layers of plant material containing essential oils and repeatedly washed with the solvent. This technique is particularly suitable for sensitive plants, as it allows for the production of larger quantities of essential oils at a lower cost, making it highly valuable in applications such as the perfume industry [26], vegetable oil processing, and biodiesel production. The quality and yield of the combined extract depend on the type of supplementary heat applied, as the process is constrained by the solubility of the compound in the chosen solvent. While relatively simple and effective, this method has certain drawbacks, including long extraction times, high solvent consumption, and often limited reproducibility [27].

4.1.4. Soxhlet Extraction

The extractor, invented in 1879 by Franz Von Soxhlet [28] was designed to extract lipids from solid materials. This method is particularly useful when the target compound has limited solubility in a given solvent, while the impurities are insoluble in it. It enables continuous operation with minimal oversight, efficiently recycling a small volume of solvent to dissolve a larger quantity of plant material. This device consists of a cellulose cartridge filled with plant material, connected to a solvent tank or flask and topped with a condenser, where the solvent vapors condense and come into contact with the solid material. This solid–liquid interaction allows one or more compounds to be dissolved into the refluxing liquid phase. In a conventional Soxhlet apparatus, the plant material is placed in a chamber that gradually fills with the condensed liquid from the distillation flask. Once the liquid reaches a set level, a siphon empties the chamber back into the flask, carrying with it the extracted compounds in the solvent [29]. This procedure is repeated until the extraction is nearly complete. Soxhlet extraction offers several advantages, including progressively enriching the solution in the distillation flask with solute during each cycle, ensuring the plant material is continuously exposed to freshly distilled solvent, preventing solvent saturation with extractable compounds, and enhancing the efficiency of analyte removal from the plant material. In addition, the system operates at a temperature close to the boiling point of the solvent, and this excess thermal energy accelerates the extraction kinetics. However, this method has notable drawbacks, including the length of the extraction time, the need for large amounts of solvent to dilute the sample, and losses due to thermal decomposition and volatilisation caused by heating the distillation flask.

4.1.5. Cold Pressing

The oil is extracted from the plant material under low temperature and low-pressure conditions. Considered one of the most effective methods for obtaining essential oils, it is suitable for most conductive oils as well as many other essential oils. This process ensures that the resulting product is 100% pure while preserving all the natural properties of the plant. Cold-pressing is a low-heat mechanical extraction method that removes the plant's oil-rich outer layer through washing or scrubbing. The entire plant is then pressed to extract the pulp and release essential oil from internal pockets. The oil naturally rises to the surface of the material, where it is separated using centrifugal force.

4.1.6. Hydrodiffusion

Hydrodiffusion extraction involves directing steam into a container filled with plant material, typically using only dried samples that might be damaged by boiling temperatures. Unlike steam distillation, where steam enters from the bottom of the generator, in hydrodiffusion it is supplied from the top. This method can be carried out under low pressure or vacuum, allowing the steam temperature to be reduced below 100 °C [30].

The steam diffusion method was further enhanced with the integration of microwave technology. Bousbia and his team investigated the performance of an innovative approach, Microwave Hydrodiffusion and Gravity

(MHG), in comparison to the conventional hydrodistillation technique [31]**.** Another study explored a new steam diffusion technique, called Microwave Steam Diffusion (MSDf), to extract essential oil from orange peel. The findings revealed that the MSDf method required only 12 minutes to obtain essential oils, achieving yields and aromatic profiles comparable to those produced by the traditional 40-minute SDf process.

4.2. Innovative essential oil extraction techniques

Traditional essential oil extraction methods remain widely used on a commercial scale, despite drawbacks linked to the thermolability of their components. Exposure to high temperatures can cause chemical changes, such as hydrolysis, isomerization, and oxidation, resulting in significant quality degradation, particularly during prolonged extraction. In modern industrial production, factors such as cost-effectiveness, competitiveness, environmental sustainability, high efficiency, and product quality are increasingly prioritized. Therefore, advancing extraction techniques is essential to meet these evolving demands and improve overall outcomes. Innovative, green extraction techniques have been developed to preserve the natural composition of essential oils, particularly for high-value or heat-sensitive products, while reducing extraction time, energy use, solvents, and CO_2 emissions.

4.2.1. Supercritical Fluid Extraction (SFE)

Supercritical Fluid Extraction (SFE) is a technique that employs supercritical fluids as solvents to separate compounds from liquid or solid plant materials. Compared to traditional methods such as solvent extraction or steam distillation, SFE offers advantages including shorter extraction times, lower solvent consumption, and the ability to preserve delicate molecules from degradation. In contrast, conventional approaches often result in the loss of volatile components, incomplete oil recovery, and the presence of harmful residues.

Supercritical fluids possess unique properties such as high diffusivity, low viscosity, and liquid-like density. Among them, carbon dioxide (CO_2) is the most commonly used due to its inert nature, non-toxicity, non-flammability, affordability, and ease of removal from the final extract. An additional advantage is its relatively low critical temperature (31.1 °C) and pressure (7.3 MPa) compared to other supercritical fluids. However, its non-polar nature limits its efficiency in extracting polar compounds, often requiring the use of co-solvents like ethanol in certain applications [32] [33]**.**

In general, supercritical fluid extraction operates by repeatedly compressing and decompressing the fluid in a closed cycle. CO_2 is first highly compressed and heated to reach its supercritical state, then passed through the raw plant material to absorb volatile compounds and extracts. The resulting CO_2-extract mixture is directed into two separators, where the fluid is gradually decompressed, allowing the extracts to be separated from the CO_2. Since CO_2 quickly returns to a gaseous state under normal pressure and temperature, it is released from the second separator, recycled back into the storage tank, and leaves no solvent residues in the final product [34].

Several studies have demonstrated the effectiveness of SFE in extracting essential oils from various plant sources. For example, it has been successfully applied to obtain the chemical constituents of rose geranium, *Eugenia caryophyllata*, clove buds, and *Marchantia convoluta*. Comparative research with conventional extraction methods has shown that SFE can yield aromatic oils of superior quality, often exhibiting enhanced pharmacological properties [35] [36]**.** SFE has also proven effective for extracting essential oils that are difficult to obtain through steam distillation. For instance, carrot essential oil produced via SFE exhibited stronger antibacterial and antifungal activities compared to that obtained through hydrodistillation [37]. In all cases, SFE offers an effective alternative for extracting plant materials, particularly essential oils. Its ability to protect heat-sensitive compounds, reduce solvent usage, and yield extracts with enhanced bioactivity makes it a promising technique in natural product extraction [38]**.**

4.2.2. Ultrasound-Assisted Extraction (EAU)

To obtain high-value compounds and contribute to the increase in the estimation of certain food by-products used as a source of natural compounds, ultrasound-assisted extraction (EAU) is considered a good, more efficient technique whose energy savings are practically perceived by using beneficial average temperatures for heat-sensitive suits [39]. In general, ultrasonic waves can improve selectivity and intensify the extraction of essential oils from plant materials, especially when combined with other methods such as solvent extraction or hydrodistillation.

