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Traditional Uses, Phytochemical Composition, and Pharmacological Activities of *Pelargonium graveolens* Essential Oil: A Comprehensive Review

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Abstract

Background: *Pelargonium graveolens* essential oil (PGEO), commonly known as rose geranium oil, has been widely utilised in traditional medicine for managing inflammatory disorders, microbial infections, skin diseases, metabolic complications, and respiratory illnesses. Owing to its rich phytochemical composition and broad therapeutic potential, PGEO has enticed increasing scientific attention in pharmaceutical, cosmetic, and food-related applications. **Aim:** This comprehensive review aims to systematically summarise the traditional uses, phytochemical composition, extraction approaches, and pharmacological activities of PGEO, with particular importance on its therapeutic potential and safety aspects. **Methods:** Literature published between 2000 and 2025 was systematically gathered from electronic databases including PubMed, Web of Science, ScienceDirect, Springer, Wiley Online Library, and Google Scholar. Similarly, the relevant peer-reviewed articles focusing on ethnomedicinal applications, phytochemistry, extraction methods, biological activities, and toxicity profiles of PGEO were critically analysed. **Results:** The current findings show that PGEO incorporates diverse bioactive constituents, predominantly citronellol, geraniol, citronellyl formate, linalool, and menthone, which significantly contribute to its pharmacological effects. Experimental studies have revealed that PEGO possesses significant antioxidant, antimicrobial, anti-inflammatory, antidiabetic, anti-cancer, antidepressant, and anti-arthritic properties in both *in vitro* and *in vivo* models. Hydro-distillation and steam distillation were documented as the most commonly applied extraction methods. Yet, geographical origin, environmental factors, and extraction techniques often modify the essential oil compositions and might influence biological efficacy. Additionally, limited clinical evidence and inadequate toxicity standardisation remain major disputes for therapeutic translation. **Conclusion:** PGEO embodies a promising natural source of biologically active compounds, potentially with rich applications in pharmaceuticals, nutraceuticals, cosmetics, and complementary medicine. However, concerning human applications, safety, efficacy, and therapeutic reliability are yet to be validated through standardised toxicological investigations, mechanistic studies, and clinical trials.

Major Findings: PGEO possesses various pharmacological activities, principally attributed to citronellol, geraniol, and linalool. Though existing solid experimental evidence, clinical validation, and toxicity normalisation are fundamental for its therapeutic development.

Keywords: Antioxidant, Anti-inflammatory, Arthritis, Essential Oil, *Pelargonium graveolens*, Pharmacological Activity.

Abbreviations: COX - Cyclooxygenase; IL-1 - Interleukin-1; IL-6 - Interleukin-6; Lipoxygenase - LTB4; LOX - Leukotriene B4; NO· - Nitric Oxide Free Radicals; PGE2 - Prostaglandin E2; PLA2 - Phospholipase A2; TNF-α - Tumor Necrosis Factor-α.

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1. Introduction

The World Health Organisation (WHO) acknowledges the critical role that herbal treatments play in attaining the objective of "Health for All"[1]. Traditional medicine is practised differently in every place for a multitude of reasons, including history, culture, philosophy, and individual attitudes[2]. Herbal remedies are gaining popularity as safer alternatives to synthetic drugs for managing various diseases. In comparison to synthetic medications, they do not have as many negative effects on the human body. Even with all of the advantages that modern synthetic treatments offer, people still prefer plant-based natural therapies over synthetic pharmaceuticals. Currently, approximately 2500 plant species are employed as herbal medicines in India, and the WHO reports that about 21,000 plants are utilised for therapeutic purposes globally. Most medicinal plants are special in that they can treat, heal and cure a range of health conditions because they contain numerous essential phytoconstituents in different plant parts[3]. In recent years, there has been a surge of studies investigating the biological effects of geranium extracts and essential oils, as well as their applications in medicine, food flavouring, fragrance, and cosmetics[4,5].

In India, rose-scented geranium is cultivated across various agro-climatic regions, including the Nilgiri and Pulney hills of Tamil Nadu, as well as in Andhra Pradesh, Karnataka, Maharashtra, and Uttar Pradesh. It is widely cropped for commercial use because of its highly valued essential oil, which ranks among the top 20 essential oils worldwide[6-10]. *P. graveolens* is a renowned aromatic and medicinal plant that has a major impact on the economy due to its diverse pharmacological, medicinal, and phytochemical properties. These include anti-inflammatory, antidepressant, anti-dysentery, anti-diabetic, anti-cancer, anti-fungal, anti-bacterial, antioxidant, antiseptic, anti-malarial, and anti-hemorrhoidal effects[11–13].

In addition to being cultivated for their essential oil, geranium plants are also appreciated for their use in floral arrangements. These plants produce volatile oils as bioactive secondary metabolites, which serve important roles in ecological adaptation and defence against microbial diseases, fungi, pests, and predators. Approximately 280 species of *Pelargonium* are known for their wide variety of these oils, which include terpenes, esters, alcohols, aldehydes, ketones, and phenols[14–17].

The Global production of geranium oil (GEO) is estimated to be around 250–300 tons per year, while the annual demand exceeds 800 tons[18]. *P. graveolens* essential oil exhibits a range of effects such as antiasthmatic, antiallergic, antioxidant, antidiarrheal, antihepatotoxic, diuretic, tonic, hemostatic, stomachic, and antidiabetic properties. Known as Geranium oil (GEO) for short, *P. graveolens* oil is a medicinal oil that can be employed to address various conditions, including depression, diabetes, biliary disorders, stomach ulcers, arthritis, diarrhoea, aromatherapy, premenstrual tension, menopausal issues, immune system stimulation, circulatory disorders, tonsillitis, asthma, haemorrhoids, phlebitis, sore throat, and excessive mucus production. It is well-recognised that GE oil helps cure dermatitis, burns, scars, shingles, eczema, acne, general infections, and skin issues[19]. The biological actions of its primary ingredients, citronellol, geraniol, linalool, and isomenthone, are thought to be the cause of this belief[20,21]. Steam and hydro-distillation are two methods used to extract essential oils from fragrant plants. China, Egypt, India, Comoros, and Reunion are the leading producers of this plant, whose essential oil is among the twenty most imported globally[9].

Additionally, it emphasises how crucial this crop is in African nations, especially in Madagascar, Algeria, Kenya, and Morocco, and this essential oil is composed of numerous secondary metabolites derived from plants[22,23]. Essential oils are primarily used in fragrances, cosmetics, and food flavouring due to their intense aromas. Furthermore, ongoing research has demonstrated the significant potential of essential oils, highlighting the crucial role of their chemical constituents in the management, prevention, and treatment of various human ailments[24]. While many bioactivities of essential oils remain unexplored, their significant potential for medicinal properties and their ability to function as natural preservatives have made them a focal point of research and interest across various sectors[25]. EO of *P. graveolens* also has a strong biological activity, and may also be used in inflammatory conditions and cancer[26].

As a result, essential oils have emerged as a promising source for identifying novel, safe, and

effective bioactive compounds with various therapeutic applications. This review focuses on the traditional uses, various extraction methods, pharmacology and applications of PGEO, specifically highlighting the various pharmacological activities of phytocompounds of PGEO.

2. Materials and Methods

A comprehensive review was conducted to collect published information related to *P. graveolens* essential oil, including its traditional uses, phytochemical composition, extraction methods, and pharmacological activities and therapeutic indications. In order to substantiate these traditional claims, relevant scientific literature was retrieved through a comprehensive search of electronic databases, including PubMed, Scopus, Science Direct, and Google Scholar. The search strategy employed keywords such as "*Pelargonium graveolens*", "geranium essential oil", "phytochemistry", "traditional uses", "antioxidant", "antimicrobial", "anti-inflammatory", "anticancer", "toxicity", and "pharmacological activities".

Peer-reviewed research articles, review articles, and ethnopharmacological studies published in English were included in this review. Studies reporting the chemical composition, biological activities, extraction techniques, safety evaluation, and traditional medicinal applications of PGEO were considered eligible.

Studies lacking sufficient experimental details, duplicate reports, conference abstracts without full text, unpublished data, and articles unrelated to *P. graveolens* essential oil were excluded from the review.

3. Traditional Uses

Plants are the foundation of an intricate traditional medical system. Medicinal plants give natural products that are a great source of lead and active chemicals that are needed in the creation of new medications. Traditional medicine is practised differently in every place due to a multitude of reasons, including history, culture, philosophy, and individual attitudes[2]. Long before the modern medical system was introduced, the indigenous communities used traditional medicinal plants to cure and treat a variety of infectious ailments[27,28].

Pelargonium graveolens, it has been traditionally used as a plant extract or essential oil. *P. graveolens* is a shrubby perennial plant endemic to South Africa that belongs to the *Geraniaceae* family and the genus *Pelargonium*. It has historically been used to treat bruising, broken capillaries, eczema, ulcers, acne, depression, and liver and kidney functions. Additional uses include analgesics, anticancer, and therapy for some hormonal problems. The plant is used as a health infusion to treat gonorrhoea, colds, sore throats, haemorrhoids, genital infections, breast inflammation, digestive disorders, wounds, abscesses, fever, colic, and nephritis. Additionally, it is used to treat diarrhoea and respiratory tract infections, combat helminthic infections, and increase milk supply[29–33].

In South Africa, *P. graveolens* is traditionally used with the leaves that are steamed, and vapours are inhaled to treat colds[34]. The magnificent plant *P. graveolens* is mostly used medicinally to treat disorders of the nervous system, gastrointestinal tract, osteoarticular cartilage, and respiratory and cardiovascular systems. In contemporary Western phytotherapy, *Pelargonium* extracts are utilised for non-tuberculosis infections, particularly in paediatrics.

The leaves were utilised topically to heal wounds and abscesses, as well as ringworm, neuralgia, rashes, and throat infections. They also help with fluid retention, menopausal issues, cellulite, and breast congestion[11,35,36]. Traditional Iranian and international folk medicine frequently uses the aerial portions of *P. graveolens* as a food and tea addition and to treat gastrointestinal, cutaneous, dental, and cardiovascular conditions[33,37]. Recently, the rising demand for natural products has led to a surge in scientific research. Since the discovery of traditional tribal remedies in South Africa, *Pelargonium* species have gained considerable importance[11,35,36].

Generally, EO is administered externally, such as topically, internally, by inhalation, or sometimes consumed orally[38]. Moreover, essential oils exhibit anti-inflammatory and wound-healing properties. Their broad application and minimal side effects make them highly effective for addressing various diseases and ailments in humans. Traditionally, essential oils have been applied topically, ingested, or inhaled to target specific areas of the body for the treatment of particular conditions[39–41].

Furthermore, *P. graveolens* essential oil is employed in traditional Mexican medicine to relieve headaches and is used in aromatherapy for its calming effects. It is widely recognised in various traditional practices as a diuretic, tonic, anti-diabetic, and anti-allergic agent. Research has also shown its effectiveness in exacerbating diabetic foot ulcers in experimental rat models. Previous studies have demonstrated the oil's utility in treating inflammatory disorders. Historically, it has been utilised as a tonic, hemostatic, stomachic, antihepatotoxic, antioxidant, diuretic, and antiasthmatic[42–44].

The French medical community utilises this oil to address a variety of conditions, including diabetes, stomach ulcers, infertility, gallbladder issues, and urinary stones. It is highly regarded for skincare, as it effectively unclogs pores and cleanses oily skin. Traditionally, this plant is used as a flavouring agent in various major categories, including both alcoholic and soft beverages, and is particularly popular in pink-coloured culinary dishes in the Western Balkan region. Additionally, geranium essential oil is increasingly being used to treat cancer, haemorrhoids, heavy menstrual bleeding, diarrhoea, and inflammation. In Tunisia, rose-scented geranium is commonly transformed into a food-friendly hydrosol for use in traditional sweets.

Numerous studies have demonstrated its potent antioxidant properties and ability to relieve sore throats[9,45,46]. Rose geranium oil has long been used in Lebanon as a gastrointestinal illness therapy, analgesic, astringent relaxant, antiviral, and anti-inflammatory for joints and muscles[47]. An oral drop containing *P. graveolens* essential oil has been used traditionally for wounds, respiratory diseases, and digestive issues. It was developed in Iran to treat depressive disorders[48,49]. *P. graveolens* nourishes dry skin externally, which was introduced by the Thoriya ethnic (baduga) in Nilgiris[50]. Moreover, this oil is utilised in different parts of the world to treat various conditions, as illustrated in Figure 1.

Traditionally, *P. graveolens* essential oil has been widely used in folk medicine for the management of musculoskeletal disorders, including rheumatism, arthritis, muscular pain, and joint stiffness. In aromatherapy and traditional medicinal systems, the oil is commonly diluted and applied topically through massage to alleviate pain, reduce inflammation, and improve circulation. In regions such as Egypt, Morocco, and South Africa, geranium oil has historically been used to relieve inflammatory pain and musculoskeletal discomfort[23].

The essential oil has traditionally been used for various dermatological and respiratory conditions. In folk medicine, it has been applied to wounds, burns, eczema, acne, and skin infections because of its cleansing, soothing, and tissue-regenerating properties. It has also been used for respiratory complaints such as sore throat, cough, bronchitis, and nasal congestion, with inhalation traditionally practised to ease breathing and relieve upper respiratory discomfort. These uses have been particularly documented in North African, Mediterranean, and European traditional medicine and aromatherapy practices[51].

