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Open Access REVIEW

Extraction of *Rosmarinus officinalis* and *Citrus bergamia* Essential Oils and Their Application in The Development of Novel Fragrances

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ABSTRACT

Rosmarinus officinalis (rosemary) and Citrus bergamia (bergamot) are two essential oils that are some of the most commercially important aromatic raw materials in the fragrance industry of the world. The critical review gives a detailed assessment of the main extraction methods used in these plant species, hydro distillation, steam distillation, cold-press expression, supercritical CO2 extraction, and microwave-assisted extraction, and critically evaluates their yields, chemical profiles, and sustainability indices. The volatile constituents of both oils, in particular, 1,8-cineole, camphor, and borneol in rosemary, and linalool, linalyl acetate, limonene, and bergapten in bergamot are the most commonly volatile and are addressed in the context of their olfactory properties, stability, and functional consideration to fragrance formulation. The review also looks at modern approaches in new fragrance creation, including molecular encapsulation, green solvent extraction, and chemo-enzymatic biotransformation and regulatory concerns in phototoxic furocoumarins in bergamot and IFRA guidelines. Recent developments in scent design with artificial intelligence, aroma profiling with GC-MS/olfactometry, and chemometrics, as well as are presented. The accruing literature highlights the critical and increasing role of such essential oils in developing advanced, bio-based, and health-conscious fragrance structures.

Keywords: *Rosmarinus officinalis; Citrus bergamia;* Essential oil extraction; Fragrance development; Hydrodistillation; Supercritical CO2; Linalool; 1,8-cineole; Green chemistry; Encapsulation.

INTRODUCTION

Essential oils (EOs) are volatile, biosynthetic, hydrophobic blends of secondary metabolites produced by aromatic vegetation mainly as chemical defenses against herbivores, pathogens and interspecific competition. It is projected that the world essential oil market will be USD 9.63 billion worth in 2023, and will rise to USD 8.6% at a compound annual growth rate in 2030 due to the growing need of natural and plant-derived ingredients in the personal care, aromatherapy, functional food and fine fragrance uses [1]. One of the hundreds of commercially traded oils is “Rosmarinus officinalis L. Citrus bergamia Risso & Poist and (rosemary). Due to their unique multidimensional olfactory profiles, proven bioactivities, and solubility with a wide range of fragrance accords, (bergamot) is placed in prime spots.

Rosmarinus officinalis is a perennial aromatic shrub that is native to the Mediterranean basin and a member of the family Lamiaceae. Its essential oil produced by cold expression of the pericarp of the fruit is primarily a monoterpene (1, 8 cineole), monoterpene (camphor), and monoterpene (borneol, Linalool) top note usually used in masculine cologne, functional fragrances, household products, and pharmaceuticals. On the other hand, Citrus bergamia is a frost-sensitive citrus It is a component of both the Eau de Cologne formula and modern Chypre, Floral, and Aromatic perfume groups, and it is the secret component of its signature scent, a floral-citrus bouquet with the background of linalool, linalyl acetate, and limonene [2].

Nevertheless, despite their centuries-old histories of application, there have been significant scientific drivers in the decade 20182025 in regard to optimization of extraction technologies and full chemical fingerprints elucidation through high resolutive chromatographic and spectroscopic methods as well as use of such oils in new fragrance engineering. The need to balance consumer locality of naturality with regulatory need of limiting allergenicity and phototoxicity of individual chemical substances, particularly, bergamot, bergapten (5-methoxypsoralen), has further accelerated research into the bergapten-free production of oils, microencapsulation and biotransformation-based methods of changing chemical profiles [3].

The review synthesizes and critically reviews peer-reviewed articles published since 2018 in the area of: (i) botanical and phytochemical profiles of the two plant species; (ii) extraction methods and their relative efficiency; (iii) chemical composition and olfactory characterization; (iv) current and future application in fragrance development; (v) safety, regulatory, and sustainability considerations.

Botanical and Phytochemical Profiles

Rosmarinus officinalis L.