In this technique, the plant material is immersed in water or another solvent while being exposed to ultrasound [40]. The intense ultrasonic waves enhance surface moisture evaporation and create rotational velocities at the interfaces, which stimulate the diffusion boundary layer. This process triggers rapid, alternating expansions of the plant material, facilitating efficient mass transfer [41].

The main advantages of using ultrasound include minimal impact on the integrity of extractable compounds, reduced or eliminated need for organic solvents (as it works effectively with generally recognized as safe solvents), and significantly shorter extraction times. These effects stem from the cavitation phenomenon, where small bubbles form and collapse. As the bubbles expand and then violently implode, they generate strong mechanical forces that break cell membranes, leading to high extraction yields and faster processing [42].

4.2.3. Microwave-Assisted Hydrodistillation (MAHD)

Solvent-Free Microwave Extraction (SFME) is an essential oil extraction technique that utilizes the plant's inherent moisture, eliminating the need for added solvents. Patented in 1990 by Paré and Bélanger as an alternative to hydrodistillation, this method employs microwave energy to release active compounds from plant material. Its efficiency primarily depends on the dielectric properties of the sample and its natural water content [43]. Microwaves, which are electromagnetic waves with frequencies between 300 MHz and 300 GHz, are used in this process to heat the solvent containing the plant material for a few minutes. The heating is usually repeated several times, with cooling intervals to prevent boiling. This hydrodistillation technique offers notable advantages, including high and rapid extraction efficiency, lower solvent consumption, and effective preservation of heat-sensitive compounds. When used in separation and extraction processes, microwave-assisted hydrodistillation can greatly shorten extraction time, reduce solvent usage and CO_2 emissions, and thus lessen environmental impact [44] [45] all while consuming only a fraction of the energy required by conventional methods [46]. Its efficiency stems from the principle of volumetric and controlled heating, which acts directly on plant material and polar solvents, involving two concurrent phenomena in most cases: ion conduction and dipole rotation [47].

4.2.4. Solvent-Free Microwave Extraction (SFME)

Developed by Chemat and colleagues [48] [44] , this technique is used to extract essential oils naturally dispersed within the water molecules of plant material, without the addition of any solvents [49] It operates by combining the energies of dry distillation and microwave heating. This method involves performing dry microwave distillation of the plant material at atmospheric pressure, without adding water or any organic solvent [50] . It combines the effects of microwave heating and dry distillation. In an SFME process, the plant material is first moistened by soaking in a measured volume of water for one to two hours, after which any excess water is drained before extraction begins. The moistened plant material was then placed in the microwave oven, where a condenser was used during the preset process to collect the extracted essential oils. The instrument's control panel regulated temperature, extraction time, and radiation power. After isolation, the essential oil was dried over anhydrous sodium sulfate and stored in the dark at 4 °C. The extraction yield was calculated using the formula: Extraction yield (mL/kg) = V/M , where V is the volume of essential oil obtained from the herb samples (mL) and M is the mass of the herb samples (kg).

4.2.5. Microwave Hydrodiffusion and Gravity (MHG)

Microwave Hydrodiffusion and Gravity (MHG) is an innovative, eco-friendly method for extracting essential oils. This green extraction approach combines microwave heating with the natural gravitational pull of the earth under atmospheric pressure, enabling large-scale, controlled extraction of essential oils from a wide variety of plant species [30].

The microwave hydro-diffusion and gravity technique is both cost-effective and efficient, offering a more environmentally friendly approach as it operates without solvents and requires less energy [51]. In addition, the reduction of extraction time (20 minutes) and environmental impact are the main benefits [30].

Table 1. Advantages and disadvantages related to the vital essential oil extraction technique [52].

Method of extraction	Advantages	Disadvantages
Hydrodistillation (HD)	-Easy-to-assemble, low-cost EO extraction technique suitable for field application.	-Elevated temperature exposure can cause thermal deterioration. -Time-consuming approach
Steam-Distillation (SD)	-In comparison to HD, it takes less time and is appropriate for field use. -Prevents oxidation from changing the organic components of EO. -A higher level of energy efficiency in comparison to HD.	-The extraction yield ranges from 0.001% to approximately 4%. -Temperatures above normal Extraordinary extraction time. -Chemical changes in the oil's composition. -The depletion of volatile molecules.
Soxhlet	-It doesn't require a significant financial outlay. yields a large amount of EO extraction. -The sample is brought into contact with fresh portions of -The solvent on a regular basis, which aids in the removal of the analyte from the matrix. -The heat generated by the excess energy helps to enhance the extraction kinetics of the system.	-It can take one to seventy-two hours to complete a Soxhlet extraction. -Concentrating the collected solutes is necessary prior to analysis. -Extraction is non-selective due to the existence of interfering molecules. -It is necessary to use highly pure, costly, and hazardous organic solvents. -Thermal deterioration and volatility losses; Use of extremely high temperatures.
Organic solvent	-Increases the amount of essential oils produced. -The approach is simple and effective.	-The extraction process takes a long time. -The consumption of solvents is atypically high. -Organic poisonous residues discovered in the product after extraction. -Reproducibility is frequently lacking. -The compound's solubility in the particular solvent utilized restricts the amount of work that can be completed.
Supercritical Fluid Extraction (SFE)	-Using a temperature and pressure that are somewhat low to get high-quality extraction yields quickly. -It is recognized as a"green alternative." -It is non-toxic, non-flammable, and comes in high purity. -Eliminates the requirement for extraction cleanup; readily extracted from the extract; capable of recovering certain organic components that HD was unable to extract.	-This process generally requires the use of difficult to-handle equipment. -With pure CO_2, extraction rates are relatively slow. -Expensive technique.
Microwave-Generated Hydrodistillation (MGH) and Microwave Hydro diffusion Gravity (MHG)	-Extraction rate is reduced. Energy resources are being used more sparingly. -Do not use a solvent. -Ecologically sustainable It is superior to other methods. -Better than natural scents in reproduction.	-Lower microwave power does not allow for complete recovery of essential oil. -Increased microwave power has the potential to burn the biomass and result in EO pyrolysis.
Microwave Assisted Hydrodistillation (MAHD)	-Increased heating efficiency, and controllable heating process. -The transfer of energy is rapid. -Removal of some process steps, leading to a rise in output. Reduced energy and CO_2 emissions, together with a shorter extraction time.	-High power could lead to lower essential oil yields. -Because of the high power, the oil components may biodegrade.
Solvent Free Microwave Extraction (SFME)	-Extraction costs are lower in terms of energy and time. -Selectivity and elevated production yield. -Protection is provided for constituents that are thermolabile. -Reduces CO_2 emissions in the atmosphere, so protecting the environment.	-This approach is more appropriate for a laboratory scale organic than an industrial pilot scale organic. -To maximize the amount of EO produced, the plant materials used in this procedure must be dried.