Geranium oil has traditionally been used in reproductive and emotional wellness, particularly for relieving menstrual discomfort, premenstrual symptoms, and menopausal complaints. It has been valued in aromatherapy for easing menstrual cramps while helping to balance mood and emotional well-being. In addition, the aromatic oil has long been used to reduce anxiety, nervous tension, insomnia, and emotional stress, with inhalation of rose geranium oil traditionally believed to promote relaxation and improve mood. These traditional uses have been especially documented in European and Middle Eastern herbal medicine and complementary therapeutic practices[23,51].

4. Approaches for Extracting and Isolating EO

Various methods extract essential oil (EO) from medicinal plants. These include advanced (non-conventional) techniques such as solvent extraction, subcritical liquid extraction, steam distillation, hydro-distillation, hydro diffusion, and solvent-free microwave extraction[52].

Hydro-distillation (HD) is the most popular and cost-effective technique utilised in the commercial sector to extract volatile oil from the plant matrix. HD is frequently employed to isolate EO[53]. Hydrodistillation can be achieved using three different methods: (a) water distillation, (b) water-steam distillation, (c) Steam distillation[54]. Steam distillation extraction is a

frequently employed technology despite the yield and process uncertainties that come with it. This is because the technology requires less capital and is less expensive to operate than other extraction processes[55].

An efficient way to extract a significant amount of EO is through steam distillation, or hydro-distillation using the Clevenger apparatus, which takes three to four hours[56]. The plant's fresh aerial components, such as the leaves and stems, were cut finely and immersed completely in water. After that, they were hydro-distilled for three hours utilising a full glass Clevenger-style equipment. The water and EO separated when the condensed substance cooled, and the yield was about 0.35%. Fresh leaves were preferred for hydrodistillation as they retain thermolabile volatile compounds that contribute to the essential oil's bioactivity. Although moisture can reduce yield, fresh samples often produce a compositionally richer oil profile compared to dried leaves[43,57–61].

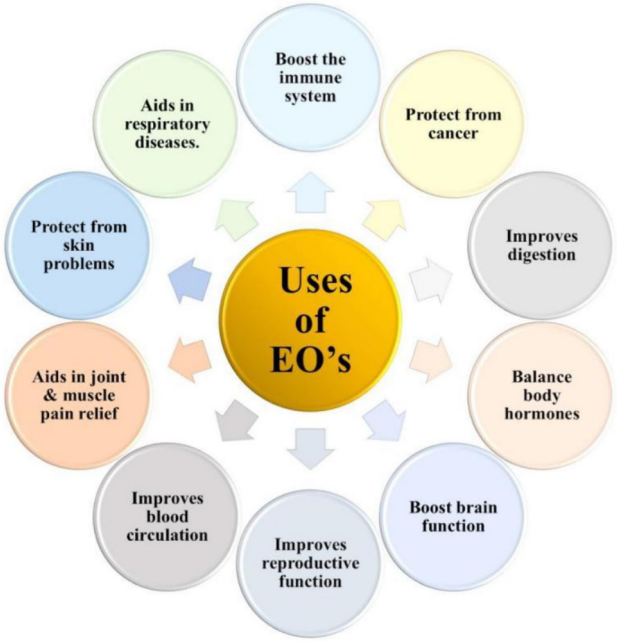


Figure 1. Overview of the medicinal and therapeutic uses of essential oils.

Following its isolation, the EO was collected in a graduated tube and dried with either anhydrous sodium sulphate or dichloromethane. After that, the oil was kept at 40°C in a dark place until GC-MS analysis and biological activity tests required it[9,62–67]. (Figure 2)

The extraction method significantly influences the yield, chemical composition, and biological activity of *P. graveolens* essential oil. Hydrodistillation remains the most commonly used technique because of its simplicity and cost-effectiveness, producing oil rich in citronellol and geraniol; however, prolonged heating may cause degradation of thermolabile constituents and alter volatile composition. Steam distillation is preferred at an industrial scale due to better preservation of volatile

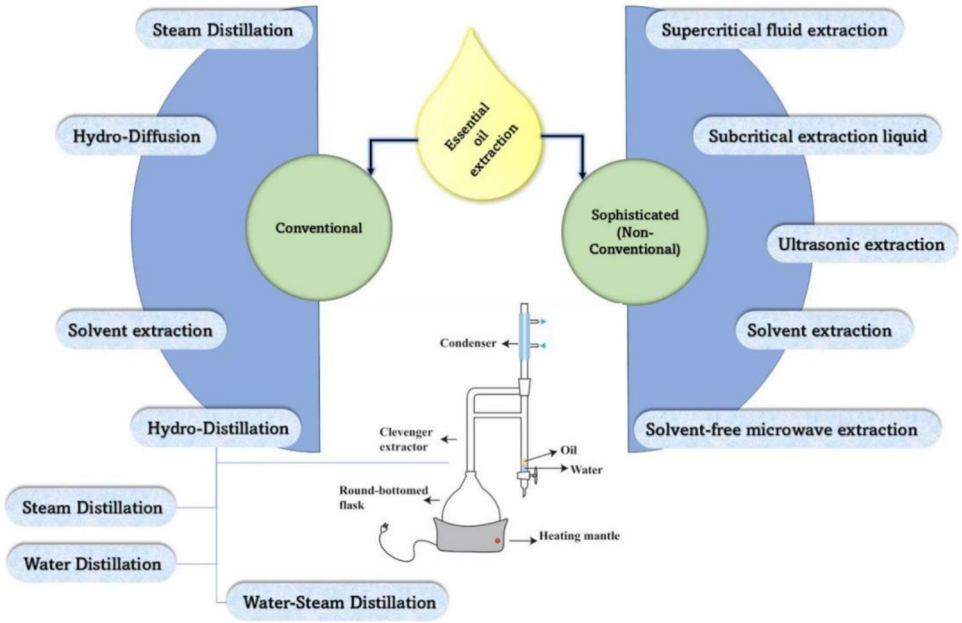


Figure 2. Schematic representation of conventional and non-conventional extraction techniques for essential oils.

compounds and higher processing efficiency. Advanced methods such as solvent-free microwave extraction and enzymatic pretreatment-assisted microwave extraction have shown improved extraction yield and enhanced recovery of oxygenated monoterpenes, particularly citronellol and geraniol, resulting in stronger antioxidant and antimicrobial activities compared with hydrodistillation. Supercritical CO_2 extraction also offers advantages by operating at lower temperatures and preserving sensitive constituents without solvent residue, although its higher cost limits widespread use. Overall, the choice of extraction method plays a critical role in determining oil quality and pharmacological potential, with modern techniques often providing improved preservation of bioactive constituents compared with conventional distillation methods[68–70].

4.1 Gas Chromatography-Mass Spectrometer (GC-MS)

The analytical method known as GC-MS uses two instruments to examine a sample's constituent parts. Because of its quick findings, high sensitivity, and improved sample identification, it is frequently employed in many different disciplines, such as drug testing and environmental analysis. This technique offers a wide variety of analytical capabilities and can identify and analyse minuscule levels of chemicals, independent of their elemental composition[71].

Several tools were used to perform the GC analysis of EO (HP-5 MS (Crosslinked 5% PH ME Siloxane) Cap. column (30 m, 0.25 mm i.d., 0.25 µm film thickness) is standard on Hewlett Packard 5890 GC models[72–74]. Hewlett-Packard HP 6890 equipped with an injector split/splitless (280 °C) or with a flame ionisation detector (FID), with a capillary tube HP-5 Cap. column (30 m X 0.25 mm, film thickness, 0.25 µm) or fused-silica Cap. column (30 m X 0.25 mm, film thickness, 0.33 µm)[75,76]. Helium served as the carrier gas, maintained at a flow rate of 1 mL/min for a total run time of 85 mins. The injector temperature was set to 220 °C, while the MS transfer line (detector) was kept at 290 °C[73,74].

GC combined with MS was used to identify the main compounds. After diluting the essential oil with diethyl ether, 0.5 µl was added to a GC (Hewlett-Packard 5890) and an MS (Hewlett-Packard 5989B) system for analysis. The GC column was a 30 m HP5MS (5% diphenyl) dimethylpolysiloxane capillary column with an i.d. of 0.25 mm and a film thickness of 0.25 µm.

The GC parameters were as follows: 240°C for the injector; 70°C for the column, which was isothermal for two minutes before being programmed to 280°C at a rate of 6°C per minute and maintained at this temperature for two minutes; 200°C for the ion source; and 300°C for the detector. The carrier gas, helium, was employed at one millilitre per minute. The MS's ion source was filled with the GC column's effluent. Spectra having an ionisation energy of 70 eV were found in the EI mode. The sector mass analyser was configured for a 5-second scan between 40 and 400 amu. The constituents of the oil were identified by matching their retention indices and mass spectra with data from the NIST Mass Spectral Library[77–79].

More than 200 compounds have been extracted from *P. graveolens* using GC and GC-MS methods, depicted in some chemical categories. PGEO is characterised by the presence of alcohols, esters, hydrocarbons, ketones, ether oxides, and aldehydes[80] (Table 1).

5. Four Chemical Groups Comprised the Majority of the EO's Components

Oxygenated monoterpenes- β-citronellol, β-thujone, chrysantheneone, *l*-linalool, *d*-pulegone, α -citral, β-citronellol camphor, α-thujone, geraniol formate, Linalool, geraniol, 4-terpineol and linalool oxide and citronellyl formate

monoterpene hydrocarbons-, β-pinene, sabinene, delta-3-carane, phellandrene, *c*-terpinene, and α-pinene

Sesquiterpene hydrocarbons- α-elemene, β-elemene, bicyclo germacrene and trans-caryophyllene, caryophyllene, humulene, germacrene D, and α-cadinene

Oxygenated sesquiterpenes- cedrol and elemol[74,83,84].

Considering large concentrations of geraniol and citronellol only make about 30–60% of the EO, these compounds are responsible for the pleasant scent in plants. The high volatile substance content of *P. graveolens* was attributed to these compounds, along with oxygenated monoterpenes and sesquiterpenes[85–87].

The primary constituents of rose geranium oil were oxygenated sesquiterpenes and monoterpenes. According to the results of the prior investigation,

Table 1. Various groups of phytoconstituents of the essential oil of *Pelargonium graveolens* and its potential uses and properties

Secondary Metabolites	Compound Present in Secondary Metabolites	Potential Uses/Properties
Aliphatic Hydrocarbons	Butane, isoprene, 1,3- pentadiene, hexane, isooctane, octadecane, nonadecane, nonadecene, eicosane, henicosane, decosane, tricosane, tetracosane, pentacosane	Fuel sources, industrial solvents, and chemical feedstocks
Aromatic Hydrocarbons	Toluene, p-cymene	Solvents, fragrances, and chemical intermediates
Terpene hydrocarbons	α-Pinene, β-pinene, α-phellandrene, β-phellandrene, camphene, myrcene, sabinene, limonene, γ-terpinene, terpinolene, cis-β-ocimene, trans-β-ocimene, dehydro-1,8- cineole, 1,4-cineole, p-menthadiene, perillene, piperitone	Aromatherapy, flavouring agents, and potential therapeutic properties
Sesquiterpene Hydrocarbons	α-Copaene, α-cadinene, γ-cadinene, δ-cadinene, guaia-6-9- diene, β-bisabolene, α-calcorene, calamenene, β-selinene, α-muurolene, γ-muurolene, α-bourbonene, β bourbonene, 11- norbourbonene, β-caryophyllene, γ-caryophyllene, bicyclo-germacrene, germacrene D, longifolene, β-gurjunene, β-farnesene, (E, E)-α-farnesene, α-cubebene, β-cubebene, β-elemene, β-maaline, α-humulene, viridiflorene, zonzrene, α-ylangene, allo-aromadendrene, selina-4,11-diene, α-guaiene	Anti-inflammatory, antimicrobial, and antioxidant properties
Aliphatic Alcohols	Methanol, ethanol, t-butanol, pentanol, 1-penten-3-ol2-propanol, hexanol, 2- methylpropanol, 2-dimethylpropanol, 2-methylbutanol, 2-methyl-3-buten-2-ol,3 metylbutanol, 3-methylpentan-1-ol, cis-3-hexenol, trans-2-hexenol, 3- hexen-1-ol, octanol, 1-octen-3-ol, 2-octanol	Solvents, antifungal agents, and flavouring agents
Terpene Alcohols	Geraniol, isogeraniol, isopulegol, 7-hydroxy-6,7-dihydrogeraniol, nerol, epi photonerol A, linalool, menthol, isomenthol, neoisomenthol, α-terpineol, citronellol, 7- hydroxydyhydrocitronellol, borneol, isoborneol, terpinen-4-ol	Fragrances, flavourings, and potential therapeutic effects
Aromatic Alcohols	2-Phenylethyl alcohol	Fragrance, flavouring, and potential anti-inflammatory effects
Sesquiterpene Alcohols	10-epi-γ-eudesmol, β-eudesmol, 11-selina-4α-ol, junenol, farnesol, guaiol, spathulenol, T-cadinol, elemol	Antimicrobial and anti-inflammatory properties
Aliphatic Esters	Methyl formate, methyl butyrate, 2-methylbutyl formate, 3-methybutyl formate, 2- methylpropyl formate, 3-methylpentyl formate, ethyl formate, butyl formate, propyl formate, 2-propyl formate, hexyl formate, benzyl tiglate, (Z)-3- hexenyl acetate	Flavouring agents, solvents, and fragrances
Aromatic Esters	2-Phenylethyl tiglate, 2- phenylethyl propionate, 2- phenylethyl butyrate, 2-phenylethyl isobutyrate, 2- phenylethyl isovalerate, 2- phenylethyl acetate	Fragrances and flavouring agents
Terpene Esters	(Z)-3-Hexenyl acetate, geranyl formate, geranyl butyrate, geranyl isobutyrate, geranyl 2- methyl butyrate, geranyl tiglate, geranyl acetate, geranyl propionate, geranyl valerate, geranyl 3-methylvalerate, geranyl 4-methylvalerate, geranyl hexanoate, geranyl heptanoate, geranyl nonanoate, geranyl isovalerate, methyl geranate, geranyl 3-methyl pentanoate, geranyl octanoate, citronellyl acetate, citronellyl formate, citronellyl butyrate, Citronellyl tiglate, citronellyl propionate, Citronellyl valerate, citronellyl 4-methylvalerate, citronelly lisovalerate, Citronellyl hexanoate, citronelly lisohexanoate, Citronellyl heptanoate, Citronellyl octanoate, Citronellyl nonanoate, furopelargonic acetate, linalyl acetate, bornyl acetate, neryl acetate, neryl formate	Fragrance and flavouring agents
Aliphatic Ketones	Acetone, 2-butanone, 2- pentanone, 3-methyl-2- butanone, 2-methyl-3-pentanone, 4-methyl-2- pentanone, 2- methylcyclopentanone, 3-methylcyclo-pentanone, 3- metylcyclohexanone, 4-methyl-3-penten-2-one, 2-hexanone, methyl heptenone, 6-methyl-5- hepten-2-one, methyl-3-methylcyclo-pentenyl ketone	Solvents and intermediates in chemical synthesis

