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A comprehensive review on traditional uses, chemical composition, pharmacological effects and applications in the food industry of *Pelargonium odoratissimum* (L.) L'Hér. in comparison to other *Pelargonium* spp

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ABSTRACT

It is estimated that about 80 % of the world's population use traditional medicine to treat various diseases. Many herbs of the genus *Pelargonium* are used in traditional medicine to treat diarrhea, dysentery, fever, respiratory tract infections, liver ailments, wounds, gastroenteritis, hemorrhage, kidney and bladder disorders, and other diseases. They are sources of various biologically active molecules such as volatiles like monoterpenes, sesquiterpenes, or non-volatile metabolites from the group of phenolics, such as tannins, phenolic acids, and flavonoids. This genus is rich in essential oils, which have a wide industrial application in perfumery, cosmetics, soap and cream production due to their good antioxidant potential and anti-ageing/rejuvenating properties. This review therefore contains and discusses the current scientific findings on *Pelargonium odoratissimum* (L.) L'Hér. – a lesser known member of the genus *Pelargonium*, alone and in comparison with other *Pelargonium* species. Studies on the composition of this particular species, as well as its biological potential and prospects for industrial use will be addressed in order to shed new light on its potential applications.

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1. Introduction

Plants are potential sources of natural bioactive molecules such as phenolics, alkaloids, tannins, terpenes, quinones, coumarins, etc. which are synthesized by secondary metabolism (Shrinet et al., 2021; Fernandez-Soto et al., 2023; Ben Hsouna et al., 2012, 2022a, 2023; Ben Akacha et al., 2023). In fact, modern pharmaceuticals contain at least 25 % of substances synthesized by plants (Olaleye et al., 2010). In recent years, therefore, there has been a lot of interest in use of medicinal plants for the treatment of various diseases, in the enrichment of extracts with active ingredients and in the extraction of plant material on a large scale sufficient for industrial application. Among the various plant species, plants of the genus *Pelargonium* from the Geraniaceae family occupy an important place. This botanical family comprises almost 280 species and about 11 genera, which are distributed worldwide. The representatives of the Geraniaceae are mainly herbaceous plants, native to South Africa (about 80 % of the species), mainly in the winter rainfall region of the south-western Cape and cultivated in the Mediterranean basin and subtropical regions (Mativandlela et al., 2006). Chemical studies have shown that plants of the genus *Pelargonium* are often rich in valuable compounds such as sterols, monoterpenes, sesquiterpenes, diterpenes, fatty acids and phenolic compounds. These are aromatic plants that are often cultivated for their essential oil (EO) (e.g. in China, the main producer of geranium oil) which is one of the most important EOs in the world, recognised for its strong antimicrobial potential (Maggs et al., 1995; Rajeswara et al., 2002). The constituents of geranium oil contain a variety of compounds that have been shown to have various pharmacological activities and have been successfully used for the treatment of many diseases (Shrinet et al., 2021; Ben Akacha et al., 2023). Scientific studies have led to the isolation of bioactive components with therapeutic properties that are used as modern medicines, while others serve as substrates for drug synthesis (Ben Hsouna et al., 2022a; Ben Hsouna, 2022b). Their EO is also used in the perfumery, cosmetics, and aromatherapy industries (Jaggali et al., 2011). The representatives of *Pelargonium* spp. are used in traditional medicine for pain relief in hemorrhoids, dysentery, inflammation, or for the treatment of cancer. The best known species of this genus are *Pelargonium purpureum* [Steudel], *Pelargonium graveolens* [L'Héritier], *Pelargonium peltatum* [L'Héritier], *Pelargonium domesticum* [Bailey], *Pelargonium inquinans* [L'Héritier], *Pelargonium odoratissimum* [Soland], *Pelargonium quercifolium* [Hoffmanns], and *Pelargonium melissinum* (Koutelidakis et al., 2009; Asgarpanah, 2015).

The aim of this work is therefore to provide a comprehensive overview of the phytochemical and pharmacological studies on *P. odoratissimum*, a lesser known representative of *Pelargonium* genus and to evaluate its potential importance due to the richness of bioactive compounds, in comparison to other species of the same genus. The study aims to shed new light on the utilisation of this species in the pharmaceutical, food or cosmetic industries. The richness of volatile compounds in its oil, which have antiseptic, antiphlogistic or spasmolytic properties, among others, and are present together with valuable antioxidants - polyphenols predispose this plant or its oil for a wide range of therapeutic and cosmetic applications, as well as for potential uses in the food industry. Considering the genetic and metabolic engineering of *Pelargonium* spp. discussed in the last section of the review, the efficiency of cultivation of *P. odoratissimum* is promising.