Table 2. Some examples of isolated essential oils using several extraction methods.

Extraction methods		Plants / References
Conventional methods	**Hydrodistillation (HD)**	Lavandula species [53]. Oregano (*Origanum vulgare*) [54]. Chinese cassia (*Cinnamomum cassia*), basil (*Ocimum basilicum*), clove (*Syzygium aromaticum*), cumin (*Cuminum cyminum*), anethum species, eucalyptus species, ginger (*Zingiber officinale*) [55]. Lemongrass (*Cymbopogon citratus*) [56].
	Steam-Distillation (SD)	Citrus fruit peels such as: grapefruit (*Citrus paradisi*), orange (*Citrus sinensis*), mandarin (*Citrus reticulata*), tangelo (*Citrus tangelo*), clementin (*Citrus clementina*) [57]. Stout camphor tree (*Cinnamomum kanehirae*) [58].
	Solvent Extraction	Fenugreek (Trigonella foenum-graecum) [59]. Pomelo (*Citrus maxima*) [60]. mandarin (*Citrus reticulata*) [61]. Aromatic litsea (*Litsea cubeba)* [62]. Stout camphor tree (*Cinnamomum kanehirae*) [58].
	Soxhlet Extraction	*Lamiaceae* Species [63]. Buah mahkota dewa (*Phaleria macrocarpa*) [64]. Neem (*Azadirachta indica* A. Juss) [65]. Geranium (*Pelargonium graveolens*) [66]. Oregano (*Origanum onites*) [67]. Tamarind (*Tamarindus indica*) [68]. Lime (*Citrus aurantifolia*) [69].
	Cold Pressing	Lemon (*Citrus limo*n) [70]. Orange (*Citrus sinensis*) [71][72]. *Citrus* fruit peel [73]. Diamante citron (*Citrus medica* L. cv. Diamante) [74]. Black cherry (*Prunus serotine*) [75].
Innovative methods	**Supercritical Fluid Extraction (SFE)**	Aniseed (*Pimpinella anisum* L) [76]. Black Pepper (*Piper nigrum* L) [77]. Bay laurel (*Laurus nobilis*) [78]. Rosemary (*Rosmarinus officinalis* L.) [79]. Chamomile (*Chamomilla recutita* [L.] Rauschert) [80].
	Ultrasound-Assisted Extraction (EAU)	Lavender species [53]. *Cinnamomum cassia* [81]. *Citrus macroptera* [82].
	Microwave-Assisted Hydrodistillation (MAHD)	Lavandula species [53]. Oregano (*Origanum vulgare*) [54]. Chinese cassia (*Cinnamomum cassia*), basil (*Ocimum basilicum*), clove (*Syzygium aromaticum*), cumin (*Cuminum cyminum*), anethum species, eucalyptus species, ginger (*Zingiber officinale*) [55]. Rose Myrtle (*Rhodomyrtus tomentosa*) [83].
	Solvent-Free Microwave Extraction (SFME)	Lavandula species [53]. Korean mountain magnolia (*Oyama sieboldii*) [84]. Jambolan (*Syzygium cumini*) [85]. Key Lime (*Citrus aurantifolia*) [86].
	Microwave Hydro-Diffusion and Gravity (MHG)	*Citrus* peels [87]. Cardamom (*Amomum compactum*) [88]**.**
	Solar Energy-Assisted Hydrodistillation	Clove (highest yield) [55]. Peppermint (lowest yield) [55].

Table 3. Comparison chart of essential oil extraction techniques.

Method	Principle / solvent	Typical temperature / Pressure	Typical extraction time	Typical yield (EO, % w/w)	Key advantages	Limitations / Risks	Ref
SFE	supercritical (CO_2): non-polar solvents, selective extraction.	35-80 °C; 80-400 bar (depending on target).	30 min to several hours.	0.1-3% (depending on matrix), often comparable to or better than HD for heat-sensitive compounds.	High selectivity, no organic residue, good for heat-sensitive compounds.	High CAPEX investment, technical complexity, high safety pressure.	[89] [90]
MAHD	Microwave + hydrodistillation	Local boiling point; atmospheric pressure	10-60 min (often significantly faster than HD).	0.5-4%; often ≧ HD and in less time (e.g., 2.72% vs. 2.61%).	Reduced time, improved kinetics, preservation of thermolabile cells.	Uniform heating, optimization required; specific industrial equipment required.	[91] [92]
SFME	Microwave without the addition of solvent or water (the wet matrix provides steam)	Atmospheric; variable microwaves	10-60 min	0.5-2%; often yields higher than HD in reduced time (e.g., 1.8% vs. 1.16%).	Very "green", short timeframe, economically attractive for certain matrices.	Requires configuration optimization; uniformity problems in large tanks.	[93] [94]
UAE	Ultrasound + solvent (often H_2O/EtOH): cavitation	20-60 °C ; atmospheric	(1 min to tens min)	Yield gains of 10-50% vs. conventional processes reported; depends on pretreatment.	Simple, reduces time and solvent use, compatible with aqueous extraction.	Effectiveness depends on intensity and configuration; scale requires sonotrode design.	[95]
MHG	Microwave + natural hydrodiffusion (gravity collection)	Atmospheric; microwave	Very short (1 min to tens min)	Variable but often competitive yields;	Very fast, green	Yields sometimes lower than SD	[96]

SFE: Supercritical fluid extraction, **MAHD**: microwave assisted hydrodistillation, **SFME**: solvent free microwave extraction, **UAE**: ultrasound assisted extraction, **MHG**: microwave hydrodiffusion and gravity.

5. Methods of identification and quantification

The analysis of a complex essential oil mixture can be performed using two complementary chromatographic techniques: high-performance liquid chromatography (HPLC) for separating the heavy fraction and gas chromatography (GC) for the light fraction, combined with a spectral identification method [52]. Traditionally, analysis is performed on the whole essential oil or crude extract. If certain constituents are difficult to identify, the process involves fractionating the sample, continuing as needed until the compound is purified through preparative chromatographic techniques.

5.1. Gas chromatography (GC)

GC analyses were performed using Chrom Perfect software on a TRACE GC system equipped with a flame ionization detector (FID).

