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Advances in extraction and standardization of bioactive compounds in Lavender (*Lavandula* spp.)

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Abstract

Lavender (*Lavandula* spp.), a prominent member of the Lamiaceae family, is an economically and therapeutically important aromatic plant widely cultivated for its essential oil and bioactive compounds. This review highlights the advances in extraction and standardization of bioactive compounds in Lavender focusing on extraction techniques, optimization strategies, analytical characterization and strategies for stability. Lavender is characterized by the presence of volatile compounds, especially oxygenated monoterpenes such as linalool and linalyl acetate, which are primarily responsible for its aroma and wide range of biological properties, including antioxidant, anti-inflammatory, sedative and antimicrobial activities. Besides terpenoids, Lavender also contains phenolic compounds, flavonoids and other secondary metabolites that contribute significantly to its pharmacological potential. The chemical composition of Lavender is influenced by several factors, including species variation, environmental conditions, and cultivation practices and processing methods. Extraction techniques play a crucial role in determining the yield, quality and stability of Lavender essential oil. Conventional methods such as hydrodistillation and steam distillation remain widely used; however, advanced technologies including supercritical CO_2 extraction, microwave-assisted extraction, ultrasound-assisted extraction and enzyme-assisted extraction offer improved efficiency, selectivity and preservation of thermolabile constituents. Optimization of extraction parameters such as solvent polarity, temperature, pressure and time is essential for maximizing bioactive compound recovery. Advanced analytical techniques like gas chromatography mass spectrometry (GC-MS), high-performance liquid chromatography (HPLC) and fourier transform infrared spectroscopy (FTIR) are extensively employed for the characterization, quality assessment and authentication of Lavender extracts. In addition, appropriate storage conditions and encapsulation techniques contribute significantly to maintaining essential oil stability and extending shelf-life. Overall, the integration of advanced extraction technologies, precise analytical tools and sustainable approaches enhances the industrial applicability of lavender, making it a valuable resource in pharmaceutical, cosmetic and food industries.

1. Introduction

Lavender belongs to the genus *Lavandula* in the family Lamiaceae, which also includes other aromatic plants such as rosemary, mint, basil and sage. This family is characterized by its distinctive floral structure, in which the petals are fused to form an upper and lower lip (Erland and Mahmoud, 2016). The genus originated in southern Europe and the Mediterranean region (Yildirim *et al.,* 2025). The term Lavender is believed to derived from the Latin word lavare, meaning to wash or to bathe, reflecting its traditional uses for cleansing, external disinfection and internal medicinal applications (Fatma Handan Giray, 2018). Today, Lavender is widely cultivated worldwide for medicinal and pharmaceutical applications (Mykhailenko *et al.,* 2025). Bulgaria leads global Lavender production, followed by France, while France tops lavandin essential oil production, with Spain a close second (Rathore and Kumar, 2022). The global Lavender oil market was valued at USD 42 million in 2022 and is expected to grow at a CAGR of 4.9% between 2022 and 2027. This steady market growth is mainly driven by the increasing demand for natural fragrances and the growing use of natural oils in home care, cosmetic products (Harshal Patil and Jyotsna Waghmar, 2024).

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In *Lavandula angustifolia*, linalyl acetate and linalool are the principal constituents, with linalool considered as the main active constituent despite the higher abundance of linalyl acetate (Donelli *et al.,* 2019). Volatile compounds such as linalool, limonene, perillyl alcohol, linalyl acetate, cis-ocimene, terpenes, coumarin, tannin, caffeic acid and camphor are regarded as the major constituents of Lavender (Batiha *et al.,* 2023). Other species contain higher concentrations of camphor-rich volatile compounds and are employed in non-aromatic applications (Habán *et al.,* 2023). Lavender flowers are also rich in anthocyanidins, flavones including luteolin and apigenin, kaempferol glycosides, rutin, quercitrin and hesperidin, phenol carboxylic acids, polysaccharides and mineral elements such as calcium, magnesium, zinc and manganese (Costea *et al.*, 2019). In *Lavandula*, phenolic acids include ferulic acid, rosmarinic acid, *p*-coumaric acid, caffeic acid and 2-O-glucosylcoumaric acid (Wells *et al.,* 2018). Terpinolene is one of the main compounds found in the leaves and flowers of several Lavender species, but it generally occurs in Lavender essential oil at low levels (less than 2%) (Wainer *et al.,* 2022). The principal constituents given in Figures 1 and 2. The antioxidant activity of Lavender essential oil has been evaluated using assay such as 2,2-diphenyl-1-picrylhydrazyl, oxygen radical absorbance capacity, metal chelating and reducing power assays. Lipoxygenase inhibition was also observed, suggesting potential anti-inflammatory activity, primarily attributed to linalool, camphor, p-cymene and limonene (Carrasco *et al.,* 2016). Lavender oil is commonly obtained using methods such as hydrodistillation, Soxhlet extraction and supercritical carbon dioxide (SC-CO_2) extraction (Kahyaoðlu *et al.,* 2024). The quality of Lavender oil is primarily influenced by plant quality, harvest timing and the distillation process (Lafhal *et al.,* 2016). Despite the increasing interest in Lavender bioactive compound, comprehensive reviews integrating advanced green extraction technologies, analytical standardization and stability enhancement strategies remain limited (Sethunga *et al.,* 2022; Hedayati *et al.,* 2025). Therefore, this review aims to summarize recent advances in extraction, characterization and standardization of Lavender bioactive compounds with an emphasis on sustainable and industrially relevant technologies.

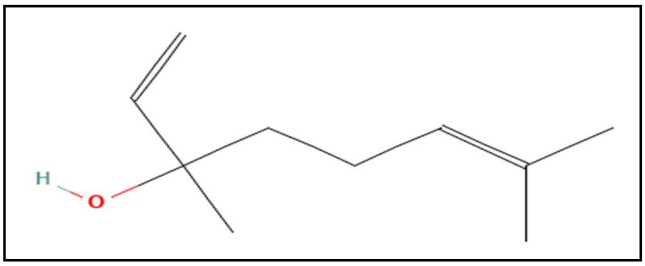

Figure 1: Linalool.

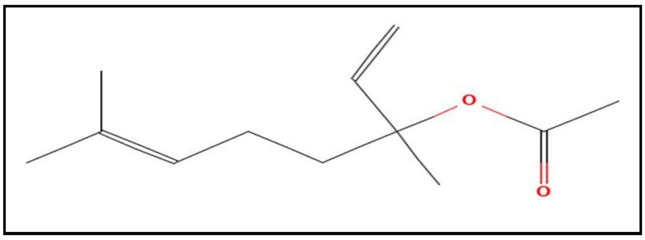

Figure 2: Linalyl acetate.