Rosmarinus officinalis (syn. Salvia rosmarinus Spenn.) is an evergreen sub-shrub, 0.5-2.0m high and with needle-like, coriaceous leaves with the margins revoluted and flowers being small and bilabiate of a white to deep blue-violet color. The species demonstrates a high level of chemotypic diversity: at least four major chemotypes, i.e., 1,8-cineole, camphor, borneol, and verbenone, have been discovered, the relative proportions of which are controlled by altitude, photo-period, edaphic factors, and genetic composition [4]. The main organs of secretory concentration of essential oil are the leaf glandular trichomes, where the oil is contained in subcuticular cavities that burst under mechanical disruption of the trichomes to give the typical camphor-eucalyptol aroma.

A high concentration of non-volatile phenolic diterpenes (carnosic acid, carnosol, rosmanol), flavonoids (luteolin, apigenin, genkwanin), rosmarinic acid and the essential oil are also a part of the plant and have strong antioxidant and anti-inflammatory effects that supplement the fragrance properties of the plant in cosmetics.

Citrus bergamia Risso & Poit.

Citrus bergamia has a botanical name of Rutaceae, subfamily Aurantioideae. The tree contains oval and pear-shaped fruits whose diameter measures 68 cm and the pericarp turns yellow green to yellow in maturity. Genome research suggests that bergamot is a hybrid of a sour orange (C.aurantium) and a lemon or lime (C. limon/C. auantiifolia), yet taxonomy is vague [5]. It is secreted in schizogenous cavities that are fundamental oil glands (hesperidia) and lodged in the flavedo (coloured outer pericarp layer). The time of harvest greatly influences the composition of the oil, and the oils of November and February are the ones that produce the most linalyl acetate and are the ones that have the most attractive olfaction [6].

One of the most important phytochemical differences of bergamot oil is that furanocoumarins, mainly bergapten (5-MOP), bergamottin, and bergaptol are present and provide strong phototoxicity. The production of furanocoumarins-free (FCF) bergamot and precise quantification of the compound are under intense research because of the regulatory requirement to prohibit or determine the content of the compounds [2].

Extraction Methodologies

1. Hydrodistillation and Steam Distillation

Hydrodistillation (HD) and steam distillation (SD) remain the most widely applied industrial methods for rosemary essential oil extraction. In HD, plant material is submerged directly in water and heated, permitting co-distillation of water-immiscible volatile compounds. SD separates the plant matrix from the boiling water by passing steam through it, reducing thermal degradation of heat-sensitive constituents. Comparative studies indicate that SD consistently delivers higher yields (1.8–2.6% w/w DW) than HD (1.2–2.0% w/w DW) for rosemary, with SD-derived oils exhibiting elevated 1,8-cineole content and improved olfactory freshness owing to reduced artifact formation [3][4].

In the case of bergamot, HD and SD are not used commercially much because they ruin the fragile citrus top notes and volatilize thermolabile esters like linalyl acetate. Such thermal processes are, nevertheless, applied to research level preparation of bergamot hydrolyte fractions, as well as manufacture of bergamot rectified oil (re-distilled to lower terpene content and enhance solubility in alcohol-based perfume bases) [6].

2. Cold-Press Expression

The industry-standard process of recovering bergamot essential oil is cold expression (also known as cold-pressing or mechanical expression). The oil glands of the fresh pericarp are broken mechanically in the pelatrice process either by rotating abrasion cups (ecuelle a piquer), or by centrifugation (3,0005,000 rpm) to obtain the aqueous phase (juice and cell sap). Even the oil of bergamot thus obtained can still retain all the non-volatile furanocoumarins and waxes that provide the oil with its characteristic opalescent appearance at room temperature, winterisation (chilling at -15degree) is often applied to remove waxes and improve clarity. Cold-pressed bergamot oil usually has 95-115 g/kg pericarp of essential oil [2]. Cold expression is inapplicable to rosemary due to the physical architecture of needle-like leaves lacking readily accessible from gland reservoirs analogous to citrus flavedo.