Table 1. Continued...

Secondary Metabolites	Compound Present in Secondary Metabolites	Potential Uses/Properties
Terpene Ketones	Menthone, isomenthone	Fragrances and potential therapeutic uses
Sesquiterpene Ketones	1,7-Dihydrofurapelargone, furapelargone A, furapelargone B, 7,8-dihydrofurapelargone	Potential therapeutic properties
Aliphatic Aldehydes	Benzaldehyde, ethanal, decanal, 2-methyl propanal, 3-methyl-2- butanal, 3-methyl butanal, 2- furfuraldehyde, nonanal, (E)-2- hexenal	Flavouring agents and fragrances
Terpene Aldehydes	Geraniol, citronellal, neral, photocitral A, epi-photocitral A, photocitral B, p-menth-1-en-9-al	Aromatherapy and potential therapeutic effects
Terpene Oxides	cis-rose oxide, trans-rose oxide, cis-linalool oxide, trans-linalool oxide, anhydrolinalool oxide, bois-de-rose oxide, nerol oxide	Fragrances and potential therapeutic properties
Sesquiterpene Oxides	Caryophyllene oxide	Antimicrobial and anti-inflammatory properties
Aliphatic Acids	Formic acid, propionic acid, acetic acid, caprylic acid	Food preservation, flavouring, and chemical synthesis
Terpene Acids	6-oxo-6-,7-dihydrocitronellic acid, geranic acid, citronellic acid	Potential antimicrobial properties and food preservation
Miscellaneous	Dimethyl sulfide, eugenol, methyl eugenol, furan, α-agarofuran, rose furan, epoxy-rose furan, juniper camphor, aspirants, vetispirans[81-83].	Flavouring agents, antimicrobial properties, and medicinal uses

oxygenated monoterpenes constituted the largest group of oil constituents[66,72,73,88].

Furthermore, citronellyl isovalerate, menthol, linalool, p-menthone, geranyl tiglate, neryl propionate, isocaryophyllene, and caryophyllene epoxide, as well as geranyl butyrate, neryl hexanoate, geranial nerolidyl acetate, areyl heptanoate, heptaminol, citronellyl hexanoate, neryl acetate, myrtanol, citronellol, are among the principal components in *P. graveolens* extract oil. Citronellyl formate, geraniol, iso-menthone, and geranyl formate, 10-epi-γ-eudesmol (Figure 3).

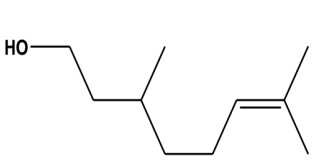
6. Pharmacological Activities

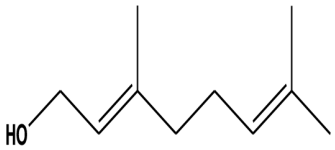
6.1 Antioxidant Activity

A significant source of naturally occurring antioxidants is plants, which can yield a variety of secondary metabolites with potentially medicinal antioxidative properties. Today, there is interest in finding better and more affordable sources of antioxidants from natural sources, particularly plants, as the use of synthetic antioxidants raises safety issues[89]. It is well-recognised that plants have a wide range of naturally occurring antioxidants that guard and maintain their structural, metabolic, and genetic integrity through their seeds[90]. The body's ability to reduce free radicals is mostly due to antioxidant enzymes such as catalase, glutathione, glutathione-S-transferase, and superoxide dismutase[91]. Some of those consequences may cause harm that might lead to diabetic problems, such as peripheral neuropathies, cancer, heart disease, blindness, renal failure, and cardiovascular[92].

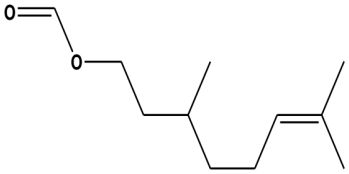
It is generally accepted that EOs have a wealth of antioxidants that may be used to prevent oxidative damage. The volatile ingredients in EOs target cellular redox activity, harm intracellular biomolecules, and produce a shield against oxidative stress. EOs, being pro-oxidants, can potentially harm cellular proteins and DNA. In addition to their potential as antioxidants, EOs' pro-oxidant activity needs to be taken into account in antioxidant investigations[24].

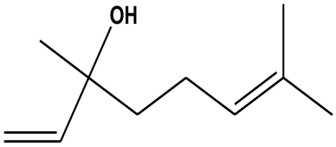
The existence of monoterpenes may potentially be responsible for GEO's antioxidant properties. Antioxidants were primarily produced by two compounds: geraniol and citronellol[21,44,93–96]. The antioxidant activity of GEO was assessed both *in vivo*



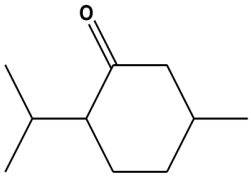


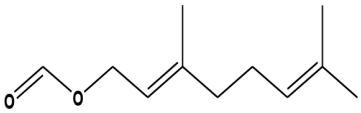
Citronellol Geraniol



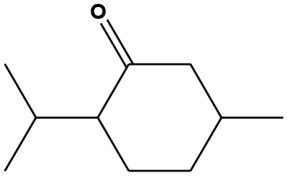


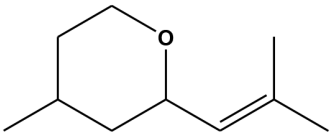
Citronellyl Formate Linalool



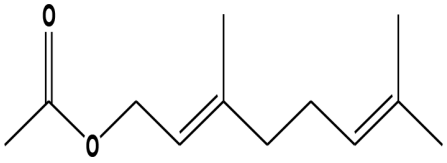


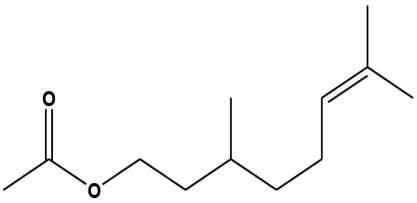
Isomenthone Geranyl Formate



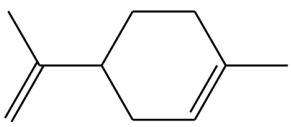


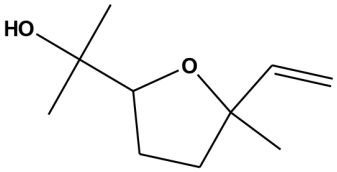
Menthone trans-Rose Oxide



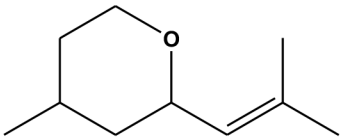
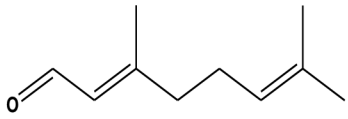


Geranyl Acetate Citronellyl Acetate

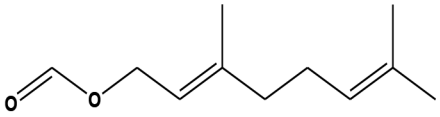
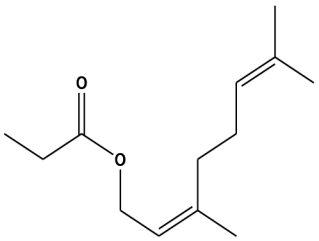




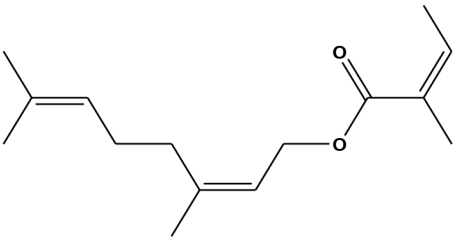
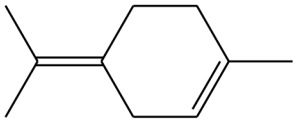
Limonene trans-Linalool Oxide

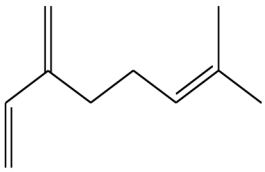
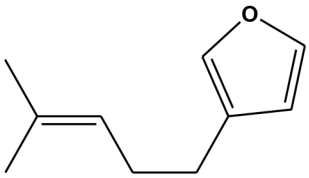
cis-Rose oxide Neral

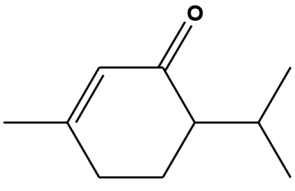
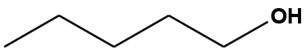
Neryl Formate Geranyl Propanoate