2. Distribution and cultivation of Lavender

Lavandula is native to the Mediterranean region, the canary island and India. In addition, several species are naturally distributed across northern, eastern and southern Africa, as well as in Bulgaria, Spain, Poland, turkey, France, England, Russia, Australia and the USA (Pokajewicz *et al.,* 2023). The genus is a well-recognized essential oil crop, comprising approximately 40 species, numerous hybrids and nearly 400 registered cultivars. However, only three species are of major commercial importance: *L. angustifolia* (True lavender), *Lavandula latifolia* (Spike lavender) and *Lavandula intermedia* (lavandin) a sterile hybrid of *L. angustifolia* × *L. latifolia* (Caprari *et al.,* 2023). *L. angustifolia* commonly known as English Lavender is frost resistant and valued for its attractive flowers and many cultivars. Other notable species include *L. stoechas* characterized by greyish green foliage, late blooming and strong fragrance and *L. latifolia* a Mediterranean Lavender with grass like foliage (Baitha *et al.,* 2023). Lavender is a shrubby perennial plant of significant industrial importance worldwide, particularly in countries such as Bulgaria. Its essential oil is concentrated primarily in the flowers and the oil content ranges from 0.8 to 2.7%, depending on whether the raw material comes from a local population or a cultivated variety (Hristova and Veleva, 2022). Lavender can be a long-lived perennial with a normal productive life of 10 years (Adam, 2006). Lavender is a compact, clump-forming plant that typically grows 40-60 cm tall. The upper portion of the stem is green, whereas the lower part becomes woody. The plant bears lanceolate leaves with rolled margins and possesses a fibrous, branched root system. The silver green leaves are covered with a fine tomentum, which provides protection against wind, intense sunlight and water loss. The flowers are usually pale violet and arranged in whorls (3-5 flowers per whorl), although white (Alba, Nana Alba) and pink (Rosea) cultivars also exist (Ahmed, 2020).

Lavender is propagated through seeds, stem cuttings, division, layering and tissue culture with stem cuttings being the most widely adopted method. These cutting are generally collected during autumn or spring (September-October or March-April) from healthy plants aged 3 to 5 years. In commercial cultivation, pruning is a routine practice because it helps rejuvenate the plants, promote better flowering and extend their productive lifespan (Crisan *et al.,* 2023). Regular feeding and effective weed control are essential during the first year of crop establishment. Harvesting typically begins in the second year, attains peak productivity during the second and third years and continues annually for about 12 to 15 years (Perović *et al.,* 2025). Lavender flowers were harvested in late June, when the spikes were fully developed and lower florets had just started to open. Flowers are harvested on sunny days when around 50-60% of the florets are open (Kakraliya *et al.,* 2022). The spikes were harvested manually using a sickle, cutting 15-20 cm below the inflorescences and retaining a small portion of leaves (Gangoo *et al.,* 2023). The chemical composition of Lavender essential oil may vary with factors such as genetic makeup, geographical origin and environmental conditions, including fertilization, harvest time and drying methods (Zheljazkov *et al.,* 2013).

3. Uses of Lavender

Lavender flowers are utilized in culinary applications in fresh, dried or candied forms to enhance the flavour and visual appeal of bakery products, jellies, confectionery and ice cream. They are also consumed as infusions with sedative and analgesic effects that may help relieve depression, headaches and anxiety (Falla *et al.,* 2022). Lavender shows a broad range of biological activities, including insecticidal, repellent and feeding-deterrent effects and its essential oil also demonstrates fumigant toxicity against the eggs of stored-product insects (Karakaş *et al.,* 2025). In Germany, a standardized oral essential oil extract of *L. angustifolia* is approved for the treating of subsyndromal anxiety. The extract contains consistent amounts of linalool and linalyl acetate, which together account for approximately 71% of its total composition and is available as 80-mg soft gel capsules for once or twice-daily use. In the United States, it is sold as an over the counter dietary supplement under the name calm aid (Malcolm and Tallian, 2017). Linalool induces sedation by interacting with Gamma-aminobutyric acid (GABA) receptors in the central nervous system (Rai *et al.,* 2020). They possess a characteristic C_6-C_3-C_6 structural framework and Lavender polyphenols serve as important bioactive compounds in protecting against oxidative damage. They comprise a complex profile of flavonoids and non-flavonoids (phenolic acids, lignans and stilbenes) that define the plant antioxidant potential (Dolzhko *et al.,* 2024). Lavender essential oil exhibits multiple pharmacological activities including anxiolytic, sedative, analgesic, antibacterial and anticancer effects (Figure 3).

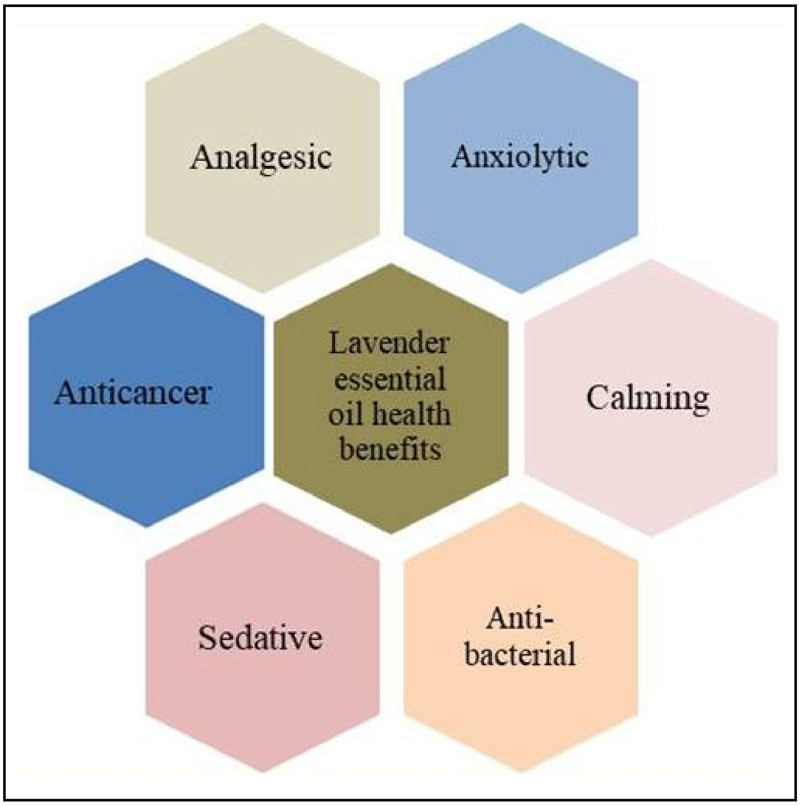

Figure 3: Lavender essential oil health benefits.