Compounds were separated on 30 m × 0.25 mm (i.d.) fused silica apolar columns coated with a 0.25 µm film of either 100% dimethylpolysiloxane or (5%-phenyl)-methylpolysiloxane (DB-5 MS). After holding at 80 °C for two minutes, both columns were programmed to increase at 10 °C per minute until reaching 270 °C, where they were maintained for ten minutes. Helium served as the carrier gas at a constant flow rate of 1 mL/min. A 1 µL liquid sample was injected with a split ratio of 1:100. For SPME GC, fiber desorption followed this procedure. The injector and detector temperatures were set at 200 °C and 280 °C, respectively. Quantification was performed by percentage peak area based on integration data after analysis [97].

5.2. Gas chromatography-mass spectrometry (GC-MS)

Gas chromatography combined with mass spectrometry is among the most commonly employed techniques in analytical chemistry.

The principle of this technique involves transferring compounds separated by gas chromatography via the mobile phase (carrier gas) into the mass spectrometer, where they are further separated based on their masses. The resulting series of fragments is recorded as peaks, each corresponding to an ion of a specific mass.

This procedure is performed under conditions involving a significant pressure differential, high pressure for gas chromatography and low pressure for mass spectrometry, which makes coupling the two techniques challenging.

For GC/MS analysis, GCQ software and an ion trap mass spectrometer (GCQ) were used. The same columns and temperature programs specified for GC were applied. Helium served as the carrier gas at a constant linear velocity of 30 cm/s. A split ratio of 1:20 was used with a 0.5 µL liquid injection. For SPME-GC, the fiber was desorbed under the following conditions: injection temperature of 200 °C, ion source temperature of 180 °C, and transfer line temperature of 275 °C. The spectrometer operated in positive electron impact (EI) mode, scanning from 35 to 300 amu at a rate of 0.8 scan/s [97].

Identification is performed by matching the retention indices and mass spectra of the separated components with those of reference compounds available in computerized libraries containing thousands of spectra [98].

5.3. High performance liquid chromatography (HPLC)

High-performance liquid chromatography (HPLC) operates on the same fundamental principles as conventional column chromatography but overcomes certain limitations, such as slow separations, limited detection options, and large sample requirements. This more advanced system allows the use of various stationary phases to perform different separation mechanisms, including partitioning (the most common), adsorption, ion exchange, or size exclusion. HPLC is commonly employed for the separation and/or semi-preparative or preparative purification of mixture components, enabling the identification and quantification of individual constituents.

The separation process relies on the same basic components as column chromatography: one or more solvents and a column packed with a stationary phase. In this setup, a pre-column (also C_{18} reverse phase) is placed before the main column to prevent clogging caused by the accumulation of large molecules. Reversed-phase C_{18} columns are particularly suited for separating polar compounds that are soluble in water or hydroalcoholic mixtures. The sample or extract to be analyzed is first dissolved in the mobile phase (solvents) and then injected under high pressure into the head of the column, a stainless-steel tube containing the stationary phase. At the column's outlet, molecules are detected using a spectrophotometric or spectrometric detector, which records a signal that is processed by a computer and displayed as a chromatogram [99].

The main distinction from conventional chromatography lies in the elution time. This increased speed is achieved by applying high pressure via a pump, which ensures a stable and consistent flow of the eluent.

Coupling the HPLC system with a Diode Array Detector (DAD) enables qualitative analysis by recording the UV spectra of isolated constituents, and quantitative analysis based on the area of each chromatographic peak compared to an external calibration curve. However, determining optimal operating conditions for effective separation can often be challenging, requiring an analytical phase dedicated to selecting the most suitable experimental parameters.

6. Biosynthesis pathways

The chemical composition of essential oils is largely determined by the metabolic pathways involved and is influenced by the extraction conditions applied to the plant's essence.

The main constituents of essential oils (EOs) are produced via three distinct biosynthetic pathways: the mevalonate pathway, responsible for sesquiterpene synthesis; the methylerythritol pathway, which generates mono- and diterpenes; and the shikimic acid pathway, which produces phenylpropenes [100].

Isopentenyl pyrophosphate (IPP), also known as isopentenyl diphosphate (IPD), and its isomer dimethylallyl diphosphate (DMAD) serve as the fundamental building blocks for the biosynthesis of plant terpenoids. These "active isoprene units" are generated via the methylerythritol phosphate and mevalonic acid pathways. Subsequently, DMAD and IPD combine to form geranyl diphosphate, a C10 molecule identified by Tisserand and Young (2013) as the precursor of monoterpenoids, named for their composition of a single pair of five-carbon units [8]**.**

6.1. Mevalonate pathway

The mevalonic acid pathway is responsible for producing terpenoid compounds and involves the following steps:

First, a six-carbon mevalonic acid molecule is formed. This molecule then undergoes a series of enzyme-catalyzed rearrangements to produce isopentenyl pyrophosphate, an isoprene unit consisting of a branched five-carbon structure. Finally, the isoprene is linked to two phosphate groups.

According to Bowles (2003) and Tisserand (2013) [101] [8], isoprene represents the fundamental building block of essential oils, initiating the synthesis of terpenoid molecules.

6.2. Methylerythritol pathway

In the mevalonate pathway, 2-C-methyl-*D*-erythritol 4-phosphate (MEP) and 1-deoxy-*D*-xylulose 5-phosphate (DOXP) are formed through the condensation of glyceraldehyde phosphate and pyruvate [102] [8]**.**

6.3. Shikimic acid pathway

Shikimic acid plays a key role in plant metabolism as an essential precursor for the synthesis of lignans and flavonoids. Moreover, in certain essential oils, benzoic acid derivatives are formed through the aromatization of shikimic acid [103]**.** Flavonoids are vital structural compounds in plants, functioning as pigments, antioxidants, and UV protectants (**Figure 1**). Lignans represent another significant class of plant-derived products [104] [8]**.**