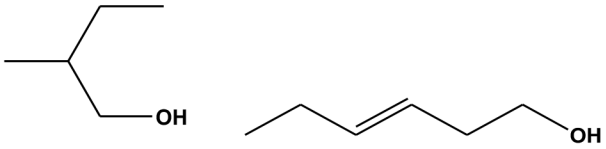
Geranyl Tiglate Terpinolene

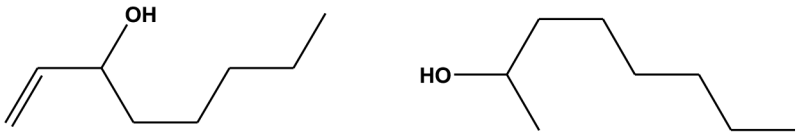
Myrcene Perillene

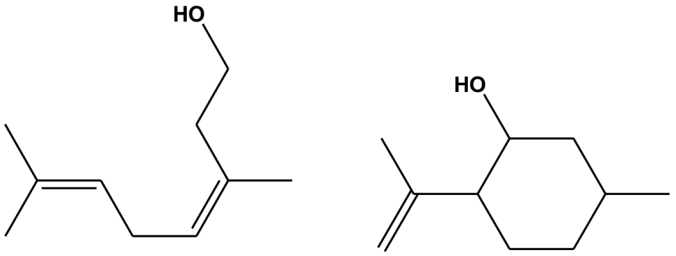
Piperitone Pentanol



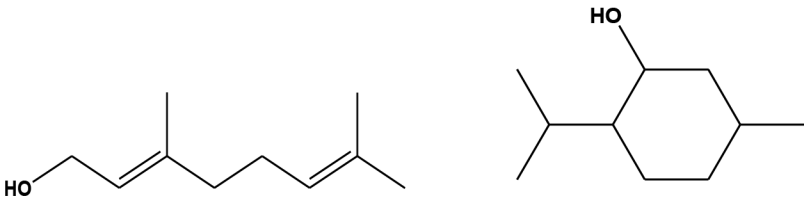
2-Methylbutanol cis-3-Hexenol



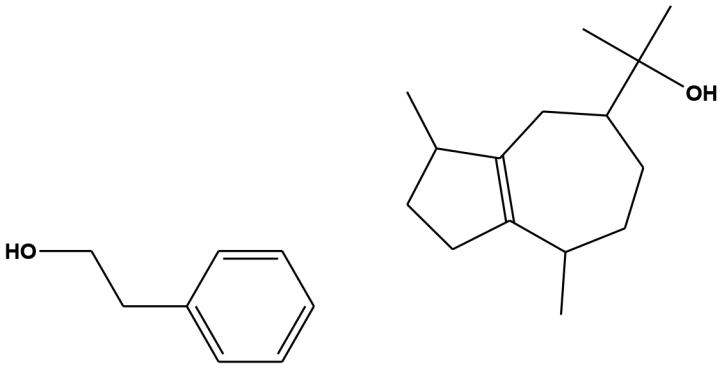
1-Octen-3-ol 2-Octanol



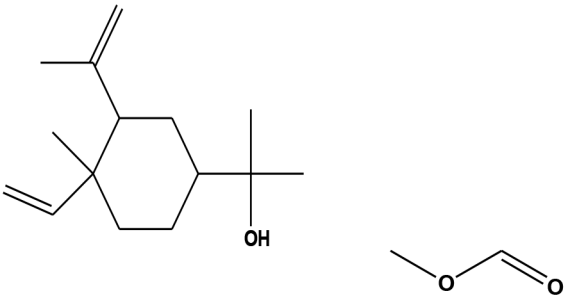
Isogeraniol Isopulegol



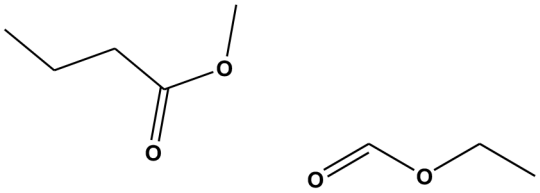
Nerol Menthol



2-Phenylethyl Alcohol Guaiol



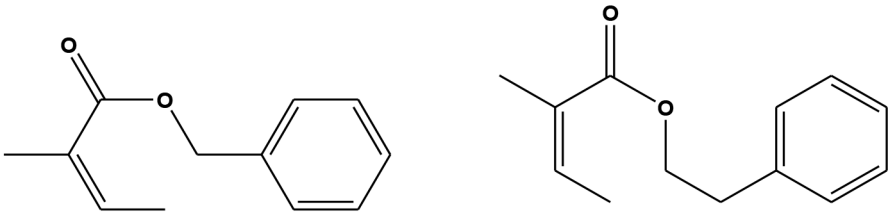
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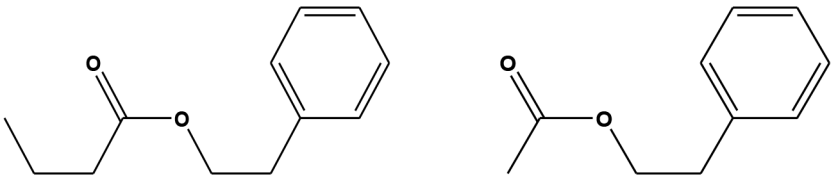
Methyl Butyrate Ethyl Formate



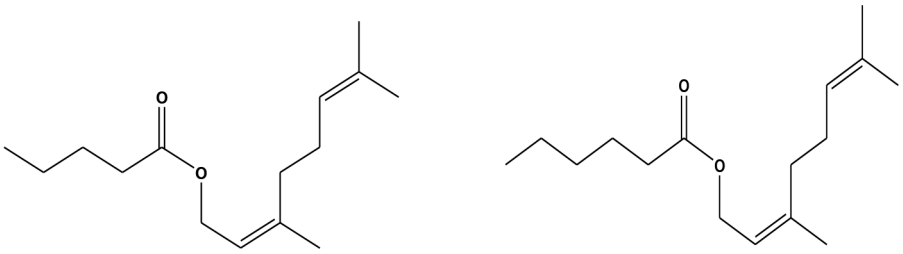
Butyl Formate Propyl Formate



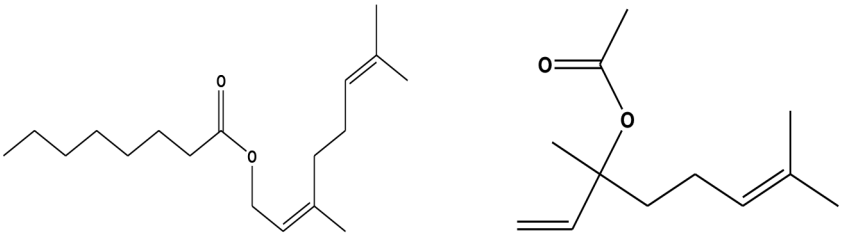
Benzyl Tiglate 2-Phenylethyl Tiglate



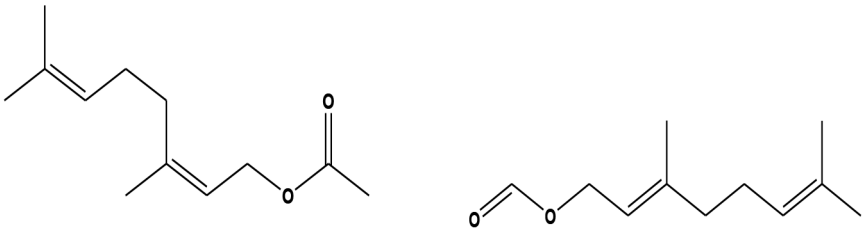
2-Phenylethyl Butyrate 2- Phenylethyl Acetate



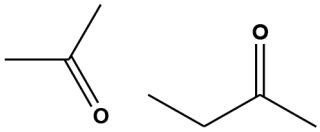
Geranyl Valerate Geranyl Hexanoate



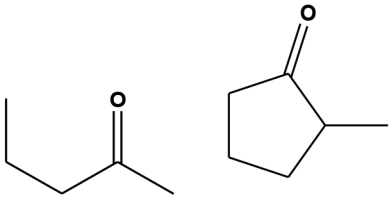
Geranyl Octanoate Linalyl Acetate



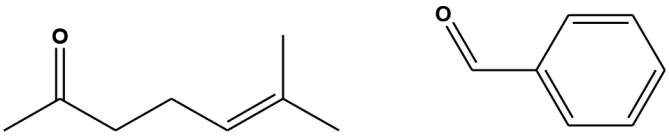
Neryl Acetate Neryl Formate



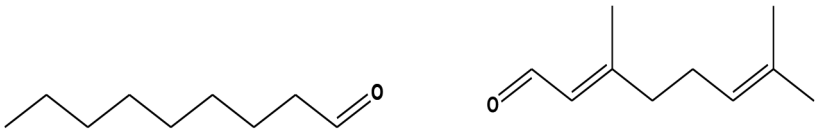
Acetone 2-Butanone



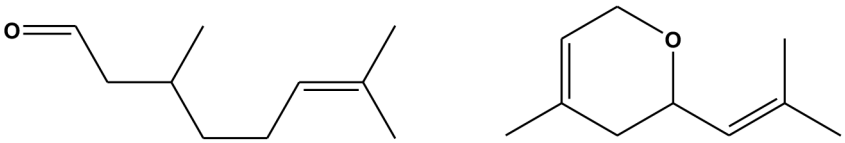
2- Pentanone 2- Methylcyclopentanone



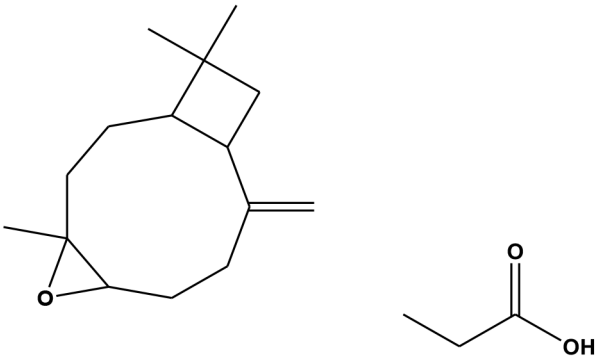
Methyl Heptanone Benzaldehyde



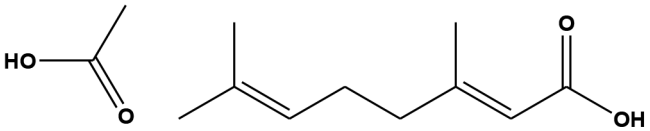
Nonanal Geranial



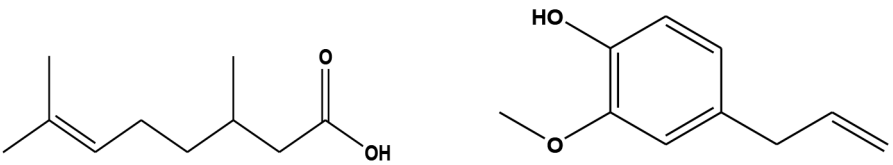
Citronellal Nerol Oxide



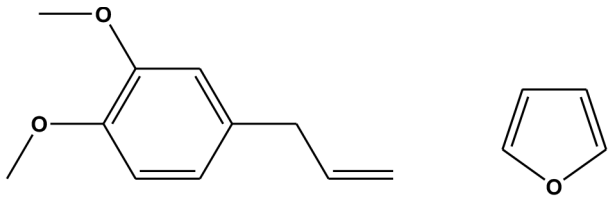
Caryophyllene Oxide Propionic Acid



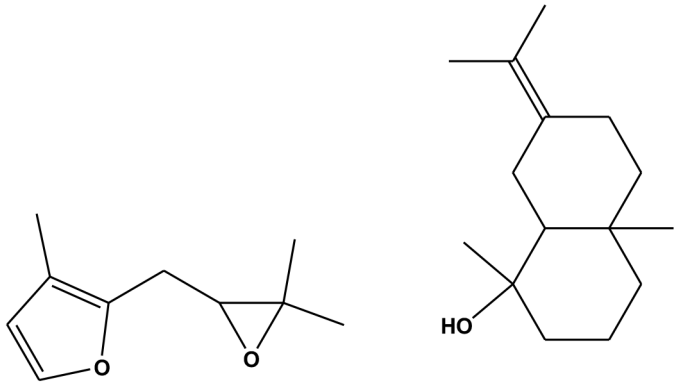
Acetic Acid Geranic Acid



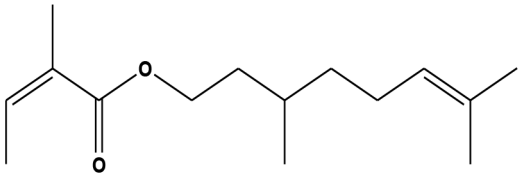
Citronellic Acid Eugenol



Methyl Eugenol Furan



Rose Furan Juniper Camphor



Citronellyl Tiglate

Figure 3. Major bioactive phytoconstituents present in *P. graveolens* essential oil.

and *in vitro*, using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) Assay[61,97–99]. Boukhris *et al.*, reported that PGEO oils control oxidative damage by reducing the generation of free radicals, which helps inhibit the development of diabetes[44].

The reduced oxidative stress and lipid peroxidation process enhanced the antioxidant defence system, resulting in GEO reducing the DPPH-free radical with an IC_{50} value of 18.02 µg/mL, preventing oxidative stress[21,94]. Boukhris *et al.*, reported that leaves of PGEO possess the greatest DPPH scavenging activities (2.62 mg/mL) and are more potent than BHT (Butylated hydroxytoluene) by inhibiting or limiting the growth of significant pathogens, thereby improving food safety and extending shelf life in the food industry[21,23,94,100]. PGEO decreased LPO in diabetes and oxidative stress by alloxan therapy in rats decreased kidney and hepatic injuries through its antioxidant activity. It also performs a vital function as a hepato- and nephro-protective product. According to Hajri *et al.*, MLE (moringa leaf extract) significantly ($P \leq .05$) increased the geranium leaves' capacity to scavenge radicals, yielding the lowest IC_{50} value of 61.44%[100]. To control the development and yield of aromatic and medicinal plants, MLE can be utilised as a substitute and environment-friendly plant growth stimulant to manage the development and yield of aromatic and medicinal plants[99].

The study demonstrated that hydrosols obtained from the stems and leaves exhibited activity approximately tenfold greater than the thymol control and that the GEO from the stems had more antioxidant activity than the leaves[9]. Jadidi *et al.*, found that geranium oil boosts plant tolerance to UV-B irradiation and effectively manages oxidative stress[96]. Meanwhile, Maher Boukhris *et al.*, found that the antioxidant activity of this oil significantly inhibited various free radicals. Additionally, when combined with -citronellol, both essential oil and -citronellol exhibited a protective effect on pGEM-T in the presence of high concentrations of H_2O_2[101].

Fayed conducted a study on antioxidant activity using a DPPH assay with different concentrations of EC_{50} of 66.45 µg/ml, and the oil had high activity due to the presence of oxygenated compounds, namely linalool, citronellol, geraniol[65]. Miroslava *et al.*, followed a research study focusing on antioxidant activity using DPPH and ABTS assays. The results showed that PGEO had a stronger ability to scavenge the ABTS radical cation, with an IC_{50} value of 0.26 ± 0.02 mg/mL. The results suggest that the superior ability of PGEO to neutralise ABTS•+ in comparison to DPPH and essential oils may be partly linked to the presence of key compounds, namely β-citronellol and geraniol[102].

Dumlupinar *et al.*, evaluated the antioxidant activity of geranium oil using DPPH and ABTS assays. The oil exhibited significant DPPH radical scavenging at concentrations of 20 to 200 µg/mL, comparable to BHT. At 100 µg/mL, it matched BHT's effectiveness in ABTS radical scavenging, and at 200 µg/mL, it demonstrated a similar antioxidant effect, preventing oxidation within the initial 60 minutes. The main components identified were citronellol, geraniol, and isomenthone[103].

Lohani *et al.*, studied the antioxidant properties of GEO using nitric oxide and DPPH scavenging activities. GEO exhibited significant DPPH radical scavenging with an IC_{50} value of 18.02 µg/mL, comparable to ascorbic acid at 10.38 µg/mL. The presence of oxygenated monoterpenes like citronellol and geraniol in GEO showed promise in preventing oxidative stress, suggesting its potential use in skincare to combat skin aging[104].