4. Bioactive compounds in Lavender

Secondary metabolites are compounds derived from primary metabolites through complex biochemical pathways. In lavender, these predominantly include terpenes (isoprenoids) and phenolic compounds, such as flavonoids and phenylpropanoids (Sethunga *et al.,* 2022). The primary constituents of Lavender essential oil originate from the five carbon precursors, isopentenyl diphosphate and its isomer, dimethylallyl diphosphate (Haban *et al.,* 2023). These precursors are synthesised through two distinct metabolic pathways, the cytosolic mevalonate pathway and the plastidial 2-C methyl-D-erythritol-4-phosphate pathway, both of which are involved in terpenoid biosynthesis (Wells *et al.,* 2018). Consequently, these biosynthetic processes significantly influence the chemical composition of Lavender essential oil, which exhibits considerable variation depending on seasonal and environmental conditions. Lavender essential oil is chemically diverse with 47 compounds identified, collectively accounting for 98.4%-99.7% of the oil composition, with 1,5-dimethyl-1-vinyl-4-hexenyl butyrate (43.73%), 1,3,7-octatriene, 3,7-dimethyl (25.10%), eucalyptol (7.32%) and camphor (3.79%) as the predominant constituents (Hui *et al.,* 2010). Oxygenated monoterpenes represent the predominant class of compound in Lavender essential oil and play a key role in defining its characteristic aroma (Dwipa *et al.,* 2024). The overall aroma profile of Lavender is influenced by compounds such as E-β-ocimene and terpinene-4-ol, which, although present in smaller amounts, enhance the scent complexity (Harshal Patil and Jyotsna Waghmare, 2024).

Beyond essential oil constituents, Lavender also contains other important phytochemical classes. Phenolic compounds, monoterpenoids and triterpenoids are generally associated with aerial parts of the plant, whereas diterpenoids are mainly localized in roots (Speranza *et al.,* 2023). These bioactive constituents contribute to multiple pharmacological properties including antioxidant activity which has been determined using the stable 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical (Silva *et al.,* 2015). Major bioactive compounds such as linalool, linalyl acetate, flavones, anthocyanin and perillyl alcohol are associated with calming, sedative, antioxidant and anticancer related activities (Donelli *et al.,* 2019; Costea *et al.,* 2019; Batiha *et al.,* 2023). Lavender essential oil reduced neurological deficit scores, infarct size and the levels of malondialdehyde, carbonyl compounds and reactive oxygen species, while increasing the activities of antioxidant enzymes such as superoxide dismutase, glutathione peroxidase and catalase. Furthermore the protective effect of Lavender oil against hydrogen peroxide and tert-butyl hydroperoxide induced oxidative DNA damage was investigated in the human hepatoma cell line HepG2 (Kozics *et al.,* 2017). Lavender essential oil also exhibits significant antimicrobial activity against various bacterial and fungal pathogens due to the presence of bioactive terpenoids such as linalool, linalyl acetate, camphor and terpinene 4-ol. These compounds disrupt microbial cell membranes, increase membrane permeability and interfere with cellular metabolism. Lavender oil has demonstrated inhibitory activity against several Gram-positive and Gram-negative bacteria as well as fungal species (Batiha *et al.,* 2019). For industrial and pharmaceutical applications quality control and standardization of Lavender essential oil is essential. The international organization for standardization (ISO) has developed and published quality standards for several Lavender species, including ISO 3054:2001 for *L. latifolia* essential oil (Abrial type) and ISO 3515:2002 for *L. angustifolia* essential oil (Hedayati *et al.,* 2024). Phytochemical composition of Lavender is explained in Figure 4. While the major bioactive compounds and their biological activities in Table 1.

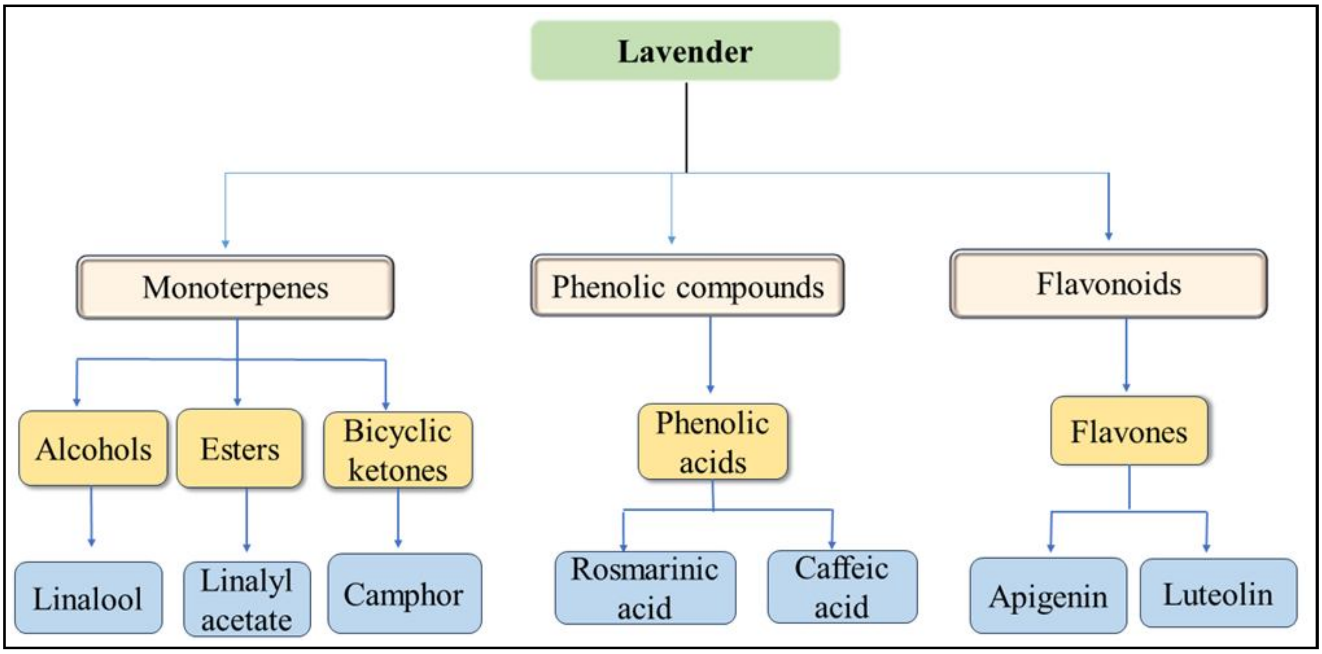

Figure 4: Phytochemical composition of Lavender.