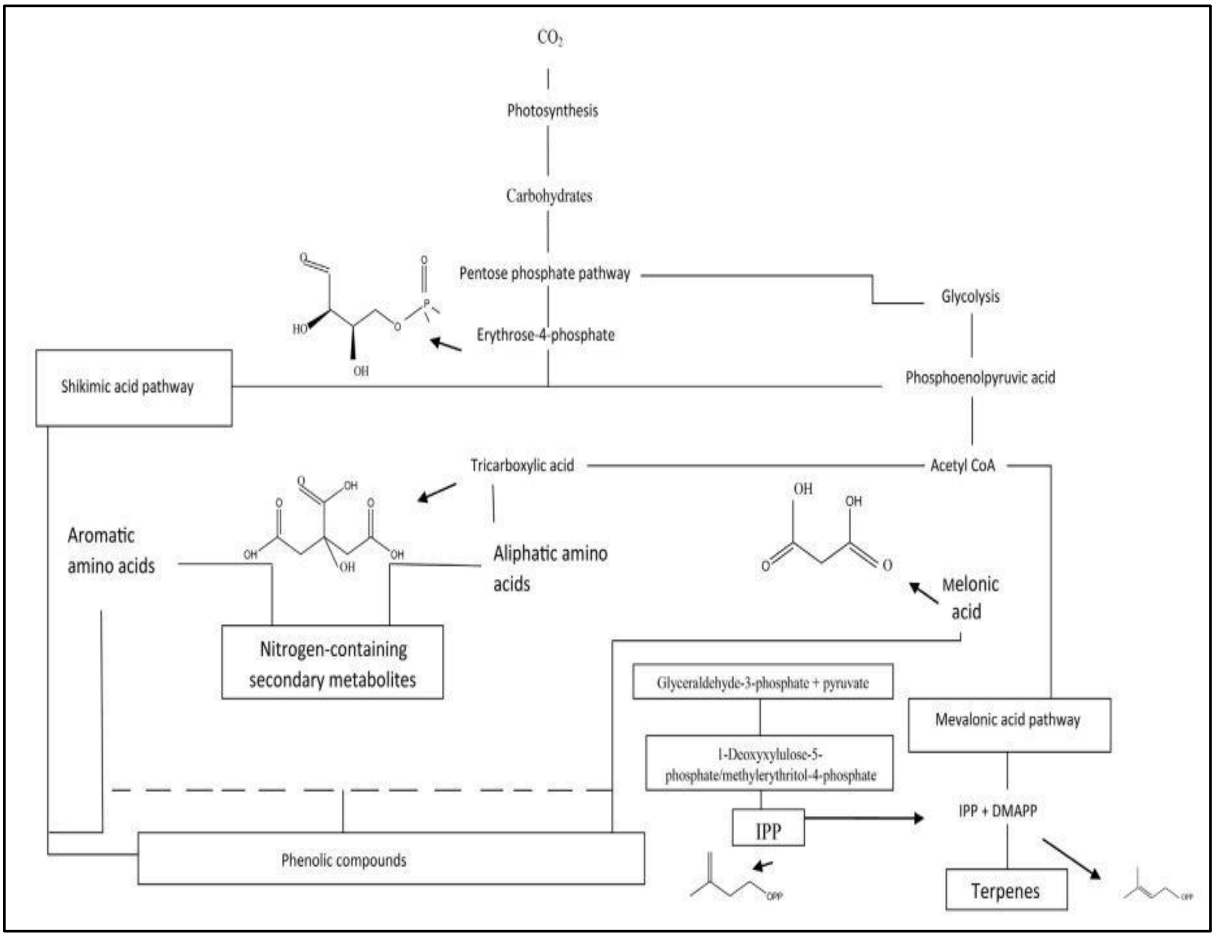

Figure 1. Plant secondary metabolite synthesis. **TPP**: thiamine diphosphate; **DMAPP**: dimethylallyl diphosphate; **IPP**: isopentenyl pyrophosphate.

7. Chemical composition of essential oils

Pure essential oils can contain over 200 constituents, typically comprising mixtures of terpenes and phenylpropanoid derivatives with only slight chemical and structural variations. They are complex blends of volatile compounds, including terpenes (primarily monoterpenes and sesquiterpenes), phenolic compounds, and alcohols [48]. However, essential oils can also contain oxygenated compounds. They are called “essential” because they were once thought to embody the very essence, the distinctive aroma and flavor of the plant world. In contrast to fatty or fixed oils, mainly composed of glycerides, or mineral and hydrocarbon oils, essential oils possess unique compositional characteristics.

Among other forms, they occur as oxygenated derivatives of hydrocarbon terpenes, including aldehydes, ketones, alcohols, phenols, acids, ethers, and esters [1]. Certain terpenes also serve as powerful therapeutic agents for treating heart disease [105] [106] [107].

7.1. Hydrocarbons

The first major class of essential oil molecules is hydrocarbons, which are composed entirely of carbon and hydrogen atoms and vary greatly in size and complexity. While their solubility in water is low, they are highly soluble in fats (lipophilic). Simple hydrocarbons, or non-terpenoid hydrocarbons, such as alkanes, alkenes, and benzenoids, are not synthesized via mevalonate or non-mevalonate (MEP) pathways [8], and this class includes:

7.1.1. Terpenes

Essential oils consist mainly of monoterpenes and sesquiterpenes. Monoterpenes are produced through the head-to-tail coupling of two isoprene units, whereas sesquiterpenes are formed by the assembly of three isoprene units [108].

7.1.1.1. Monoterpenes

Monoterpenes are the simplest 10-carbon terpenes, consisting of two isoprene (C_5H_8) units derived from geranyl pyrophosphate (GPP) through a head-to-tail linkage (**Figure 2**). They are typically associated with various functional groups, such as alcohols (e.g., *cis*-carveol), aldehydes (e.g., perillaldehyde), acids (e.g., geranic acid), simple hydrocarbons (e.g., limonene, myrcene), and esters (e.g., bornyl acetate). Structurally, they can be acyclic, cyclic (mono- or bicyclic), or aromatic, and are key constituents of floral essences, essential oils, and resins [109].

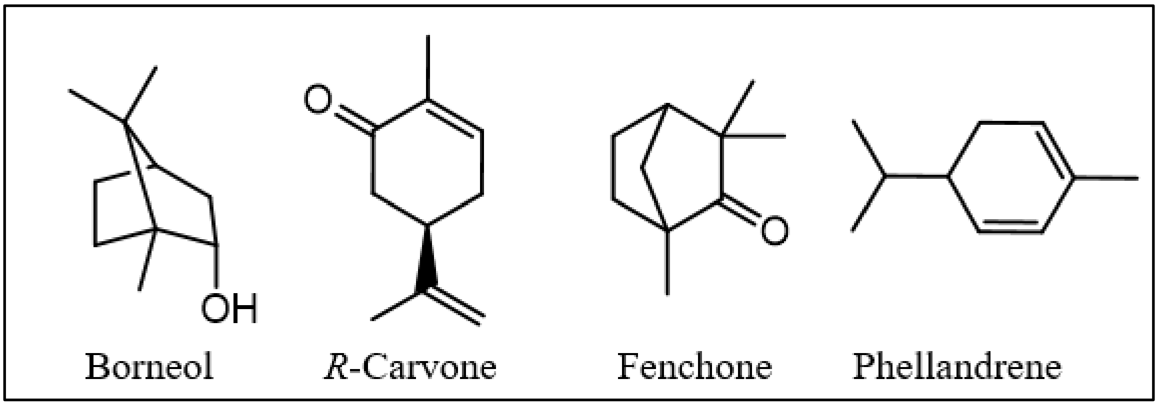

Figure 2. Examples of some monoterpenes.