Boukhris and team assessed the antioxidant study of *P. graveolens* essential oils at various stages using DPPH and ABTS methods. The essential oil showed a strong inhibitory effect against free radicals, especially during the flowering stage. Exposure to the essential oil and β-citronellol showed a protective effect on pGEM-T, even under high concentrations of H_2O_2 that induce DNA strand breaks through reactions with Fe (III)[101].

The reduction in oxidative stress and lipid peroxidation seen in GEO-treated animals is likely associated with the oil's potent antioxidant activity. The primary compounds of the essential oil, β-citronellol and geraniol, might have had an impact on its effects. The antioxidant properties of GEO appear to successfully alleviate deltamethrin-induced oxidative stress in the testes of mice[45] (Table 2).

6.2 Antimicrobial Activities

6.2.1 Antibacterial Activity

EO's antimicrobial activity affects phytochemical ingredients and interactions between various components that might result in antagonistic or synergistic effects. Both major and minor components of EO can potentially modify activity through antagonistic or synergistic effects[24]. Research was carried out to find out exactly how powerful the plant is against bacteria[73,115]. GEO has demonstrated a strong antibacterial potential, often surpassing that of conventional drugs; nevertheless, the findings are based on ATCC isolates[116]. Geranium oil has antimicrobial properties and is practically non-toxic, making it suitable for use in food preparation. Apart from its contribution to food flavour, the food industry continues to use it for the same purposes[116].

Less research has been conducted on the antibacterial properties of *Geranium* species essential oil compared to solid-liquid extracts. The inhibitory potential of many hydrodistilled EO was evaluated against a range of bacterial strains, including several plant diseases. The investigation began by assessing *P. graveolens*' ability to combat both Gram-positive (+) and Gram-negative (–) bacteria. GEO that is rich in monoterpenes and sesquiterpenes possesses antibacterial effects against Gram-positive bacteria[116].

A wide range of Gram-positive (G+) bacteria are efficiently targeted by GEO, such as *Micrococcus luteus, Bacillus subtilis, Enterococcus faecalis, Staphylococcus aureus, Bacillus cereus, Listeria monocytogenes, Streptococcus sanguinis*, and *Micrococcus agalactiae*.

Table 2. Pharmacological properties of the essential oil of *P. graveolens*

Pharmacological Effects	*In Vitro / In Vivo*	Phytoconstituents Responsible for Pharmacological Effects	Specific Compounds Responsible for the Effects	Mechanism/Pathways	References
Antioxidant	*In vitro / In vivo*	Citronellol, citronellyl formate, γ-eudesmol, iso-menthone, Geraniol, β-citronellol, citral, linalool, farnesene, camphor, myrcene, terpineol	Citronellol	Citronellol elevated Nrf2 and antioxidant enzymes (GSH, SOD, catalase) and reduced lipid peroxidation in rotenone-exposed rats.	59,105
Antibacterial	*In vitro*	β-citronellol, caryophyllene oxide, Citronellol, geraniol, linalool, iso menthone, menthone, α-pinene, myrtenyl acetate, limonene, citral	Linalool	LE decreased intracellular ATP levels by disrupting key enzymes in energy-producing pathways, thereby suppressing bacterial proliferation and ultimately leading to cell death.	106
Antifungal	*In vitro*	Citronellol, geraniol, menthol, terpinene-4-ol, linalool, α-pinene, limonene, isomenthone, geranyl formate	Limonene	At MIC, reduced intracellular protein levels may be due to impaired synthesis and increased degradation caused by D-limonene–induced alterations in membrane potential and permeability in *C. tropicalis* SH1.	107
Antiviral	*In vitro*	Geraniol, Citronellol, Citronellyl formate, linalool, neryl acetate	Citronellol	*In vitro* antiviral efficacy of EOs and EOCs is mainly evaluated by their ability to inhibit cytopathic effects, reduce or prevent plaque formation, lower viral yield, and interfere with viral functions in specific host cell cultures.	108
Anti Inflammatory	*In vitro / In vivo*	Citronellol, geraniol, β-citronellol, γ-eudesmol, linalool, citral	Citral	Citral inhibited TNF-α–mediated neutrophil adhesion, suppressing iNOS/NO and LPS-induced pathways, blocking NF-κB signalling, reducing COX-2 and PPAR-α (60–70%), and markedly decreasing tissue inflammation (80–90%).	109
Anticancer	*In vitro / In vivo*	Geraniol, Linalool, Citronellol, citral	Geraniol	Geraniol suppressed cholesterol production in A549 cells and lowered serum cholesterol levels in mice bearing A549 xenografts, likely through inhibition of HMG-CoA reductase activity.	110
Antidiabetic	*In vitro / In vivo*	Citronellol, Linalool, linalyl acetate, β- phellandrene, β-citronellol, Geraniol, citral	Citral	Citral compounds showed their impact on 3T3-L1 adipocytes. The mechanism of action for antidiabetic effects in adipocytes established a correlation with the expression levels of SREBP1 and C/EBPR, as well as effects on the AMPK/ACC pathway.	111
Antidepressant	*In vitro / In vivo*	Linalool, geraniol, limonene, citronellol	Geraniol, citronellol	Components like citronellol and geraniol are involved in the modulation of the serotonergic synapse signalling pathway, which regulates the expression of relevant proteins in the ERK-CREB-BDNF pathway	112
Anti-hyperlipidemic	*In vitro / In vivo*	Linalool, geraniol	Linalool	Inhibition of lipid production HMGCR expression reduction	113,114

Additionally, it exhibited mild to moderate antibacterial effects against several Gram-negative (G-) bacteria, including *Escherichia coli, Helicobacter pylori, Aeromonas hydrophila, Citrobacter koseri, Enterobacter cloacae, Citrobacter freundii, Enterobacter sakazakii, Acinetobacter baumannii, Proteus mirabilis, Salmonella enterica, Pseudomonas aeruginosa*, and *Salmonella typhimurium*[30,31,67,115–118].

Researchers demonstrated that both Gram-positive (+) and Gram-negative (–) bacteria were found to be in a zone of inhibition. The zone was larger in Gram (+) bacteria, though *P. aeruginosa* and *K. pneumonia* were not affected by the rose geranium oil, but it was efficient against the Gram-negative bacteria *E. aerogenes, E. coli,* and *P. vulgaris*[32,119]. One more study revealed the same results as the previously described study. This investigation also examined the oil's predilection for Gram (+) bacteria as opposed to Gram (–) bacteria. The study concluded that because Gram (+) bacteria do not have the hydrophilic polysaccharide chain that serves as a barrier for Gram-negative bacteria, they are preferred. Gram-negative bacteria are less vulnerable to PGEO because of this difference[68].

Dorman and Decans discovered that more Gram-negative bacteria were impacted when an alkyl substituent was added to the non-phenolic ring structure[120]. This suggests that alkylation affects Gram sensitivity and that adding an alkylic side chain to the oil could increase its effectiveness and make it a highly potent disinfectant, food preserver, or chemotherapeutic agent[73,120–122].

The disk diffusion method revealed that G-ve bacteria, specifically *S. marcescens* and *C. freundii*, were more liable to PGEO compared to G+ve bacteria. Notably, PGEO showed the strongest effect against the biofilm-forming bacterium *S. enterica*, producing an inhibition zone of 14.33 ± 0.58 mm. Overall, PGEO demonstrated natural antibacterial properties effective against both Gram (+) and Gram (–) bacteria, making it a potential solution for preventing food contamination by foodborne pathogens[102] (Figure 4).

Sienkiewicz *et al.*, investigated geranium oil's antibacterial effects on Gram-negative (–) bacteria, such as *P. mirabilis, E. coli, C. freundii, E. sakazakii, E. cloacae, P. aeruginosa*, and *C. freundii* using the microdilution method[123]. The minimum inhibitory concentration (MIC) against clinical isolates of *E. coli* ranged between 3.0 and 3.75 mL/mL. Geranium oil, containing geraniol and citronellol, demonstrated potent antibacterial activity against challenging Gram-negative pathogens commonly associated with difficult-to-treat wound infections, with MIC values ranging from 9.25 to 10.5 ml/ml for *Pseudomonas* and 9.25 to 10.25 ml/ml for Proteus[123].

In another study, PGEO was specifically tested against six bacterial strains: *S. enteritidis, P. aeruginosa, E. coli, L. monocytogenes, S. aureus,* and *B. subtilis*. The results showed that all strains, except *L. monocytogenes* and *E. coli*, were susceptible, with *S. aureus* once again proving to be the most sensitive. Prior studies connected the effects of *P. graveolens* and its active ingredients to DNA and protein synthesis inhibition, along with cell membrane damage. The different cell membrane architecture of the pathogens explains why the geranium extracts exhibited a stronger antibacterial impact against G+ve bacteria than against G-ve bacteria[124]. Citronellol was the most active isolated chemical, exhibiting excellent antifungal activity and the lowest MIC against *E. coli* (0.007 ± 0.0003 mg mL^{-1})[67].

One of the major global health concerns is antimicrobial resistance (AMR) to conventional antimicrobial drugs, which is associated with increased morbidity, mortality, and economic burden[125]. Both commercial pharmaceutical medications and herbal cures are derived from a variety of medicinal plants and their secondary metabolites, which include essential oils. The amounts of these EOs needed to provide an effective antibacterial activity, however, might be more than what consumers would desire[126]. In natural medicine, essential oils have long been utilised as antifungal and antibacterial agents. The pharmaceutical business and contemporary society's growing interest in medicinal plants make scientific research targeted at validating these benefits and developing novel therapeutic agents essential[127].

Since the EO outpaced the amoxicillin and chloramphenicol controls, it may be a more effective antibacterial agent than the ones already on the market[37]. Promising antibacterial effects have been demonstrated by geranium oil, especially against several species of *Mycobacterium*, such as *M. abscessus, M. massiliense, M. smegmatis*, and *M. avium*. Studies reveal that it can successfully suppress these infections at minimum

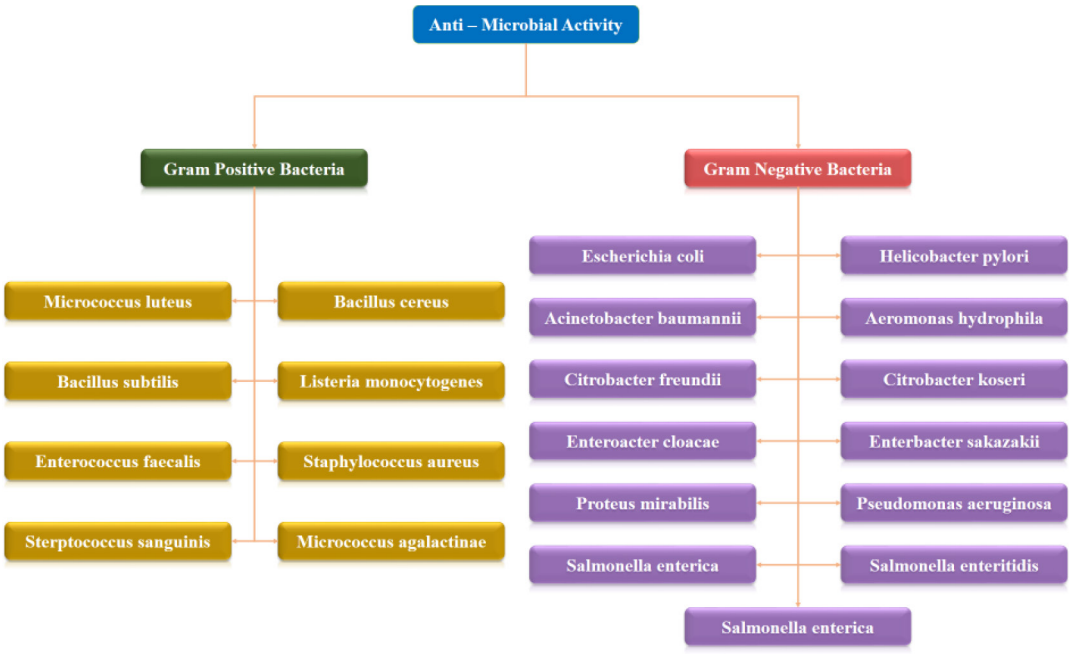


Figure 4. Antimicrobial activity of *P. graveolens* essential oil against various microorganisms.

inhibitory concentrations (MICs) between 17.9 and 35.9 µg/ml. Geranium oil exhibits notable effectiveness against several pathogenic bacteria, including but not limited to *Streptococcus, L. monocytogenes, P. aeruginosa, S. aureus*, and *S. enteritidis*, apart from its action against *Mycobacterium* spp. These results demonstrate geranium oil's potential as a medicinal agent to treat a range of bacterial illnesses[128]. The major components of *P. graveolens* volatile oils were (36.4%) citronellyl formate, β-citronellol, citronellol, cis-Menthone, and linalool (except eudesmol), which showed comparable activity to antibiotics that were noted in the tabular column[37,67] (Table 2).