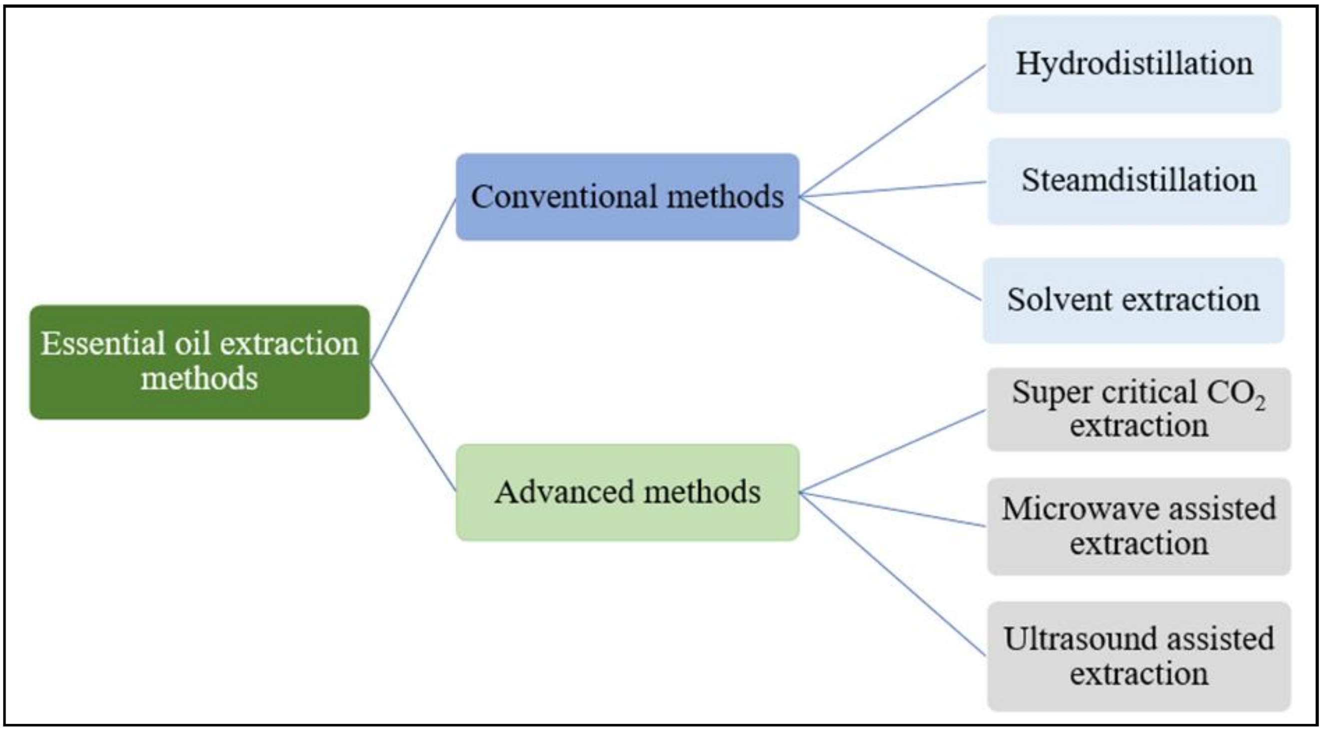

Figure 5: Essential oil extraction methods.

Table 1: Major bioactive compounds of Lavender and their biological activities

Compounds	Biological activity	References
Linalool	Calming and sedative	Donelli *et al.,* 2019
Linalyl acetate	Calming and sedative	Donelli *et al.,* 2019
Flavones	Antioxidants	Costea *et al.,* 2019
Anthocyanidins	Antioxidants	Costea *et al.,* 2019
Perillyl alcohol	Cell proliferation	Batiha *et al.,* 2023
Camphor	Antimicrobial	Batiha *et al.,* 2023
Linoleic acid	Fat oxidation	Batiha *et al.,* 2023

5. Extraction methods

Extraction methods for active compounds aim to obtain the highest possible yield of essential constituents from plant material (Tabarasu *et al.,* 2023). The different extraction methods are listed in Figure 5.

6. Conventional extraction techniques

6.1 Hydrodistillation

Hydrodistillation was carried out using a clevenger-type apparatus (Solomakou *et al.,* 2025). The extraction principle is based on isotropic distillation (Rassem, 2016). In hydrodistillation, the plant material is immersed in water. When heated, the vapours of water and volatile compounds form a heterogeneous mixture that boils at a temperature close to that of water, even though the individual volatile components have higher boiling points (Sethunga *et al.,* 2022). The mixture of water and essential oil vapours is then cooled and converted into a liquid as it moves through the cooling system (Perović *et al.,* 2025). Prolonged distillation yields only a small amount of essential oil and can lead to the formation of unwanted high-boiling compounds and oxidation products (Rassem, 2016). The essential oil was collected, dried, weighed and stored at 4°C prior to analysis. Each extraction was performed at least 3 times (Filly *et al.,* 2016). The essential oil yield was 2.5% (v/w), based on the dry weight of the plant material (Rezazadeh *et al.,* 2008).

6.2 Steam distillation

Steam distillation is a separation or extraction technique used for temperature-sensitive plant materials, such as natural aromatic compounds. In this method, the plant material is placed in the distillation apparatus and exposed directly to steam without being immersed in water (Rassem, 2016). Upon heating, water undergoes vaporization as heating increases the molecular activity of liquid water, allowing some molecules to transition into the vapour phase. As the temperature of the water rises, molecular motion becomes more intense, resulting in the generation of steam (Chiaia *et al.,* 2025). During steam distillation, steam passes through the plant material, allowing volatile molecules to escape as the pores of the material are exposed. The decomposition of organic compounds can be controlled by keeping the temperature below their decomposition point (Sethunga *et al.,* 2022). After distillation, the essential oil is typically separated, dried over anhydrous sodium sulphate (Na, SO_2) and stored in amber vials at low temperature to prevent degradation (Filly *et al.,* 2016). Furthermore, the antioxidant activity of the essential oils extracted using steam distillation was assessed using 2,2-diphenyl-1-picrylhydrazyl (DPPH). The technique has been shown to produce essential oils with higher antioxidant concentrations than those extracted by hydrodistillation (Aziz *et al.,* 2018).