3. Supercritical Fluid Extraction (SFE-CO2)

SFE-CO2 has demonstrated itself to be a high-quality method to extract both species due to near-ambient temperatures (35-60 degree C) to extract oil, lack of residual solvents, adjustable selectivity by controlling pressure (80-500 bar) and produces oils with improved thermal stability characteristics. Selective extraction of sesquiterpene and diterpene fractions (beta-caryophyllene, alpha-cedrene) which are typically low in HD/SD oils with SFE at 90 bar, 40 degree C and concomitant extraction of antioxidant diterpenes (carnosic acid) amplifies the preservative qualities of the extract in the case of rosemary.

Comparative SFE studies on bergamot pericarp demonstrate that pressure modulation permits selective production of terpene-free bergamot fractions — rich in oxygenated compounds (linalool, linalyl acetate) — without the traditional fractional distillation steps required for terpene-free conventional expression oil. A 2021 study by Sicari et al. reported that SFE at 200 bar, 50°C yielded bergamot extracts with linalyl acetate content of 41.3% compared to 30.2% in cold-pressed oil, with undetectable bergapten levels, addressing both quality and phototoxicity concerns simultaneously.

4. Microwave-Assisted Extraction (MAE)

Microwave-assisted extraction (MAE) and solvent-free microwave extraction (SFME) have been confirmed in the extraction of rosemary EO to take 15 to 30 minutes compared to 3 4 hours (HD), with equal yield (1.6-2.2% DW) and better retention of oxygenated monoterpenes. Microwave irradiation heating rate (2,450 MHz) is not very selective in dislodging the secretory structures and in releasing volatile compounds, making it more effective than thermal gradient-based methods. Chemat et al. (2019) stressed that SFME is indeed a green technology of rosemary: the technology requires no solvent addition, and requires up to 70 percent less energy than HD to produce one, undiluted EO product that does not require azeotropic dehydration [11].

5. Ultrasound-Assisted Extraction (UAE)

UAE uses the principle of acoustic cavitation - formation, growth, and violent collapse of microbubbles in liquid media - to break the cell walls of plants and hasten mass transfer of volatile compounds into extraction solvent. Rosemary research has established that moderate temperatures (304 degree C) at moderate frequencies (UAE 2040Hz, 15-30min) yield EO production and compositions comparable to those produced by conventional HD with much less energy consumption [12]. UAE is especially favourable with respect to extraction of minor constituents that are thermolabile and are destroyed during the long hydrodistillation procedure.

6. Enzyme-Assisted Extraction (EAE)

Pre-treatment with cellulase, pectinase or hemicellulase before distillation has shown considerable EO yield increases of both rosemary (up to 28% increase) and bergamot pericarp (1522% increase) due to breaking down cell wall polysaccharide barriers and oil release in glandular structures. The extraction is performed by using enzymes at a controlled pH (4.5-5.5) and temperature (40-50℃) to maintain the activity of the enzymes and prevent chemical hydrolysis of the acid constituents of the estrangements like linalyl acetate [10]. The methodology is also in line with the principles of green chemistry as it allows for the use of lower distillation temperatures and times.

Chemical Composition and Olfactory Characterisation

Rosemary Essential Oil — Key Constituents

The chemical composition of rosemary EO includes more than 100 different volatile compounds, the large portion of which includes monoterpene hydrocarbons and oxygenated monoterpenes. The major constituent in most compositions is 1,8-cineole (eucalyptol), usually 15-55 percent of the total composition based on chemotype and geographical origin, and provides a penetrating, freshening and slightly medicinal quality that is important in functional and sport fragrance products. Camphor (8-30 % provides a strong, hard, cold scent to give herbal accords a unisex and male emphasis. Beta-pinene (2-9%) and alpha-pinene (5-20%) also provide resinous, woody and crisp forest-like aromas that are heavily used in the aromatic fougere arrangement.