6.2.2 Antifungal Activity

Pelargonium graveolens, often recognised for its antioxidant and antibacterial qualities, also possesses antifungal qualities. *P. graveolens* extracts have been found in studies to prevent the growth of several fungal pathogens, suggesting they are a viable natural treatment for fungal infections. These benefits are due to the existence of a variety of bioactive substances, which increase its utility in the sectors of cosmetics and therapy. Its value as a multifunctional natural resource is highlighted by its combination of antibacterial, antioxidant, and antifungal properties[73]. Additionally, GO is effective against the fungus *C. albicans* and *C. neoformans*, which cause serious health conditions in people[129]. *P. graveolens* was tested against 11 strains of *Candida*, including *C. tropicalis*, according to the studies. The concentration of geraniol that inhibits the production of *C. tropicalis* biofilms and kills the biofilm population is lower than that which inhibits 50% of the viability of human lung fibroblasts (666.36 µg/ml)[76]. Several commercially significant fungi, such as *C. albicans* (ATCC 12066), *A. flavus* (ATCC 9643), *P. ochrochloron* (ATCC 48663), *A. ochraceus* (ATCC 12066), *A. Niger* (ATCC 6275), and *P. funiculosum* (ATCC 56755), were used to assess the antifungal effects. The positive control was ketoconazole[67].

By screening PGEO's anti-candidal activity against *C. albicans* ATCC 10231, Mohaddese Mahboubi *et al.* demonstrated that PGEO's anti-candidal effects (n = 16) fell into four subsets. However, the primary ingredients of PGEO, geraniol, and citronellol, are crucial to their anti-candidal properties against clinical isolates[43]. PGEO against both fluconazole-sensitive and -resistant against a strain of *C. albicans* that is resistant to fluconazole, the oil from the *Candida* species showed a synergistic impact with the antifungal medication fluconazole[130]. EO showed the best inhibitory effect against yeast and substantial antibacterial efficacy against a variety of food-spoiling microbes. Compared to *S. aureus*, geranium EO exhibited higher efficacy against C. *albicans*[119].

When used medicinally, *P. graveolens*' antifungal qualities work well against *Malasezia* species. Pityriasis versicolor (PV) is among the numerous skin conditions attributed to the *Malassezia* genus. *P. graveolens* was evaluated by Naeini *et al.*, against strains of three different *Malassezia* species—*M. globosa, M. furfur,* and *M. obtuse*—that were obtained from PV patients[131,132]. All of the examined isolates were found to be susceptible to the effects of rose GEO, but *M. obtuse* was the only one against which the oil produced an inhibitory zone larger than 50 mm. *P. graveolens* was shown to create an inhibitory zone that was twice as large as that produced by the control group, which was administered ketoconazole, the medication recently used to treat *Malassezia* species illnesses[133] (Table 2).

6.2.3 Antiviral Activity

Numerous essential oils have demonstrated antiviral properties against a range of both enveloped and non-enveloped viruses, including influenza, adenovirus type 3, Junin virus, HSV, poliovirus, norovirus, coxsackievirus B1 and norovirus. These oils may serve as potential therapeutic agents due to their ability to inhibit viral activity and provide a natural alternative for combating various viral infections[134]. Considering bioactive plant-based and pure natural products have higher chemical diversities due to genetics, they present a fresh source of rich antiviral medicines. Many components of EOs, such as triterpenes, sesquiterpenes, and phenylpropanes, have been found to have potent antiviral properties against the rhinovirus and herpes simplex[24]. *P. graveolens* has been shown to suppress influenza, coronavirus, respiratory syncytial virus, and H1N1 neuraminidase (NA-1), among other viruses. According to *in vitro* research, geranium oil at a dosage of 0.3% inhibited the Influenza type A (H1N1) virus by 80%; after 30 minutes, this inhibition increased to 95%. Notably, it has not been proven to be effective against the Influenza type A (H3N2) virus[135].

In terms of the antiviral effect, research has primarily concentrated on viruses belonging to the class that cause respiratory diseases, like A (H1N1, H3N2). Investigating how *P. sidoides* aqueous solutions affect HIV has shown significant anti-HIV1 benefits. Many research works have investigated the antiviral activity of geranium essential oil against a range of viruses, mostly concentrating on viruses that cause respiratory infections. Two noteworthy discoveries demonstrate the antiviral properties of geranium oil: immune system activation and direct antiviral activity. According to a study conducted in 2022 in the journal Molecules, geranium essential oil prevented Influenza type A virus and other respiratory syncytial viruses from replicating[136–138].

A possible prophylactic approach against SARS-CoV could involve targeting ACE2 or TMPRSS2 receptors due to their unique enzymatic processes and tissue distribution. Consequently, without having a cytotoxic effect, GEO greatly decreased ACE2 activity[139]. Moreover, with a CC10 value of 533 µg/mL, studies show that geranium has inhibitory effects on Ross River virus infection (RRV-T48). Additionally, geranium has shown promise in combating the yellow fever virus[140]. Also, geranium may block adenovirus-signalling pathways that are needed for the production of viral genes. By preventing the virus from entering A549 cells through certain interactions with viral attachment factors, this suppression is accomplished[141].

GEO stimulates the immune system and aids in the fight against some infections, especially those that damage the mouth. Recent studies suggest that GO has a stronger antiviral effect, especially against *P. graveolens* and *P. roseum*. However, there have only been a few clinical trials on human volunteers, and research in this area is still in its early phases and needs more study[137,138].

This medication showed notable inhibitory effects against multiple tested viruses, including strains of the influenza A virus (H1N1, H3N2), coxsackie virus, parainfluenza virus and human coronavirus, in tests against several viruses linked to respiratory diseases. But against rhinovirus, adenovirus, and pathogenic avian influenza A virus (H5N1), it was found to be ineffective[142] Germany has authorised the use of EPs® 7630, a medication made from root extract from *P. sidoides*, to treat bronchitis. The medication has cytoprotective and immunomodulatory properties that prevent germs from interacting with host cells. Additionally, it increases the frequency of the ciliary beats of respiratory cells, stimulating them[143].

This medication's effectiveness against respiratory infections is attributed to its dual antiviral and antibacterial qualities. The discovery of medications that target the human immunodeficiency virus (HIV)

is a global priority due to the scarcity of anti-HIV-1 medicines. Significant anti-HIV-1 activity was found in this context when the aqueous extract of *P. sidoides* root was examined against HIV-1. Because of the activity of its phenolic components, this extract has a unique mode of action that sets it apart from the processes previously stated. It inhibits the attachment of HIV-1 to host cells[138] (Table 2).

6.3 Anti-inflammatory Activity

As plant-based medications and herbal remedies are inexpensive, readily available, and have few adverse effects, their popularity is increasing[144]. Inflammation is a complicated biological reaction of vascular tissues to damage stimuli. Redness, stiffness, discomfort in the joints, swelling in the joints, and decreased joint function are its signs. Acute inflammation is associated with increased leukocyte migration, damage to capillaries, and permeability of the blood vessels. An important physiological reaction associated with the onset of many chronic illnesses, such as cancer, autoimmune disorders like diabetes and arthritis, and Alzheimer's disease, is inflammation and permeability of the blood vessels[145]. The long-term, catastrophic immune-mediated disease known as chronic inflammation has both hereditary and environmental components[146].

Citral, the most important component of this essential oil, is an active ingredient due to its ability to reduce COX-2 and activate PPAR α and γ[147].

Sulfasalazine, when administered orally, effectively reduces inflammation severity and extent, diminishes crypt damage, and lowers the total colitis index in damaged colons. This aligns with previous research indicating that geranium oil, specifically from *P. graveolens*, may impact the release or synthesis of inflammatory mediators, demonstrating anti-inflammatory properties similar to its efficacy against carrageenan and collagen II-induced inflammation in mice. Additionally, *P. graveolens* essential oil has shown the ability to alleviate oxidative stress by inhibiting free radical generation, thereby impeding inflammation progression[95].

In a study by Boukhatem *et al.*, geranium essential oil (RGb vEO) demonstrated anti-inflammatory effects[148]. A single injection reduced paw oedema, while repeated administration suppressed arthritis in mice. Geraniol, a key component, showed protective effects against vaginal candidiasis and inflammation when applied vaginally with washing, inhibiting *Candida* growth. Boukhatem *et al.*, demonstrated the efficacy of *P. graveolens* essential oil in improving diabetic foot ulcers in rats[119,148]. The oil, showing dose-dependent suppression of nitric oxide and prostaglandin E2, highlights its potential for reducing inflammation in wound healing stages and promoting tissue regeneration in herbal cream[43].

In an *in vivo* study, *P. graveolens* was examined, revealing anti-inflammatory properties in both phases of inflammation within the carrageenan-induced oedema model. The combined essential oils (EOs) exhibited significant anti-inflammatory activity, demonstrating inhibition percentages of 84.84%, respectively[93]. The essential oil extracted from geranium demonstrated noteworthy anti-inflammatory effects in mice with induced ear oedema caused by Croton oil. Substantial reductions of approximately 73–88% were observed at dosages of 5 and 10 ml of oil annually.

The anti-inflammatory impact was further validated through histological analysis[119]. The anti-inflammatory effect was emphasised in mice-induced oedema with croton oil, and it seems to result from the decrease in 2,2-diphenyl picrylhydrazyl radicals. Geranium oil alleviates inflammation in the body due to its constituents, including geraniol and citronellol[137,138,149].

Geranium oil provides anti-inflammatory advantages by reducing inflammation and alleviating discomfort linked to conditions like tendonitis, rheumatoid arthritis, and sprains. Its ability to diminish inflammation not only decreases joint pain but also enhances the mobility of the affected joints[128,137]. Geranium oil is effective in addressing dermatological conditions like dermatitis, resulting in decreased redness, alleviated itching, and expedited healing of affected tissues[128,137,138]. Another substance called pinene dramatically decreased the synthesis of TNF-α and IL-6 in response to lipopolysaccharide-induced inflammatory reactions[150] (Table 2; Figure 5).

6.4 Anticancer Activity

A growing body of research has documented the antitumor properties of essential oils against several cancer cell lines *in vitro*, utilising Petri dishes. Since reactive oxygen species are the primary cause of oxidation and inflammation, essential oils have been

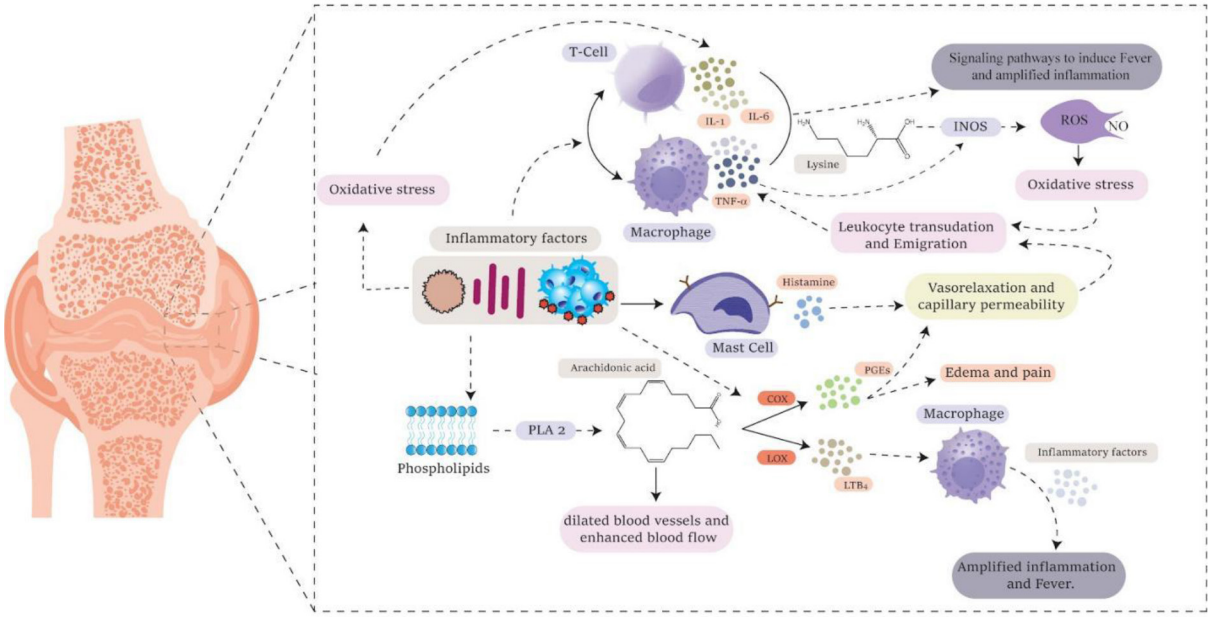


Figure 5. Schematic representation of inflammatory and oxidative stress pathways in rheumatoid arthritis. Inflammatory stimuli activate immune cells (T cells, macrophages, and mast cells), leading to the release of pro-inflammatory mediators (IL-1, IL-6, TNF-α, histamine) and activation of iNOS, COX, and LOX pathways. This promotes ROS generation, leukocyte migration, vasodilation, increased vascular permeability, oedema, pain, and amplified inflammation, ultimately contributing to joint damage.

demonstrated to have substantial anti-inflammatory properties, which suggests that they may also have anti-cancer benefits[24].

With linalool having harmful effects on cancer cells at doses of 20, 40, and 80 µm, geranium oil has inhibitory effects on the proliferation of T24 cells in prostate cancer. On the other hand, citronellol, which has antimetastatic and anti-angiogenic qualities, turns out to be the key ingredient in breast cancer. Regarding cervical cancer, geranium oil damages DNA[137].