6.3 Solvent extraction

Solvent extraction is widely used for the preparation of flower extracts, where leaching facilities the dissolution of soluble constituents from solid matrices. The choice of solvents including methanol, ethanol and non-polar solvents such as hexane or dichloromethane, is based on their solubility properties (Perovic *et al.,* 2025). The solvent extraction process involves a series of steps, including penetration of the solvent into the matrix, dissolution of the solute in the solvent and diffusion of the solute out of the matrix. After extraction, the solvent is typically removed by evaporation under vacuum conditions using a rotary evaporator to obtain the extract (Sethunga *et al.,* 2022). The quality and yield of the extracted mixture are influenced by factors such as the type of heat applied and the purity of the solvent (Rassem, 2016; Patil and Waghmare, 2014).

The conventional technologies hydrodistillation, steam distillation and solvent extraction are widely employed because of their simplicity and low operational cost. However, these methods often require longer extraction times, higher energy consumption and may lead to degradation of thermolabile compounds.

7. Advanced technologies

In contrast advanced extraction techniques have gained increasing attention due to their higher extraction efficiency, lower solvent requirement, reduced processing time and improved preservation of bioactive constituents.

7.1 Super critical CO_2 extraction

Supercritical CO_2 (SC-CO_2) is widely considered an effective extraction solvent because it is eco-friendly, non-toxic and can be used at mild temperatures, which helps maintain the stability of volatile compounds (Zanotti *et al.,* 2023). In addition, SC-CO_2 extraction allows precise control of temperature and pressure, which can improve solvation efficiency and enhance extraction selectivity (Tăbărasu *et al.,* 2023). The method has been applied at 60°C and pressures of 180 or 250 bar, using CO_2 volumes of 20, 50 and 100 L, with a maximum oil yield of 6.9% was reported (Hedayati *et al.,* 2025). In another study, extraction was conducted at temperatures below 60°C to minimise thermal degradation and preserve thermolabile constituents in the extract (Perović *et al.,* 2025).

The extraction yield has been reported to depend on interactions between pressure and CO_2 flow rate, as well as between temperature and CO_2 flow rate (Tyskiewicz *et al.,* 2019). Moreover, CO_2 is considered a moderately non-flammable, non-explosive and non-toxic solvent that is low-cost, available in high purity and can be readily removed from extracts through simple depressurization below its critical point (Chiaia *et al.,* 2025).

7.2 Microwave-assisted extraction

The principle of microwave-assisted extraction is based on the transfer of energy through an electric field, which interacts with polar compounds to induce dipole rotation and realignment with the applied field. Its key benefits include simple operation, low energy consumption, shorter extraction time and improved essential oil yield

(Bodea *et al.,* 2025). The resulting molecular motion generates heat (Sethunga *et al.,* 2022). It primarily facilitates cell disruption by rapidly heating the intracellular water, thereby increasing internal pressure, which results in the rupture of secretory tissues and the release of aromatic organic compounds (Chiaia *et al.,* 2025). The microwave frequency typically ranges between 300 MHz to 300 GHz. In the extraction process, microwave energy acts as a non-contact heating source, enabling faster extraction, improved energy efficiency and higher recovery compared to conventional techniques (Hegazy *et al.,* 2025). A multimode microwave reactor operating at 2.45 GH$^+$, with a maximum power output of 1000 W, was utilized for the extraction process. The temperature was continuously monitored using an external infrared sensor to ensure controlled heating conditions. The resulting distillate was continuously condensed using a clevenger apparatus positioned outside the microwave cavity (Liu *et al.,* 2018). In microwave-assisted extraction of Lavender oil, the yield is not consistent and can vary with several factors, including the quality and amount of Lavender flowers used, the type and concentration of the solvent and the extraction duration. Reported yields range from 0.6% to 2.5% of the dry mass of Lavender flowers processed using this method (Patil and Waghmare, 2024).

7.3 Ultrasound-assisted extraction

Ultrasound-assisted extraction is an effective approach that provides higher extraction yields in a shorter time and at a lower temperature, primarily due to improved mass transfer efficiency and decreased solvent use (Sethunga *et al.,* 2022). The advantages of ultrasound application include minimal impact on extractable compounds, reduced or eliminated use of organic solvents and shorter extraction time (Stratakos and Koidis, 2016). The frequency of ultrasound-assisted extraction ranges between 20-50 KH$^+$ and produces a combination of effects such as cavitation, vibration, fragmentation and mixing (Zhou *et al.,* 2023). The ultrasound waves within the solvent induce alternating compression and rarefaction cycles, resulting in pressure variations that promote the formation of cavitation bubbles in the aqueous phase. This cavitation process facilities the movement of the liquid phase into plant cells, thereby enhancing the extraction efficiency of essential oils (Hedayati *et al.,* 2025). The plant raw material is immersed in water or an appropriate solvent such as methanol or ethanol and simultaneously subjected to ultrasound treatment. This approach has been extensively used for the extraction of essential oils (Rassem, 2016). It has been applied to dried Lavender flowers using an ethanol-water mixture (70:30, w/w) at a 1:40 solvent-to-material ratio. However, this method required relatively large volumes of organic solvent to process small quantities of raw material (Zanotti *et al.,* 2023). Ultrasound has also been widely applied for the extraction of phenolic compounds (Dobros *et al.,* 2023).

7.4 Enzyme-assisted extraction

In enzyme-assisted extraction, specific enzymes facilitate the release of bioactive compounds from plant tissues. This approach is considered environmentally safe and is preferred because it avoids the use of denaturing agents such as heat, light or solvents (Panigrahi *et al.,* 2025). Enzymes are obtained from bacteria, fungi, animal organs or vegetable and fruit extracts for the extraction of essential oil (Puri *et al.,* 2012). Enzyme-assisted extraction utilises enzymes such as cellulase, pectinase, hemicellulose and protease to break down plant cell wall components, thereby facilitating the release of intracellular compounds (Vimal *et al.,* 2025). Enzyme assisted extraction offers advantages, including low solvent consumption, environmental friendliness and mild processing conditions, thereby reducing reliance on harmful solvents while improving extraction efficiency and yield (Cao *et al.,* 2025). The different Lavender extraction methods along with their mechanism, advantages and yield are compared in Table 2.