Borneol (2-16%), bornyl acetate and verbenone provide soft, earthy and balsamic tones which provide tenacity and diffusion in fine fragrance blends. A recent GC-MS/olfactometry study by Jiang et al. established camphor, 1,8-cineole, borneol, and alpha-terpineol as the four compounds with the most odour activity values (OAV > 100) in rosemary EO and, thus, as character-impact compounds that affect overall olfactory perception.

Table 1. Major chemical constituents of Rosmarinus officinalis and Citrus bergamia essential oils (2018-2025 literature data ranges)

Compound	Plant Species	Range (%)	Olfactory Descriptor
1,8-Cineole (Eucalyptol)	*R. officinalis*	15-55	Fresh, eucalyptus, medicinal
Camphor	*R. officinalis*	8-30	Sharp, cold, camphorous
alpha-Pinene	*R. officinalis*	5-20	Crisp, piney, resinous
Borneol	*R. officinalis*	2-16	Earthy, balsamic, herbal
beta-Caryophyllene	*R. officinalis*	2-8	Woody, spicy, dry
Linalool	*C. bergamia*	6-18	Floral, lavender-like, sweet
Linalyl acetate	*C. bergamia*	28-42	Bergamot, floral, fruity-sweet
Limonene	*C. bergamia*	12-22	Citrus, fresh, zesty
gamma-Terpinene	*C. bergamia*	5-12	Citrusy, herbaceous
Bergapten (5-MOP)	*C. bergamia*	0.1-0.4	Non-odorous; phototoxic

Bergamot Essential Oil — Key Constituents

Bergamot EO is organoleptically characterized by a wonderful floral richness (linalool, linalyl acetate), citrus brightness (limonene, gamma-terpinene), and slight spicy-balsamic depth (beta-caryophyllene, neryl acetate). The quantitatively predominant oxygenated ester (28-42 percent), linalyl acetate, gives bergamot its signature bergamot smell, a sweetly floral, herbaceous-citrus smell, which has been the top-heart note of classical Colognes since the 18th century. In addition to its odorant role, Linalool (6 to 18 %) also has proven anti-anxiety and sedative properties in low doses, which places bergamot oil at the border of perfumery and aromatherapeutic action [2].

Recent GCxGC-ToFMS studies published 2019-2024 have separated peaks previously co-eluting in bergamot EO and so far have identified over 350 trace compounds including sesquiterpenes (betabisabolene, germaacrene D), esters (geranyl acetate, neryl acetate), and aliphatic aldehydes (de The chemometric PCA analyses show distinct separation of geographic ecotypes (Reggio Calabria, Locri, Palmi) by ratios of linalyl acetate to limonene and specific sesquiterpene indicators [6].

Applications in Novel Fragrance Development

1. Classical Fragrance Architectures and Role of Both Oils

The concept of a structured fragrance — articulated through a pyramidal top-heart-base architecture — places rosemary and bergamot predominantly in the top-note and heart-note segments due to their volatility profiles (log P: rosemary EO major components 2.1–4.3; bergamot EO major components 2.5–3.9). In Fougere accords — the structural backbone of many masculine fine fragrances - rosemary oil serves as the definitive herbal-aromatic element alongside lavender and oakmoss. In Cologne and Citrus fragrance families, bergamot provides the luminous, zesty opening that defines the genre, while in Chypre compositions it bridges the gap between citrus top notes and mossy-amber bases.

Contemporary perfumers increasingly employ these oils as part of natural, bio-based fragrance strategies demanded by clean beauty and sustainability-conscious consumers. Market surveys indicate that 73% of European consumers prefer fragrances labelled as containing natural essential oils, with bergamot and rosemary among the five most positively perceived natural ingredients [7].

2. Microencapsulation and Controlled Release

One of the technical problems in the use of volatile essential oils in fabric conditioners, cosmetic products, and functional textiles is that the oil soon evaporates and loses stability when subjected to light, oxygen, and alkaline pH. Microencapsulation - entrapment of EO droplets between polymeric or lipid shells of 1-500 micrometre diameter - can greatly increase the olfactory life by offering a physical barrier that releases the fragrance material only after mechanical friction, temperature variation or exposure to moisture.