Research exploring the antitumor effects within the realm of dentistry is still in its initial phases. Nevertheless, some studies suggest that geranium essential oil exhibits properties capable of impeding the proliferation of malignant cells[151,152]. In 2018, the Journal of Oral Medicine published a study that observed the effects of geranium essential oil on malignant cells in the oral cavity. The results suggested the possibility of both inducing cell death and inhibiting cell proliferation. It is crucial to note that the research was limited to cell cultures and not human patients[152].

The popularity of geranium essential oil is rising due to its use in treating haemorrhoids, inflammation, dysentery, heavy menstrual flows, and potentially cancer. Several dietary monoterpenes exhibit antitumoral properties, effectively hindering the initiation or advancement of cancer and promoting tumour regression. Geranium essential oils predominantly consist of monoterpenes, which have demonstrated the ability to prevent lung, skin, mammary, liver, and forestomach cancers in rat models[153].

The anticancer activity of geranium essential oil may be connected to its primary components, citronellol and trans-geraniol[154]. Geraniol increases the sensitivity of colon cancer cells to 5-FU, thereby strengthening the drug's cytotoxic effect. This effect is attributed to improved uptake of 5-FU along with suppression of both structural and functional differentiation in cancer cells[155]. Human colon cancer cells' ability to proliferate is strongly inhibited by geraniol, exhibiting potent antiproliferative properties. Notably, geraniol lacks cytotoxicity, primarily acting as a cytostatic agent. It hinders DNA synthesis, resulting in the accumulation of Caco-2 cells in the S phase[156].

Geranium induces apoptosis in the HT-29 human colon cancer cell line, ATL and MT-2 leukaemia cell lines, and MCF-7 breast cancer cells by generating reactive oxygen species (ROS). Through modulation

of various apoptosis-regulating signals, geranium effectively promotes apoptosis. In MCF-7 gastric cancer cells, geranium suppresses survivin production and elevates levels of apoptosis-related markers such as caspase-3, Bcl-2, miR-21, miR-92a, p53, and ki-67[157].

In the human glioblastoma U87-MG cell line, linalool has been shown to upregulate the levels of pro-apoptotic proteins like Bak and Bax while concurrently lowering the expression of anti-apoptotic factors like Bcl-xl and Bcl-2. As a result, the intrinsic apoptotic pathway is triggered[158.] Linalool has been shown to have effects on tumour development suppression and apoptosis in both *in vitro* and *in vivo* investigations, with S-180 tumour-bearing mice serving as primary subjects. Reactive oxygen species (ROS) formation is linked to these consequences, as is the activity of antioxidant enzymes being decreased[159]. Furthermore, urokinase-type plasminogen activator (uPA) and matrix metalloproteinases (MMPs) play critical roles in the development of new blood vessels and the spread of tumours. It has been demonstrated that uPA and MMP activity inhibition reduces the migration and invasion of cancer cells. Studies showed that geranium can suppress MMP-2, MMP-9, and MMP-1 in breast cancer and melanoma cells via altering signalling pathways such as NF-κB, PI3K-Akt, and p38 MAPK[56,160].

Notably, in MCF-7 breast cancer cells, geranium extract reduced the phosphorylation of mTOR and its downstream target, 4E-BP1[160]. In addition, geranium was shown to inhibit the growth of tumour cells and lower L-tyrosine hydroxylation and L-DOPA oxidation in B16F10 melanoma cells. This implies that the inflammatory signalling pathway caspase-1/IL-1β may be down-regulated as part of the process[161]. Furthermore, it has been shown that linalool reduces the amounts of several indicators of proliferation, including COX-2, TNF-α, IL-6, and NF-κB. In addition, it suppresses the excessive expression of angiogenic factors, including TGF-β1 and vascular endothelial growth factor (VEGF). Furthermore, by suppressing mutant p53 and concurrently lowering levels of the anti-apoptotic protein Bcl-2, linalool induces apoptosis[162].

Fayed conducted an *in vitro* study on the inhibition of human promyelocytic leukaemia cells (HL-60 and NB4)[65]. In this research, PGEO demonstrated its most significant anticancer activity, exhibiting LC_{50} values of 62.50 µg/ml in the NB4 cell line and 86.5 µg/ml in the HL-60 cell line. Monoterpenes are responsible for the oil's higher effectiveness on the NB4 cell line as opposed to the HL-60 cell line[65] (Table 2).

6.5 Antidiabetic Activity

High blood sugar levels are the sign of diabetes mellitus (DM), a chronic illness that, if left untreated, can cause major problems with the heart, blood vessels, eyes, kidneys, and nerves. Plants are thought to be an abundant source of chemicals with potential antidiabetic effects that work through different mechanisms[163].

Diabetes, which presents a serious global health concern, is characterised by hyperglycemia brought on by compromised insulin action. A study examined how the essential oil from *P. graveolens* leaves affected diabetes caused by alloxan and discovered that it has notable antioxidant and hypoglycemic properties similar to glibenclamide.

In diabetic rats, treatment with the oil decreased oxidative damage, suggesting that it may prevent the development of diabetes by lowering oxidative stress and the production of free radicals[44].

The oil was tested for its anti-diabetic properties by inhibiting α-amylase, α-glucosidase, and lipase enzymes. It effectively inhibited these enzymes, with significant IC_{50} values. Additionally, α-pinene, a component of the oil, demonstrated the ability to lower fasting blood glucose levels in alloxan-induced diabetic mice[61]. EO derived from *P. graveolens* leaves exhibited concentration-dependent inhibition of the α-glucosidase enzyme, with IC_{50} values for PGEO and acarbose determined as 93.72 ± 4.76 and 80.4 ± 2.17 µg/mL, respectively, against α-glucosidase. This highlights the potential of PGEO in acting as an antidiabetic agent by effectively controlling postprandial hyperglycemia through the inhibition of α-glucosidase, leading to a reduction in available monosaccharides for absorption in the bloodstream and, consequently, regulation of post-meal blood glucose levels[66].

The reports investigated the antidiabetic properties of *P. graveolens* and explored potential mechanisms of action[44,164]. A study showed that geranium and its constituents enhanced antioxidant defences, decreased lipid peroxidation, and had notable hypoglycemic effects[165,166].

The anti-diabetic properties of geranium are attributed to its ability to enhance glucose metabolism

and alleviate insulin resistance (IR), thereby aiding in the prevention of diabetes-related issues arising from oxidative stress. Geranium treatment led to a marked reduction in major pro-inflammatory mediators, including IL-6, iNOS, TNF-α, and COX-2, which are closely linked to diabetes, inflammation, and oxidation[167]. The potent acute antihyperglycemic effect in starch-fed rats was confirmed through the robust combined inhibitory activity of geranium-derived α-amylase and *in vitro* α-glucosidase[164].

Pelargonium graveolens showed potential as a supplemental treatment for type 2 diabetes and prediabetes, despite the fact that it does not enhance postprandial glycaemic responses in fasting rats. Insulin resistance symptoms were successfully treated with a dose of 65 mg/kg/day for 13 days, which improved body weight, hyperglycemia, hyperinsulinemia, and hypercholesterolaemia[43]. PGEO exhibited superior inhibitory effectiveness against α-glucosidase when compared to Acarbose, with respective IC_{50} values of 52.44 ± 0.29 µg/mL and 37.15 ± 0.33 µg/mL. EO displayed specific inhibitory activity targeting COX-1 (IC_{50} = 14.03 µg/mL), while PGEO exhibited a modest suppressive impact on COX-2 (IC_{50} = 275.97 µg/mL)[136].

Hsiu-Fang-Yen *et al*. investigated the anti-diabetic properties of citrals in a variety of essential oil samples, paying particular attention to how they affected the production of lipid droplets and the absorption of glucose in 3T3-L1 adipocytes. Citral compounds showed considerable potential as antidiabetic agents, especially in adipocyte function, according to research which looked at 29 commercial essential oils, including three varieties of Melissa essential oils. The study found impacts on the AMPK/ACC signalling pathway and a mode of action linked to the production of SREBP1 and C/EBPR, two proteins that are crucial for lipid metabolism. These results imply that by controlling adipocyte activity, citrals found in essential oils may offer therapeutic alternatives for the treatment of diabetes[111] (Table 2).

6.6 Other Activities

In a mouse model, the study sought to determine how well a blend of essential oils from *P. graveolens* (geranium) and thymol (PGT) treated *Eimeria papillata*. To find the best dosage, researchers gave mice infected with *Eimeria* three different doses: 50, 100, and 150 mg/kg. The maximum dosage of 150 mg/kg led to a noteworthy 56.92% drop in oocyst production ($P < 0.001$), which was linked to a 66.19% decrease ($P < 0.001$) in the parasite's jejunal developmental stages[168].

The PGEO contains food-grade alcohol (96%), medium-chain triacylglycerols (MCT), and α-tocopherol containing 40% and 60% capric and caprylic acid. The formulation's various biological activities, including antimicrobial, anti-inflammatory, analgesic and antiviral effects, have been substantiated by experimental investigations. Interestingly, following 140 hours of incubation with the SARS-CoV-2 virus, the spray inactivated 85% of the viral titer given at a 1:640 dilution and was not cytotoxic. As a result, this combination of ingredients can be taken as a dietary supplement to treat various bacterial or viral infections in addition to preventing SARS-CoV-2 infection[65,169] (Table 2).

Ne-BPEO's antifungal and aflatoxin B1 inhibitory mechanism was linked to a reduction in ergosterol concentration, increased ion leakage, reduced carbon source utilisation, and compromised ver-1 gene function. Furthermore, the model food's (maize grain) nutritional qualities and organoleptic (colour, taste, aroma, and texture) characteristics are successfully preserved by Ne-PGEO[170].

With higher antifungal efficacy than both essential oil dilution and nanoemulsion formulations, the hydrogel containing PGEO has tremendous potential as a therapy for vaginal candidiasis. It efficiently targets a variety of *Candida* species with MIC values 64 times lower. In comparison to the nanoemulsion, this formulation also has improved mucoadhesive qualities, a positive zeta potential, smaller droplets under 300 nm, and a lower risk for discomfort. These qualities improve the treatment's overall effectiveness by extending its retention on the vaginal mucosa and increasing its stability and bioavailability. This formulation's use of biodegradable components also satisfies the rising desire for safer and more environmentally friendly healthcare choices[171].

The essential oil was found to include 45 different components, which accounted for 94.2% of its makeup. Citronellol (30.2%), citronellyl formate (9.3%), and geraniol (7.6%) were the main ingredients. In both liquid and vapour phases, the essential oil's antibacterial qualities were assessed against 23 food-spoiling

microorganisms at three distinct concentrations (10, 20, and 30 µl/disc). Although it was less effective against Gram-negative bacteria, the oil had promising antibacterial action against Gram-positive bacteria and showed notable inhibitory effects on *Candida* strains. Additionally, a bigger zone of inhibition was associated with higher oil content, and the vapour phase showed noticeably higher antibacterial activity[73].

For genotoxicity, many mouse groups were examined: Group I served as the negative control; Group II was given 0.9 ml/kg of PGEO orally; Group III received an intraperitoneal injection of DOX at a dose of 20 mg/kg; Groups IV–VI were given oral doses of 0.3, 0.6, and 0.9 ml/kg of PGEO was administered for five consecutive days, along with a single intraperitoneal dose of DOX given on the 5th day. Following DOX treatment, bone marrow cells showed significant genotoxicity as shown by an increase in the frequency of micronuclei, sister chromatid exchanges, and chromosomal abnormalities. On the other hand, spermatocyte chromosomes were unaffected by DOX. Regarding all of the studied genotoxicity endpoints, PGEO had no effect. Additionally, the oil guarded against DOX-induced genotoxicity. Additionally, PGEO demonstrated potent cytotoxic effects on every human cancer cell line examined[172].

The effects of PGEO on the viability of *Harmonia axyridis* were evaluated by measuring the insects at varying concentrations in a Petri dish to gauge the insecticidal activity of the substance. The results show that the tested EO has its highest insecticidal effect at applied concentrations of 50% and 100%. However, PGEO did not exhibit strong repellent qualities when administered to *H. axyridis* at doses of 6.25% and 3.125%. In *H. axyridis*, PGEO affected 50% of the population at a concentration of 25%, and 33.33% of the insects were exposed to 12.5% of the PGEO[99].

Significant antibacterial and antioxidant qualities were shown by the essential oil, and its actions against pneumococci were amplified when mixed with other drugs. The oil's main constituents were citronellol, geraniol, and isomenthone. A synergistic impact against *S. pneumoniae* was demonstrated when geranium oil and antibiotics were combined. When G.O. and antibiotic combinations were used to treat *S. pneumoniae*, the viable cell count dramatically dropped from the sixth hour, according to a study of time-kill data. This suggests that adding G.O. to current antibiotics might increase their efficacy and aid in the prevention of bacterial resistance[103].