Table 2: Comparative overview of essential oil extraction methods

Method of extraction	Primary mechanism	Advantages	Yield	References
Hydrodistillation	Azeotropic distillationplant material is soaked in water.	Standardized method, simple apparatus.	2.5% (v/w) yield.	Solomakou *et al.,* 2025; Rassem, 2016; Rezazadeh Sh *et al.,* 2008
Steam distillation	Direct steam exposure, plant material not immersed.	Protects thermo-sensitive compounds.	Higher antioxidant concentrations.	Rassem, 2016; Sethunga *et al.,* 2022; Aziz *et al.,* 2018
Solvent extraction	Leaching sequential penetration, dissolution and diffusion.	Effective for flower extracts dissolution of soluble constituents.	Influenced by the heat type and the solvent purity.	Perović *et al.,* 2025; Sethunga *et al.,* 2022 Patil and Waghmare, 2024
Supercritical CO_2 extraction	Supercritical solvation; precise control	Eco-friendly, non-toxic, maintains stability of volatiles.	Maximum yield of 6.9% reported.	Zanotti *et al.,* 2023; Hedayati *et al.,* 2025; Chiaia *et al.,* 2025
Microwave-assisted extraction	Dipole rotation; rapid internal heating.	Shorter extraction time-low energy, consumption.	0.6% to 2.5% yield.	Bodea *et al.,* 2025; Chiaia *et al.,* 2025; Patil and Waghmare, 2024
Ultrasound-assisted extraction	Cavitation, vibration, fragmentation and mixing.	Improved mass transfer efficiency minimal impact on compounds.	High efficiency for essential oil and phenolic compounds.	Sethunga *et al.,* 2022; Zhou *et al.,* 2023; Hedayati *et al.,* 2025
Enzyme-assisted extraction	Enzymatic breakdown of cell wall components.	Environmentally safe and avoids denaturing agents.	Enhanced extraction efficiency and yield.	Panigrahi *et al.,* 2025; Vimal *et al.,* 2025; Cao *et al.,* 2025

8. Optimization of extraction parameters

8.1 Effect of solvent type and polarity

Solvent polarity is a key factor affecting the extraction of phenolic and flavonoid compounds from *L. stoechas*. Among the solvents examined, chloroform showed the highest efficiency in recovering polyphenols and flavonoids, followed by ethyl acetate highlighting the need for suitable solvent polarity to achieve optimal extraction. Higher concentrations of phenolics and flavonoids were closely linked to stronger antioxidant activity. These findings indicate that Lavender is a valuable natural source of bioactive antioxidant with potential use in food, pharmaceutical and cosmetic applications (Lahmar *et al.,* 2023). The composition and yield of these essential oils are highly dependent on the extraction method employed. Traditional hydrodistillation and microwave-assisted hydrodistillation have been compared, showing similar qualitative and quantitative profiles in terms of major constituents like α-terpinolene and borneol (Kýrkýncý *et al.,* 2024). In addition, solvent environment and extraction conditions also influence the recovery of volatile compounds. For instance, a green ultrasound-assisted supercritical CO_2 method was found to efficiently isolate Lavender essential oil, tripling the yield of linalyl acetate compared to hydrodistillation and achieving high selectivity for linalool and linalyl acetate (Wei *et al.,* 2024). Solvent type and polarity significantly affected the green extraction of antioxidant phenolic compounds from *L. angustifolia* using ultrasound-assisted extraction. Among the natural deep eutectic solvents evaluated, the choline chloride-glycerol system (1:2) exhibited superior extraction efficiency compared with conventional aqueous ethanol and methanol, indicating the importance of solvent polarity in enhancing phenolic and flavonoid recovery. The optimized natural deep eutectic solvents (NADES) system yielded high phenolic content and antioxidant capacity, demonstrating its effectiveness as a sustainable solvent for Lavender bioactive compound extraction (Hamza Alasalvar and Zeliha Yildirim 2021).

8.2 Influence of temperature, pressure and time

The yield and compositional quality of essential oil in *L. angustifolia* are strongly influenced by environmental conditions, especially temperature and rainfall. The highest oil accumulation typically occurs when about 60% of the plants are in bloom, temperatures remain above 26°C and there has been no rainfall for at least ten days before harvesting (Hassiotis *et al.,* 2014). Drying temperature has a strong impact on both the yield and chemical composition of the essential oil. Drying at 35°C helps retain a higher oil content, whereas higher temperatures decrease the overall yield and lead to increased levels of camphor and borneol, accompanied by a reduction in 1,8-cineole (Turkmen *et al.,* 2024). Supplementary irrigation contributes to increased fresh and dry leaf yield and enhances essential oil production. Moreover, the method of drying influences the chemical composition, with oven drying at 30°C, yielding higher essential oil and phenolic acid contents compared to natural drying (Salata *et al.,* 2020). The duration of distillation plays an important role in determining both the yield and chemical composition of the essential oil. A steam distillation period of two hours provides the maximum yield, with linalool and linalyl acetate as the main constituents, while shorter or extended distillation times alter their relative proportions (Wesolowska *et al.,* 2023). Storage under elevated temperature, light and oxygen exposure results in the degradation of sensitive compounds, including ocimenes and caryophyllene. Hence, preserving essential oil stability requires storage in an inert atmosphere and protection from light (Odak *et al.,* 2021). Supercritical CO_2 extraction of *L. angustifolia* phenolics, optimized by box behnken design, reveals that pressure, temperature 40 to 50°C, and time govern yields of 4.3-9.2 wt % with peak phenolic content and antioxidant activity at 55°C, 298 bar and 45 min (Tyskiewicz *et al.,* 2019). Supercritical CO_2 extraction of *L. angustifolia* essential oils rich in linalool and linalyl acetate at 180 to 300 bar and 40-60°C yields a peak at 250 bar/60°C, further enhanced by a 0.2 % v/v ethanol cosolvent. Gas chromatography mass spectrometry profiling identified dominant volatiles with robust antioxidant activity, surpassing those of Soxhlet extracts for nutraceutical and biomedical applications (Sanchez *et al.,* 2024).

9. Analytical techniques for characterization of bioactive compounds

Chemometric models built on GC-MS data can classify Lavender oils into high- and low-quality grades with 100% correct prediction, using 15 key marker compounds (Beale *et al.,* 2017). Mid-IR ATR-FTIR spectroscopy plus PCA and PLS quantifies adulteration of Lavender oil with vegetable oils up to 0-50%with high accuracy (Truzzi *et al.,* 2021). NIR, mid-IR and raman spectra combined with PCA/PLS-DA allow 100% discrimination between Lavender vs. lavandin and among several varieties for traceability and quality control (Lafhal *et al.,* 2016). Integrated GC/MS, NMR and chemometrics (Q-index) detect adulteration and poor-quality Lavender oils, with authentic samples showing Q-index >100 (Wang *et al.,* 2021).