7.1.1.2. Sesquiterpenes

They are composed of three isoprene units ($C_{15}H_{24}$) and represent the most diverse class of terpenes, classified into several structural types: acyclic, monocyclic, bicyclic, tricyclic, and polycyclic. In nature, they occur either as simple hydrocarbons or as oxygenated derivatives, including alcohols, ketones, aldehydes, acids, and lactones **(Figure 3)** [101].

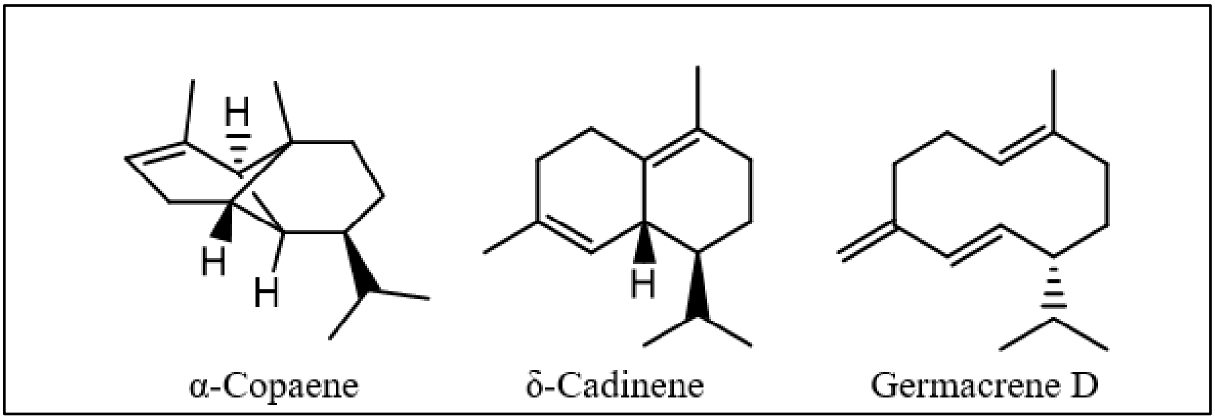

Figure 3. Examples of some sesquiterpenes.

7.2. Functional Groups

A functional group is an atom or group of atoms that largely determines the specific chemical properties of the molecule in which it is found. In essential oils, most functional groups contain heteroatoms, mainly oxygen [110]**.** Oxygenated compounds form the second major class of essential oil constituents. Composed of carbon, hydrogen, and oxygen, they are divided into various chemical categories, including: alcohols, aldehydes, esters, ethers, ketones, lactones, oxides, peroxides, and phenols [111]**.**

7.2.1. Hydrocarbon groups

Due to their high electron density, carbon-carbon double bonds in hydrocarbons display distinctive chemical behavior similar to that of functional groups containing heteroatoms. In essential oils, alkenes, often termed monoterpene hydrocarbons (**Figure 4**), are commonly present [8].

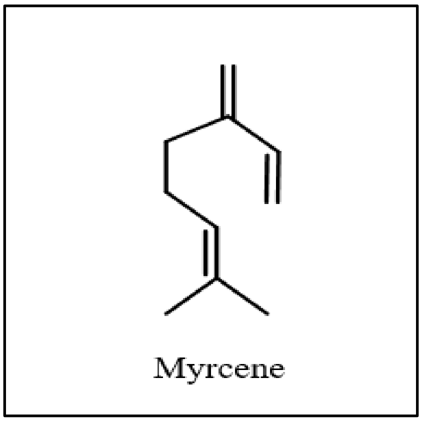

Figure 4. Example of hydrocarbon groups (Myrcene).

7.2.2. Hydroxyl groups

Two major hydroxyl-containing groups present in essential oils are alcohols and phenols. Among the various terpene derivatives in essential oils are alcohols, typically identifiable by names ending in "-ol" Monoterpene alcohols are common in essential oils, while sesquiterpene alcohols are comparatively rare. In general, alcohols are characterized by low irritation potential, minimal allergenicity, and the absence of toxicity or mutagenic effects. Monoterpene alcohols, such as menthol, possess notable antifungal and antibacterial activities. Like alcohols, phenols also contain a hydroxyl group, but it is attached to a benzene ring, often accompanied by an isopropyl side chain. Common phenols in essential oils include eugenol, carvacrol, and thymol, each known for their distinctive biological activities in clove, oregano, and thyme, respectively **(Figure 5)** [8] .

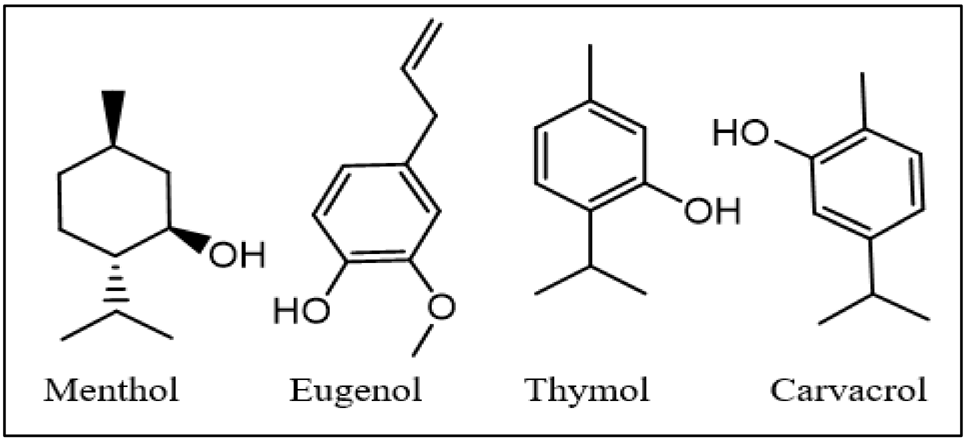

Figure 5. Example of hydroxyl groups.

7.2.3. Carbonyl groups

The following important class of molecules present in essential oils consists of compounds containing carbonyl groups.

7.2.3.1. Aldehydes

Aldehydes are characterized by the carbonyl functional group (-CHO), where a carbon atom at the end of a carbon chain is double-bonded to an oxygen atom. Commonly found in essential oils, they often exhibit a subtly fruity aroma. Examples include geranial and cumin aldehyde **(Figure 6)** [53] [101].