The essential oil under investigation had strong anti-glucosidase, antioxidant, and antibacterial qualities; it is especially efficient against *C. albicans, S. aureus*, and MRSA. It also showed a particular suppression of COX-1 enzyme activity and significant cytotoxic effects on Hep3B, MCF-7, and HeLa cancer cell lines. According to these findings, PGEO may be a useful source of organic antioxidants that support detoxification procedures linked to avoiding oxidative stress-related illnesses. In addition to its fascinating cytotoxic and COX-1 inhibitory actions, it offers potential as an alternative and supplementary therapy for infections caused by dangerous bacteria. All things considered, PGEO has potential as a new therapeutic agent with useful uses in food items, medications, and dietary supplements[136].

In addition to increased antioxidant activity, *P. graveolens* generated higher amounts of essential oils, total phenols, and flavonoids when UV-B and photosynthetically active radiation (PAR) rose. On the other hand, total phenols and flavonoids, antioxidant activity, and essential oil levels were not substantially impacted by UV-A radiation. Furthermore, the total flavonoid content and antioxidant capability were further enhanced by the combination of UV-B and high PAR intensity. However, because of the combined impacts of high PAR intensity and elevated UV-B, the ratio of citronellol to geraniol—a crucial quality indicator for PGEO slightly reduced, increasing the total proportion of PGEO[96].

When administered at a dose of 1 µL/mL, the essential oil (EO) caused chromosomal aberrations of 11.40% after 72 hours of exposure and had a moderate effect on the mitotic index of 15.32%. These results imply that the *P. graveolens* EO strain from Northeast India has promising type-II anti-diabetic and skin-whitening qualities. These qualities might be used in the creation of anti-diabetic and skin-whitening compositions with additional confirmation from clinical studies[173].

Geranium essential oil was isolated and subsequently incorporated into electrospun ultrafine bean starch fibres to develop an effective antibacterial formulation. A rich composition of volatile chemicals, such as β-linalool, cis-geraniol,

citronellyl formate, citronellol, and linalool formate, was found by GEO analysis. Interestingly, fibres with 40% GEO showed a considerable decrease in the bacteria under study (*L. monocytogenes, S. aureus*, and *E. coli*), indicating their potential uses in active packaging to prolong food products' shelf lives and minimise food loss[174].

The pathophysiology of *Tinea corporis* is influenced by dermatophytes, a form of saprophytic fungus that penetrates the skin. Dermatophytes' resistance to traditional antifungal drugs, which is frequently brought on by biofilm development, necessitates the urgent need for effective therapies. Endophytic fungi with high bioactivity frequently inhabit the culinary fragrant plant *P. graveolens*, which is well-known for its antibacterial qualities. Eight substances were identified by a phytochemical investigation carried out after *A. caespitosus* AUMC 14405 was isolated from *P. graveolens* leaves. Furthermore, 27 metabolites might be identified in part thanks to GC/MS analysis[175].

THP-1 human macrophages expressing an NF-κB reporter were used to test the reduction of NF-κB activation at dosages up to 0.25 μL/mL. The results of this screening showed that wormwood essential oils (EOs) were the most beneficial, followed by geranium and coriander. In LPS-stimulated THP-1 macrophages, these wormwood EOs were reported to drastically lower mRNA synthesis of IL-6, IL-1β, TNF-α, and COX-2 by more than 50%. The chemical makeup of a few chosen EOs was examined using gas chromatography–mass spectrometry (GC–MS). The two main ingredients, which make up more than half of each EO, were examined at the same concentrations as the entire oils. The principal component or a combination of the two primary ingredients may be responsible for the anti-inflammatory properties of crude essential oils. Additionally, these EOs were found to inhibit caspase-1 activity by more than 50%[176].

Van Wyk *et al.*, reported that leaves were steamed and vapours were inhaled as a treatment for tuberculosis (TB)[34].

P. graveolens essential oil has several beneficial effects on the skin, including the removal of metabolic waste, improvement of lymphatic circulation, and anti-cellulite action[177].

6.7 Applications of Essential Oil

6.7.1 Cosmetics

In the discipline of cosmetics, the potential of PDGB (a byproduct of Geranium oil) was explored in 2022 by Patil *et al.*, who uncovered the strong antioxidant, anti-tyrosinase, as well as antimicrobial activities from the methanol and ethyl acetate extracts[178]. The extract's safety was also validated by *in vitro* examination using 3T3 fibroblast cell lines (ATCC 1658), showing its applicability in cosmetics as well as offering the probability of additional revenue for oil extractors. Essential oils are widely used by the cosmetics industry as skin regenerators in products such as soaps, shower gels, lotions, creams, and safe tonics. Essential oils can be used in sunscreen formulations to prevent photoaging, sunburn, wrinkles, and other skin issues since they can absorb the majority of UV radiation (with wavelengths between 290 and 400 nm)[94]. The aromatic odour in EOs makes it fit as a substitute for dandruff shampoos, issuing a good fragrance[179]. These EOs (Geranium) may exhibit complementary outcomes while employed in shampoo formulation at a pH range of 5.5 – 6.5. The energetic factors in EOs actively penetrate the scalp, nourish hair follicles and stimulate growth, supplying nutrients, root hair moisturising, hair strengthening, and are also effective in clearing unwanted metabolites and preventing hair damage[180]. The elements of essential oils, such as menthol, limonene, carvacrol, linalool, α-pinene, or terpineol, stimulate the transepidermal pathway, which increases skin permeability to hydrophilic components of cosmetic preparations[177].

When added to shampoo formulations with a pH of 5.5 to 6.5, *P. graveolens* can exhibit synergistic benefits. Purifying the scalp, for example, decreases irritation and manages excessive oiliness and dandruff, strengthening the hair fibre, promoting circulation in the hair shafts, and ultimately speeding up hair development. Furthermore, it's critical to manage excessive scalp oiliness, which can hinder healthy hair development and encourage offensive smells. As a result, the addition of certain aromatic compounds to EOs together with their unique chemical makeup in hair formulations encourages mental, emotional, and physical equilibrium while also giving the hair and scalp pleasant scents[181,182].

6.7.2 Aromatherapy

Aromatherapy is a subfield within herbology stipulated to focus on the medicinal use of fragrances and volatile compounds. Or also this is a practice used to aid with the relief, treatment, or prevention of various illnesses and infections through inhalation[183,184]. Generally considered one of the best natural perfumes, geranium oil is used in many soaps and detergents because of its ability to remain fragrant even when mixed with soap alkalies. Furthermore, this oil is frequently used in aromatherapy to support emotional well-being[185,186]. In 2021, a study conducted by Gazerani *et al.*, showcased that inhalation aromatherapy using GEOs effectively diminishes the pain and equilibrates the physiological factors in patients after appendectomy[187]. This aromatherapy is a safe, simple, and efficient alternative to the long-term use of painkillers after surgery, resulting in dependence and negative effects. The approach of aromatherapy to patients after surgery can alleviate pain, equilibrate physiological factors, intensify patient care, and also boost the outcomes after surgery, providing added value for appendectomy patient management. Another study in 2019, conducted by Pujiati *et al.*, studied the involvement of EOs during menstrual pain by comparing two treatment groups[188]. For the 1st group, a blend of lavender, ginger, clary sage, and GEOs is administered through effleurage massage, and for the 2nd group, only lavender essential oils are administered as such. Using the Mann-Whitney test, it was found that there was a remarkable difference in the pain between the two groups ($p = 0.001$), also stated that 1st group was more effective in relieving menstrual pain in comparison with the 2nd group. Safarzadeh *et al.* demonstrated that the GEOs massage is better than routine labour care in reducing the pain during birth pangs[189].

6.7.3 Food Industry

The EO obtained from *P. graveolens* were utilised not only as an antioxidant in food industries but also for flavouring agents, fragrance agents, and a component of active packaging. These flavouring agents are employed in the production of sweets as well as chewing gums[190]. Together with alcoholic and non-alcoholic beverages, people use this flavouring agent for foodstuffs, and they are even effective in insect-repellent properties[185,186].

Owing to their antibacterial properties, they are employed in active packaging since their effectiveness against the *L. monocytogenes, S. aureus*, and *E. coli*, these GEOs have the potential to prevent losses and enhance the product's shelf life[191]. The application of GEOs in the food industry is a valuable option for enhancing food preservation and safety, because of their antimicrobial and antioxidant properties, they are useful in prolonging fresh and processed foods' shelf life[192].

Another important application of GEO, as a wash solution it can inhibit *L. monocytogenes* and *E. coli,* enhancing the antibacterial and antimicrobial safety in fresh-cut vegetables, thus promoting potential use in food safety practices[193].

6.8 Toxicity and Safety

Pelargonium graveolens should be used with caution according to acute toxicity studies. Azzam *et al.*, investigated the protective potential of *P. graveolens* oil against liver and kidney damage caused by cefotaxime in rats[194]. Their findings demonstrated that geranium oil significantly reduced serum liver enzyme activities and renal markers while enhancing protective tissue biomarkers such as glutathione and catalase. This suggests its potential role in mitigating oxidative stress and cellular damage. Similarly, Sabah reported the hepatoprotective effects of *P. graveolens* essential oil (PGEO) against paracetamol-induced toxicity in Wistar rats[195]. The study highlighted its ability to reduce lipid peroxidation, restore antioxidant enzyme activity, and improve liver and haematological parameters, with no observed direct toxicity, supporting its potential as a safe antioxidant and hepatoprotective agent. Beyond its medicinal benefits, *Pelargonium* essential oils have also demonstrated significant insecticidal properties. Tabari *et al.*, explored the toxicity of *Pelargonium* essential oil against *Culex pipiens* mosquitoes, attributing its effects to its major components citronellol, geraniol, and linalool[196]. The oil exhibited strong toxic effects on both larvae and egg rafts, with LC_{50} values of 5.49 µg/mL and 0.45 µg/mL, respectively. Similarly, M'hamdi *et al.*, assessed the toxicity of *P. graveolens* essential oil and extracts against *Sitophilus oryzae*[197]. The essential oil demonstrated the highest toxicity, with an LC_{50} of 19.22 µL/L after three days, likely due to its high monoterpenoid content. Additionally, ethanolic and aqueous extracts exhibited notable toxicity, with LC_{50} values of 1.38 g/50 seeds and

6.30 g/50 seeds, respectively. These findings suggest that *P. graveolens* essential oil holds promise as a natural insecticide. The essential oil extracted from the entire *P. graveolens* plant was evaluated by Boukhatem *et al.*, who found that the LD_{50} was 1,000 mg/kg body weight in mice via the intraperitoneal route. Despite this, geranium essential oil was granted GRAS (Generally Recognised as Safe) status and approved for use in food by the U.S. Food and Drug Administration (FDA)[73]. An *in vitro* assessment of multiple *Pelargonium* species was carried out, where Lalli *et al.*, used IC_{50} values as the primary indicator of toxicity. *P. graveolens* exhibited a relatively high IC_{50} value, suggesting low toxicity[32]. It has also been reported that the essential oil derived from *P. graveolens* offers substantial protection against oxidative stress–related harm. Every day administration of 67 mg/kg was adequate to decrease protein oxidation in the tests and to alleviate both oxidative stress and lipid peroxidation. Additionally, this oil enhanced sperm quality[45].

Pelargonium graveolens essential oil is generally considered safe at therapeutic doses, with studies reporting low acute toxicity and good tolerability in animal models at 50–400 mg/kg/day. Topical application is usually well tolerated when diluted, although constituents such as geraniol and citronellol may cause skin irritation or allergic sensitisation in sensitive individuals. Experimental studies have also shown hepatoprotective and renoprotective effects at therapeutic doses, with no significant organ toxicity reported. However, excessive or prolonged use may increase the risk of irritation and systemic adverse effects due to the concentrated nature of volatile terpenes. Although current evidence supports a favourable safety profile, further long-term toxicity and clinical studies are needed to confirm its safety in broader therapeutic applications[70,83,194].

The reports on toxicity were limited, as they failed to specify which organs were affected or how biological indices were influenced. Current literature does not indicate any confirmed adverse or toxic effects of *P. graveolens* in human use, other than warnings related to pregnancy.

7. Conclusions

The comprehensive review highlights the promising therapeutic potential of PGEO as a natural source of biologically active compounds, with potentially rich applications in pharmaceuticals, nutraceuticals, cosmetics, and complementary medicine. The bioactive compounds present in PGEO contribute to modulating inflammatory pathways, reducing oxidative stress, and improving joint function, making it a valuable complementary approach alongside conventional treatments. Additionally, its favourable safety profile and non-toxic nature reinforce its suitability for long-term use.

Despite these promising findings, there exists few limitations, such as variability in essential oil composition and lack of standardisation. Further research is necessary to bridge the existing gaps in scientific understanding. Further research is needed to clarify the exact mechanisms involved, refine the dosage and formulation, and carry out large-scale clinical studies to confirm its safety and effectiveness. Investigating potential interactions with standard pharmacological treatments will also be crucial for integrating *P. graveolens* oil into mainstream therapeutic strategies.

By addressing these research gaps, *P. graveolens* could pave the way for innovative, natural treatment options that enhance patient quality of life while minimising the side effects associated with conventional medications.

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9. References

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Author Contribution

Monish Santhosh R.: Collected literature and drafted the manuscript; Sonia G. B.: Helped in manuscript revision; Anandraj L.: Helped in drafting the phytochemistry portion; Nishu S.: Supervising and drafting the paper; Hariprasath L.: Conceptualisation, helped in finalisation of the manuscript. All authors have read and agreed to the published version of the manuscript.