9.1 Gas chromatography-mass spectrometry analysis

Gas chromatography-mass spectrometry (GC-MS) is widely used to identify constituents of essential oils. It is a simple and efficient technique that provides rapid results ad is routinely applied in essential oil analysis. The GC-MS profile serves as a chemical fingerprint for a specific batch, allowing the oil properties to be inferred from its composition and, in most cases, indicating its purity (Azizl *et al.,* 2018).

Chiral gas chromatography-mass spectrometry is a valuable technique for essential oil authentication, as chiral columns enable the separation of enantiomers and the determination of characteristic ratios linked to biological origin. This method can detect Lavender oil adulteration with synthetic linalool, linalyl acetate, lavandin oil or grapefruit and minor constituent profiling can further differentiate oils by geographical origin or harvest season (Beale *et al.,* 2017). Lavender essential oil obtained from fresh aerial parts by hydrodistillation yielded 1.3% (v/m, ml/g). Gas chromatography mass spectrometry analysis was performed using HP-5 ms, HP-INNO Wax columns and relative contents were calculated from normalized peak areas with a 0.8 % integration threshold. A total of 40 compounds were identified, representing 92.03% of the volatiles. The oil was rich in esters (43.23%) and linalyl acetate (12.68%) as the main constituents. The isolated compounds were further characterized by NMR (Dong *et al.,* 2020).

The relative percentage of each compound was determined by dividing its integrated ion peak area by the total area of the total ion chromatogram (TIC) and expressing the result as 100% (Vârban *et* *al.,* 2022). For breeding programs of *L. angustifolia* aimed at essential oil production, reliable comparison of flower volatile profiles across large plant populations is required. A comparative gas chromatography mass spectrometry method based on standardized flower sampling and direct solvent extraction has shown good reproducibility, revealed developmental changes in volatiles and demonstrated minimal diurnal and short-term variation, making it suitable for routine analysis in breeding populations (Zagorcheva *et al.,* 2016). Linalool and linalyl acetate were the most prominent compounds, although their relative levels varied across extracts (Debczak *et al.,* 2022).

9.2 Gas chromatography analysis

International organization for standardization 11024 outlines a gas chromatographic method for profiling essential oils based on characteristic compounds used to assess quality. The approach relies on comparison with an authenticated reference standard after peak integration and alignment, requires skilled analytical expertise and can be time consuming when multiple samples from different batches are analyzed (Beale *et al.,* 2017). The chemical components present in the Lavender extracts were identified by matching their gas chromatography retention indices and mass spectra. The amounts of individual essential oil constituents were then quantified using a gas chromatography 2010 equipped with a flame ionisation detector and an AT-5 capillary column (5% phenyl, 95% dimethyl siloxane; 30 m × 0.25 mm i.d., 0.25 µm film thickness), with concentrations calculated by area normalisation using electronic integration (Danh *et al.,* 2013).

9.3 High performance liquid chromatography (HPLC)

Compound identification by HPLC was performed using a waters e2695 (Alliance HPLC system) equipped with a 2998 PDA detector. Phenolic compounds were separated on an ACE Super C18 column (250 mm × 4.6 mm, 3 µm). The mobile phase comprised solvent A (0.1% v/v trifluoroacetic acid in water) and solvent B (acetonitrile) (Mykhailenko *et al.,* 2025). Compounds were identified by matching them with authentic standards and assessing their exact molecular masses, fragmentation profiles, isotopic distributions and retention times. Ultrahigh performance liquid chromatography-MS/MS measurements were conducted using electrospray ionization. All extracts were analyzed in duplicate under both negative and positive ionization modes and full-scan spectra were collected across an m/z range of 100-1500 Da (Zengin *et al.,* 2023).

9.4 Fourier transform infrared (FTIR) spectroscopy

Fourier-transform infrared (FTIR) spectroscopy is a widely preferred spectroscopy-based method for the authentication of Lavender essential oil. It assesses molecular absorption of infrared radiation, providing information on functional groups (Rashede *et al.,* 2025). Essential oils are concentrated, homogeneous mixtures of volatile compounds and typically contain complex chemical profiles with more than 100 constituents in each species (taxon). Their FTIR spectra can be difficult to interpret because signals from different components overlap and several vibrational modes occur together, while major constituents usually contribute no more than 25% of the overall composition (Agatonovic-Kustrin *et al.,* 2020).

9.5 Near infrared and mid-infrared spectroscopies

Near-infrared (NIR) spectroscopy combined with chemometric analysis is a rapid and non-destructive technique for the characterization, quality control and authentication of Lavender essential oil (Lafhal *et al.,* 2016). Near infrared and mid infrared datasets are treated as independent blocks and quantified using PLS regression. Lavender oils are rich in linalool and linalyl acetate, with moderate terpenes and variable 1,8-cineole and camphor. Five constituents were quantified and compared using separate and multiblock PLS models (Dupuy *et al.,* 2014). Lavender and lavandin essential oils and liquid standards were recorded in a 2 mm quartz cell from 4000-10,000 cm^{-1} (4 cm^{-1} resolution, 64 scans) using a nicolet antaris II near infrared spectrometer with an InGaAs detector. Background spectra were collected using an empty cell at 21°C. Solid standards (camphor and borneol) were measured in diffuse reflectance mode with an integrating sphere under the same conditions. Near infrared spectra were recorded using a near infrared Flex N500 with a liquid cell, employing 50 µl samples in 0.20 mm path-length cuvettes. Duplicate transmittance measurements were acquired by averaging 32 scans at a spectral resolution of 4 cm^{-1} over the 10,000-4,000 cm^{-1} range (Tankeu *et al.,* 2014). Analytical techniques for characterization, authentication and quality evaluation of Lavender essential oil and bioactive compounds are given in Table 3.