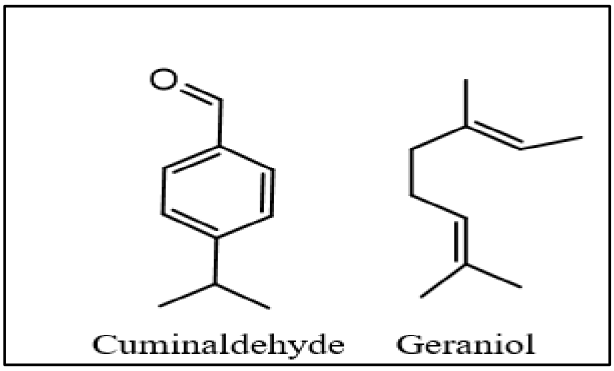

Figure 6. Example of aldehyde groups.

7.2.3.2. Ketones

Ketones, like aldehydes, contain a carbonyl group and share a similar structural framework. They are formed through the oxidation of secondary alcohols and feature a carbon atom double-bonded to an oxygen atom and bonded to two other carbon atoms. Generally stable and resistant to further oxidation, ketones are notable constituents of essential oils, with carvone being a well-known example **(Figure 7)** [8] [101].

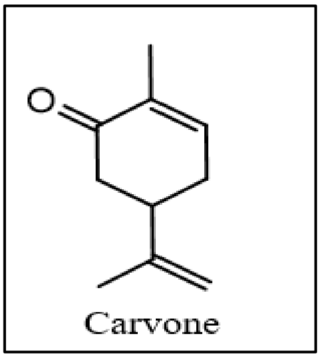

Figure 7. Example of ketone groups.

7.2.3.3. Carboxylic acids

Carboxylic acids, which contain the COOH functional group, are formed through the oxidation of aldehydes. Due to their low volatility, they are rarely present in essential oils. These compounds are weak acids with strong, distinctive odors, with cinnamic acid being a common example **(Figure 8)** [112] [8].

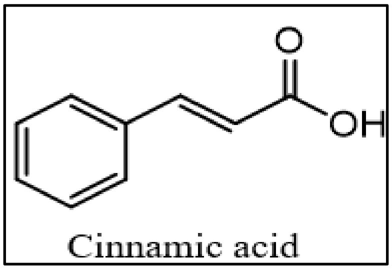

Figure 8. Example of carboxylic acid groups.

7.2.3.4. Carboxylic esters

These compounds are characterized by intensely fruity and sweet aromas. They are typically formed from the reaction between a carboxylic acid and a corresponding terpene alcohol **(Figure 9)** [112] [8].

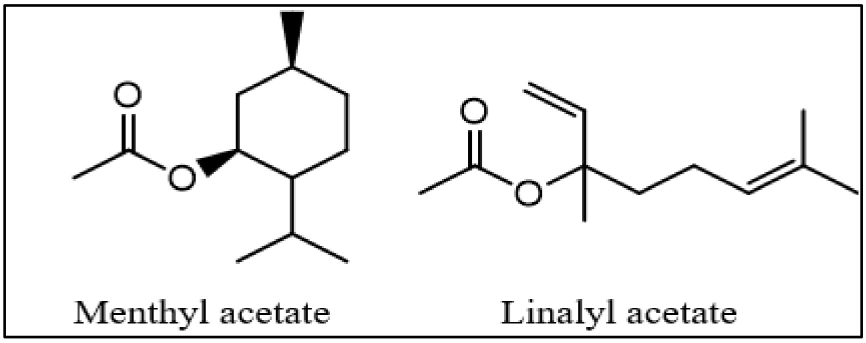

Figure 9. Example of carboxylic ester groups.

7.2.3.5. Lactones

Lactones, derived from lactic acid, are cyclic esters characterized by a closed ring in which an oxygen atom is double-bonded to a carbon atom. In essential oils, they can occur in both simple and complex forms, with ring sizes that vary. Some lactones, such as *γ*- and *δ*-decalactone, have a fruity aroma. Sesquiterpene lactones are well known for causing skin sensitization. Many essential oils also contain coumarin, a benzenoid lactone responsible for the scent of freshly cut hay (**Figure 10**) [113] [8].

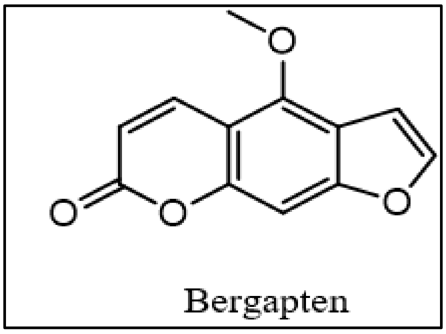

Figure 10. Example of lactone groups.

These carbonyl-containing groups play a key role in shaping the aromatic properties and diverse chemical composition of essential oils.

7.2.4. Oxygen-bridged groups

Within essential oils, oxygen-bridged functional groups form a significant chemical class. Ethers are characterized by a single oxygen atom bonded to two carbon atoms and may exist as simple ethers, cyclic ethers, or oxides. A notable example is 1,8-cineole, a common oxide in essential oils, which occurs in two distinct isomeric forms. Epoxides, on the other hand, arise from the oxidative metabolism of alkenes or as degradation products, and are defined by a strained three-membered ring composed of an oxygen atom and two carbon atoms [8]**.** Ethers, such as methyl-eugenol, play a notable role in the complex chemical makeup of essential oils. A rare example of another functional group found in essential oils is the peroxide, characterized by a direct oxygen-oxygen bond linking two carbon atoms. One such peroxide is ascaridole, a toxic compound present in wormseed oil [8]**.** Furans, composed of an oxygen atom within a five-membered aromatic ring, are rare in essential oils, although menthofuran is particularly abundant in mint oils. Additionally, furanocoumarins, compounds incorporating a furan ring, exhibit phototoxic effects, such as methoxsalen found in rue oil. These oxygen-bridged functional groups greatly enhance the chemical diversity and complexity of essential oils **(Figure 11)** [8]**.**

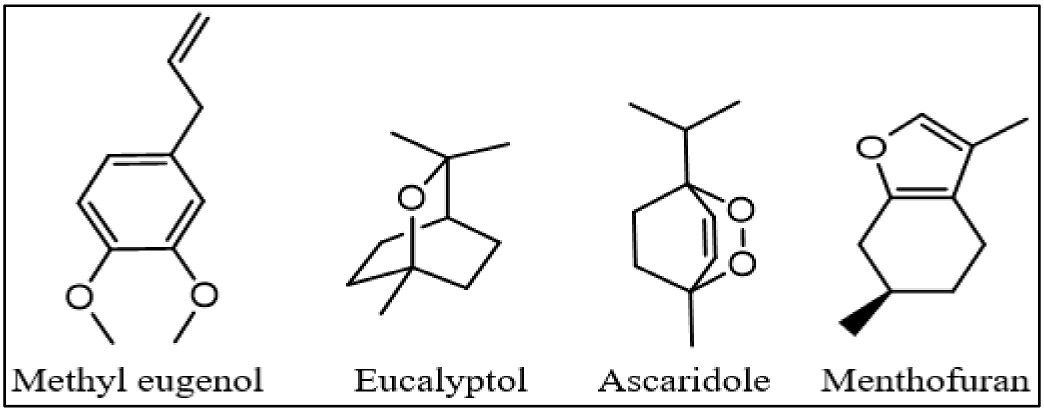

Figure 11. Example of oxygen-bridged groups in essential oil.