Inclusion complexes of bergamot and rosemary EOs based on cyclodextrin have been widely characterized within the period 20182025. A 2022 study by Ambrogi et al. showed that the complexation of bergamot EO (1:1 molar ratio) with beta-cyclodextrin decreased the evaporation rate of the linalyl acetate by 68% at 25 o C compared to the free oil, and also removed bergapten phototoxicity since the larger furanocoumarin molecule In a comparable study, EO-loaded poly(lactide-co-glycolide) (PLGA) nanocapsules displayed long-term antimicrobial efficacy (28 days) in textile use [8].

Gum arabic, maltodextrin, whey protein isolate, shellac, and zein have been found to be useful as wall materials in encapsulation studies and spray-drying, coacervation, and interfacial polymerisation are key encapsulation methods. Wall material selection is the critical factor in determining encapsulation efficiency (usually 60-95 percent), core loading (10-40 percent), and release kinetics.

3. Terpene-Free and Bergapten-Free Oils in Fine Fragrance

A molecular distillation or liquid-liquid extraction method to isolate terpene-free bergamot oil (BEO-TF) provides better dissolvability in hydroalcoholic perfume bases (usual dilution 10 to 30 percent alcohol), better light stability (less photo-oxidation of monoterpene hydrocarbons) and better tenacity due to the enriched concentration of higher-m According to the guidelines of the International Fragrance Association, the maximum concentration of bergapten in leave-on cosmetic products is 1 ppm, which imposes a necessity to use FCF bergamot in the formula of sunscreens, hairs, and lotions [9].

Recent studies have optimized the production of FCF bergamot oil using molecular distillation (Saporita et al., 2021), with residual bergapten levels lower than the GC-MS limit of detection (<0.5 ppm) and >92% of the original linalyl acetate content. The single-step process that has been suggested to provide similar quality metrics with reduced thermal stress on the oil is supercritical CO_2 fractionation at different pressures.

4. Biotransformation and Bioconversion Approaches

Biotransformation is a new frontier in the derivatization of EO constituents with the objective to obtain new aroma chemicals with improved or altered sensory properties. Rhodotorula minuta and Bacillus cereus strains have oxidized 1,8-cineole of rosemary to produce 2-exo-hydroxy-1,8-cineole and 2-endo-hydroxy-1,8-cineole, which have very different creamy, coconut-like odour properties than the parent oil, and has greatly enriched the arom Linalyl propanoate, linalyl butyrate, and linalyl caprate, homologous series of esters with increasingly fruitier and creamier top notes, have been prepared by enzymatic transesterification of linalool with different fatty acid vinyl esters with Candida antarctica lipase B (Novozyme 435) [10].

5. Sustainability, Green Chemistry, and Supply Chain Considerations

The world fragrance market is under pressure to embrace sustainable supply chains, lower carbon footprint, and curb the ecological effects of extensive harvesting of plant materials. The rosemary collected by North African and Southern European communities as a wild plant is under more pressure due to habitat degradation, the intensified of drought caused by climate change, and the over-exploitation of the plant to extract essential oils. In a life cycle assessment (LCA) comparing HD, SFE, and MAE on producing rosemary EO, it has been established that MAE uses less energy (65%), less water (80%), and emits less CO2 equivalent (55) compared to conventional HD at pilot scale [11].

The production of bergamot is associated with unique sustainability issues: the extreme localization of the production area in Reggio Calabria makes the supply chain susceptible to climatic changes, outbreak of diseases (citrus tristeza virus, Phytophthora root rot), and conversion of agricultural land. Legal protection of traditional methods of production is offered by Protected Designation of Origin (PDO) status of Bergamotto di Reggio Calabria essential oil, granted in 2001, although limiting the growth of certified supply. The production of organic bergamot, which is growing according to sustainability requirements of retailers, sells at a 25-40 percent premium compared to conventional production [2].