Table 3: Analytical techniques for characterization, quality evaluation of Lavender essential oil and bioactive compounds

Techniques	Principle/application	Advantages	References
Gas chromatography mass spectrometry (GC-MS)	Identifies and profiles volatile constituents of essential oils based on retention time and mass spectra	Provides rapid, simple and efficient analysis, acts as a chemical finger print for purity and composition assessment	Azizl *et al.,* 2018
Chiral GC-MS	Uses chiral columns to separate enantiomers for authentication studies	Detects adulteration with synthetic linalool, linalyl acetate, lavandin oil	Beale *et al.,* 2017
GC-MS with HP-5 ms and HP-INNOWAx columns	Analysis of Lavender oil volatiles after hydrodistillation	Identified 40 compounds representing 92.03% volatiles, esters (43.23%) and lavandula acetate (12.68%) were major compounds	Dong *et al.,* 2020
Comparative GC-MS method	Standardized flower sampling and solvent extraction for breeding studies	Good reproducibility with minimal diurnal variation, suitable for routine breeding population analysis	Zagorccheva *et al.,* 2016
Gas chromatography (GC)	Quality assessment based on characteristic compounds and retention indices	Requires authenticated standards and expert analysis, useful for quantification of essential oil Constituents	Beale *et al.,* 2017; Danh *et al.,* 2013

High performance liquid chromatography (HPLC)	Separation and identification of phenolic compounds using C18 column and PDA detector	Accurate identification through molecular mass, fragmentation profile and retention time analysis	Mykhailenko *et al.,* 2025
Ultrahigh performance liquid chromatography-mass spectrometry (UHPLC-MS)	Electrospray ionization with full scan spectra analysis	Duplicate analysis under positive and negative ionization modes over m/z 100-1500 Da range	Zengin *et al.,* 2023
Fourier transform infrared spectroscopy (FTIR)	Measures infrared absorption to identify functional groups	Rapid authentication technique; interpretation is difficult due to overlapping signals from multiple constituents	Rashede *et al.,* 2025; Agatonovic kustrin *et al.,* 2020
Near-infrared spectroscopy	Non-destructive spectroscopic method combined with chemometrics	Rapid quality control and authentication of Lavender oil	Lafhal *et al.,* 2016
NIR and mid-IR spectroscopy with PLS regression	Quantification of Lavender oil constituents using multiblock analysis	Quantified linalool, linalyl acetate and other terpenes with good comparative modelling	Dupuy *et al.,* 2014
NIR spectroscopy using nicolet anataris and NIR flex N500	Spectral analysis of Lavender and lavandin oils	High resolution spectra obtained with duplicate scans and controlled conditions for accurate controlled conditions for accurate characterization	Tankeu *et al.,* 2014

10. Stability and shelf-life of standardized extracts

The stability and shelf-life of Lavender essential oil are strongly influenced by factors such as temperature, light exposure and oxygen, which accelerate degradation *via* processes such as auto oxidation and hydroperoxide decomposition. Storage at low temperatures, particularly under refrigeration conditions, help preserves the primary quality of Lavender essential oil by reducing the loss of volatile compounds (Najafian, 2016). Encapsulation protects sensitive substances by enclosing a core material (payload/internal phase) within a wall material (shell/carrier). Effective protection depends on the selection of suitable wall materials, typically biodegradable polymers, with natural polymers being preferred because of their safety and biocompatibility. Proteins, polysaccharides, lipids and their composites are commonly used for encapsulating essential oils. (Hedayati *et al.,* 2024).

Encapsulation of Lavender essential oil is system such as liposomes, emulsions, spray-dried microcapsules, hydrogels, nano emulsions and nanostructured carriers improves stability, protects volatile constituents and enables controlled release during storage. Spray drying with gum arabic/maltodextrin or similar wall materials yields microcapsules with high encapsulation efficiency and good oil protection, facilitating conversion to essential oil into stable powders for food, cosmetic or pharmaceutical application (Pilicheva *et al.,* 2021; Bajac *et al.,* 2025). Hydrogel particles and eggshell based protein-polysaccharide microcapsules further delay Lavender essential oil release and create sustained release system by forming dense cross-linked networks around the oil (Deng *et al.,* 2020; Zhang *et al.,* 2024). Essential oil stability is strongly influenced by temperature and light exposure. According to the arrhenius equation and Van't hoff rule, increasing temperature accelerates reaction rates, leading to faster hydroperoxide breakdown and auto oxidation, while oxygen solubility at lower temperature also affects stability. In addition, exposure to ultraviolet and visible light promotes auto-oxidation through the formation of alkyl radicals, with monoterpenes generally degrading more rapidly than other components. The extent of light induced degradation varies among different plant species (kumar *et al.,* 2024).

11. Future prospects

The future of Lavender (*Lavandula* spp.) research focuses on integrating advanced extraction technologies, molecular approaches and sustainable production systems to enhance the yield and quality of bioactive compounds. Green extraction methods such as supercritical CO_2, microwave-assisted and enzyme assisted techniques are expected to be optimized using artificial intelligence and process modelling to improve efficiency, selectivity and industrial scalability. Advances in metabolomics, genomics and biotechnology will improve understanding of biosynthetic pathways of key compounds like linalool and linalyl acetate, enabling the development of high yielding cultivars with improved phytochemical profiles. Nanotechnology based delivery systems and encapsulation techniques offer promising strategies to enhance the stability, bioavailability and controlled release of Lavender bio actives, increasing interest in natural deep eutectic solvents (NADES) supports the shift toward ecofriendly extraction process. Rapid, non-destructive analytical tools such as NIR spectroscopy combined with chemometrics will further strengthen real time quality control and authentication. Future research should also explore lesser-known Lavender species and expand their applications in pharmaceuticals, food preservation and agriculture. Overall, interdisciplinary approaches integrating green chemistry, biotechnology and advanced analytical will drive sustainable utilization of Lavender bioactive compounds.

12. Conclusion

Lavender *(Lavandula* spp.) is a valuable aromatic plant rich in bioactive compounds particularly oxygenated monoterpenes such as linalool, linalyl acetate which contribute to its characteristic aroma and biological activities. Genetic factors, cultivation practices, harvest stage and processing conditions strongly influence the chemical composition and quality of Lavender extracts. Extraction methods play an important role in determining yield, selectivity and compound stability. While conventional techniques such as hydrodistillation are widely used advanced methods including supercritical CO_2, microwave assisted, ultrasound assisted and enzyme assisted extraction provide improved efficiency, selectivity and preservation of thermolabile compounds. chromatographic and spectroscopic techniques support quality control, authentication and standardization of Lavender products. Sustainable and green extraction technologies are increasingly important because they reduce solvent use, energy consumption and environmental impact while improving extraction efficiency and product quality. Encapsulation and nano delivery systems further enhance the stability, bioavailability and controlled release of Lavender bioactive compounds expanding their applications in pharmaceuticals, cosmetic, food and agricultural industries. Future research should focus on nano-technology based formulations, AI assisted process optimization and ecofriendly green solvents such as natural deep eutectic solvents to improve industrial scalability and sustainability. Overall, the integration of sustainable extraction methods, advanced analytical techniques and innovative delivery systems highlights the significant industrial and therapeutic potential of Lavender bioactive compounds for further sustainable applications.

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Conflict of interest

The authors declared no conflicts of interest relevant to this article.

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