7.3. Other compounds

Essential oils contain a diverse array of reactive and often pungent molecules, including compounds that incorporate sulfur and nitrogen. Some essential oils contain sulfur compounds, such as sulfides, disulfides, and isothiocyanates, which contribute to their distinctive aromas. Allyl isothiocyanate is a well-known example [114]**.** Some essential oils contain nitrogen compounds, such as indole, which can produce a variety of odors, ranging from a strong fecal odor at high concentrations to a pleasant floral scent when diluted. These compounds are often used as fixatives in floral perfumes and as flavoring agents in products such as ice cream and tobacco [115]**.** Additional nitrogen-containing compounds found in essential oils include methyl anthranilate, skatole, and pyridine. These molecules play a role in plant defense mechanisms and enhance the flavor profiles of various foods and beverages (**Figure 12**) [105].

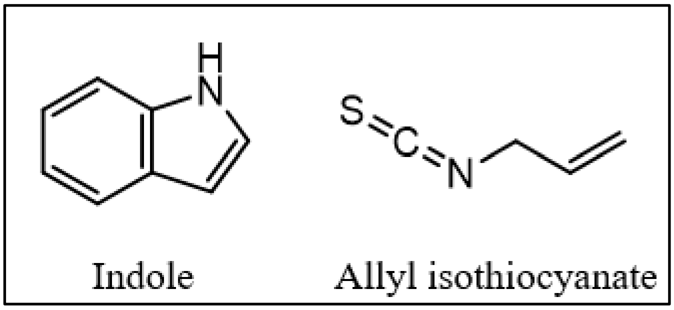

Figure 12. Examples of sulfur, and nitrogen chemical compounds in essential oil.

8. Therapeutic, ecological and economic benefits of essential oils

Aromatherapy, the practice of healing with essential oils, has evolved into a systematic science through the classification of these oils based on their antibacterial potential. Around two decades ago, Dr. Maurice Girault and Dr. Paul Belaiche introduced the aromatogram, a technique similar to the microbial susceptibility test, designed to identify which essential oils are most effective against a specific germ [116].

This thriving era of phytotherapy in France came to a halt with the 1991 decree that ended reimbursement for all magistral preparations, prepared by pharmacists according to a doctor's prescription for a specific patient's case. This decision dealt a significant blow to herbal medicine. A comparable measure was implemented in Belgium in 1997. Since then, herbal practitioners have observed a marked decline in patient visits. Moreover, interest in studying herbal medicine has waned, investments in related research have diminished, and clinical trials have become increasingly rare. Nevertheless, herbal medicine has not vanished but rather evolved in its practice, with self-medication largely replacing prescriptions. However, awareness of the potential toxicity and contraindications of many plants has grown. The belief that all plants are harmless must be challenged, for instance, *Aconitum napellus* contains aconitine, a highly potent poison. During a survival exercise, trained paratroopers lost their lives after consuming the roots of *Aconitum napellus* as food. Likewise, belladonna berries, rich in atropine, are highly lethal. Similarly, foxglove leaves contain cardiotonic heterosides which, when taken in large quantities, offer little chance of recovery for the person who ingests them.

Essential oils, obtained from plants through distillation, are among the most significant active constituents of botanical sources and are extensively used in perfumery. In their natural state within plants, these oils are oxygenated compounds, often of terpenoid origin, and frequently feature an aromatic core. Essential oils possess a wide range of properties. Tea tree (*Melaleuca alternifolia*), for example, is known for its strong antiseptic activity and contains varying proportions of key components, including terpinen-4-ol (40%), *γ*-terpinene (24%), *α*-terpinene (10%), and cineole (5%). First studied in Australia in 1923, these oils demonstrated notable antiseptic effects, particularly in managing infectious diseases such as fungal infections, as well as dermatological conditions like vaginal candidiasis, ringworm, corns, acne, warts, and boils [117] [118]. In addition, they are effective in healing infected burns, stings, and insect bites [119].The main constituents of chamomile essential oil (*Chamomilla recutita*) include pro-azulene, farnesene, α-bisabolol, spiroether, and chamazulene, which possess anti-allergic properties. Notably, the presence of spiroether contributes to its antispasmodic activity, making the plant particularly valuable for relieving muscle cramps, menstrual pain, and related contractions [120]. Scots pine oil (P*inus sylvestris*) is recognized as a respiratory disinfectant, making it useful in the treatment of asthma and bronchitis, as well as certain digestive issues such as flatulence. The leaves possess mild antiseptic properties and are also employed in managing arthritis and rheumatism. Additionally, the seeds yield an essential oil that supports respiratory function and helps combat bronchitis and urinary tract infections [120]. A plant species' resistance to insect and microorganism attacks is often linked to its essential oil content. These oils protect plants from herbivores and rodents, exhibit allelopathic effects in arid environments, and can act as bioactive solvents for lipophilic compounds [121]. Volatile compounds in higher plants release scent signals that attract specific pollinating insects. Traditionally, essential oils have been extensively used in the food industry for flavoring, as well as in perfumery, adhesives, cosmetics, detergents, and other sectors.

Conclusion

Progress in essential-oil extraction has shifted the field from heat-intensive, solvent-heavy practices toward faster, cleaner, and more selective “green” technologies. Innovations such as supercritical CO_2 extraction, ultrasound-assisted techniques, solvent-free and microwave-assisted hydrodistillation, and microwave hydro-diffusion and gravity collectively shorten extraction times, lower energy use and solvent consumption, and better preserve thermolabile constituents. These process gains are mirrored by advances in phytochemical investigation, GC-FID/MS, HPLC-DAD/MS, and targeted fractionation that deliver higher-resolution chemical fingerprints and more reliable quantitation. Together, modern extraction and analytical platforms not only improve yield and compositional integrity but also reveal finer chemotypic variation and bioactivity profiles, enabling safer, more consistent, and application-specific essential oils. In practical terms, the convergence of process intensification and robust analytics is redefining quality standards, supporting sustainability goals, and accelerating translational use in food, cosmetic, pharmaceutical, and aromatherapeutic domains.

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