A considerable opportunity is waste valorization: rosemary distillation hydrolate (aromatic water) has significant concentrations of water-soluble aroma compounds (verbenone, alpha-terpineol hydrate, camphor derivatives) and non-volatile phenolics with anti-oxidant properties, and bergamot pressing residues (pomace) have a large amount of pectin, pol The circular biorefinery model, in which each fraction of the plant material is valorized, is economically and environmentally advantageous and has been promoted as the model of choice in producing EO in the 2020s [11][13].

Recent Advances and Future Directions (2021–2025)

These five years between 2021 and 2025 have been one of the most paradigm-altering years in the science of rosemary and bergamot essential oils. Extraction efficiencies of dynamic pressurized liquid extraction (DPLE) using ethanol as GRAS solvent have been shown in less than 30 minutes with the added benefit of co-extracting phenolic antioxidants of rosemary that will improve the performance of cosmetic formulations. With the hyphenation of ion mobility spectrometry-mass spectrometry (IMS-MS) in analytical chemistry, it is now possible to track EO composition on-line in real-time during distillation and selectively enrich a process dynamically [14].

The nano-emulsions formulation technology has enabled the formulation of stable aqueous dispersions of 50200 nm size droplet rosemary and bergamot EOs which has considerably improved bioavailability and skin penetration of EO in cosmetic applications. In a 2023 investigation, bergamot EO nano-emulsions containing the same concentration of the bioactive aroma compounds as conventional emulsions showed 3.4-fold higher transdermal flux of linalool through excised human skin, paving the way to the use of fragrance-based cosmeceuticals with intentionally designed dermal delivery of bioactive aroma compounds [8].

In synthetic biology, bergamot biosynthetic pathway Linalool, limonene and 1,8-cineole have been synthesized in microbial fermentation, which theoretically can be scaled to avail a theoretically inexhaustible supply of these substances that is independent of variability in agriculture. High concentrations of linalol at enantiomeric excesses (ee) of over 99.9% of the natural R- (-) conformation have been reported to be produced by fermentation, at 10-L scale, and is now being optimised to be economically viable at a cost less than linalool produced by natural EO reactions. The developments are potentially capable of changing the dynamics of the supply chain of both natural and nature-identical aroma chemicals.

The identified priorities of future research in the literature of 2023–2025 include: (i) a systematic explanation of trace olfactophore compounds at concentrations less than 0.1% by odorant dilution analysis (AEDA) and recombination studies"; (ii) temporal evaluation of fragrance performance and EO stability under commercial conditions of product storage.

CONCLUSION

The paper has critically reviewed the extraction procedures, chemical formulations, olfactory characterisation, and fragrance development use of the Rosmarinus officinalis and Citrus bergamia essential oils within the 2018–2025 scientific literature. The two oils hold a place of exceptional significance in the world of fragrance, based on their complex chemical structure, multifunctional biological role, and long cultural heritage in the world of perfumery.

Steam distillation and hydrodistillation are still the most popular methods of extracting rosemary oil in industries, and cold-press expression is still the most popular approach to extracting bergamot, but the emerging technologies, such as SFE-CO2, MAE, UAE, and enzyme-assisted extraction, present very promising opportunities in terms of sustainability, energy conservation, and compositional finesse. Both rosemary and bergamot have had their chemical landscapes of their oils greatly enhanced by high-resolution analytical innovations that have indicated all the minor constituents that have always been present but not readily visible before with their major olfactory and functional potential.

Both oils remain a source of innovation in fragrance development, in both classical accord construction, functional neuroscent, microencapsulated release technology, and AI-assisted formulation, and are also undergoing an ever-tougher regulatory landscape in terms of allergenicity and phototoxicity. The gradual combination of green chemistry, biorefinery, and biotransformation concepts places the science of these essential oils at a moving junction between natural product chemistry, sensory science, consumer psychology, and sustainability.

With the dual demands of naturality and safety taking their place in the fragrance industry, the Rosmarinus officinalis and Citrus bergamia essential oils are not a thing of the past but rather an animate object of scientific rediscovery, oils whose complete olfactory, biological, and commercial possibilities are yet to be tapped.

CONFLICT OF INTEREST

Authors declare for none conflict of interest.

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