1.1. Review methodology

This review uses a comprehensive approach relying on databases such as ScienceDirect (https://www.sciencedirect.com/), PubMed/Medline (https://pubmed.ncbi.nlm.nih.gov/), and Scopus (https://www.elsevier.com/solutions/scopus) as well as established search strategies to collect relevant literature on *P. odoratissimum* and related species. It includes "botanical descriptions", "genetic and metabolic engineering studies", "chemical composition analyses", and "pharmacological activities". The methodology includes an in-depth study of the identified compounds, mechanisms of action and potential applications for the different *Pelargonium species*. The critical evaluation of the collected data serves as a basis for the conclusions and the future direction of the research. The ultimate goal is to compile a comprehensive review that meets academic standards and provides a coherent understanding of the scientific background of *P. odoratissimum.* For the preparation of the present manuscript, a thorough screening of the scientific literature databases was performed. In particular, we only considered (i) studies from the 21st century, and (ii) studies evaluating the potential biological effects of *Pelargonium* spp. treatment. Durnig the literature search, we find two review papers on *Pelargonium* species - by Roman et al. (2023), and by Blerot et al. (2016), neither of which discussed the potential of *Pelargonium odoratissimum* in detail.

2. Botanical description of *Pelargonium odoratissimum*

Taxonomically, *P. odoratissimum* belongs to the Geraniaceae botanical family, to the genus *Pelargonium* (Maggs et al., 1995). The species is commonly known as apple geranium because of its distinctive, apple-like smell (Khalid et al., 2010). Interestingly, the name 'Pelargonium' comes from the resemblance of the fruit shape. The plant has been found to be similar to the beak of a stork (in Greek, *pelargos*). The name of the species 'odoratissimus' refers to its pleasant fragrance. Historically, the Irish botanist William Henry Harvey divided the genus *Pelargonium* into 16 different sections and more than 800 different species based on the different morphological characteristics and growing conditions (Plaschil et al., 2022). According to this classification, *P. odoratissimum* was assigned to the section *Cortusina* (Mativandlela et al., 2006). Two different species groups were distinguished in the section *Cortusina*. The first includes the species *P. eortusifolium, P. crassicaule, P. echinatum, P. magenteum, and P. sibthoitifolium,* commonly known as the *P. cortusifolium* group. The second group, the *P. reniforme* group, includes *P. album, P. dichondrifolium, P. odoratissimum, P. reniforme*, and *P. sidiodes* (Dreyer et al., 1992). The species classification is also summarized in the following table (Table 1).

Pelargonium odoratissimum is a low-growing herbaceous plant that rarely grows taller than about 30 cm. Its main stem is coarse and has old stipules at the base which give it a scaly appearance. The roots are slightly tuberous and the leaves are typically roundish to ovate-cordate and measure between 30 and 40 mm in diameter, having crenulate margins. The leaves are apple-green in colour and covered with fine, short hairs, making them pleasant to the touch and giving off a strong apple-mint scent. The flowers of the plant are generally pale pink and relatively small (Rosato et al., 2008). Morphological analysis revealed that the symmetrical leaves are characterized by a largely obtuse basal angle and a basal petiole. In addition, a light microscopy experiment described that the leaves have a concave and

Table 1
Taxonomical classification of *Pelargonium odoratissimum.*

Taxonomical rank	**Taxon**
Kingdom	Plantae
Division	Spermatophyta
Class	Dicotyledones
Order	Geraniales
Family	Geraniaceae
Genus	*Pelargonium*
Species	*P. odoratissimum*
Binomial name	*Pelargonium odoratissimum* (L.) L'Hér.

convex rib characterized by a large number of short trichomes along the midrib and the druse (Romitelli and Martins, 2013). In terms of geographical distribution, *P. odoratissimum* is widespread in the south-non-western and eastern Cape. There are also locality reports from the Lowveld of Mpumalanga and KwaZulu-Natal, South Africa. It generally grows in the undergrowth of forests or in shady areas sheltered by rocky ledges or taller shrubs (Mativandlela et al., 2006). In terms of growing conditions, *P. odoratissimum* is a robust and versatile plant that can adapt to a wide range of environmental conditions. It generally prefers full sunlight, although it can tolerate some shade. It prefers a soil with good drainage, moderate moisture and warm temperatures, but can survive in low temperatures (down to 0°C) (PFAF, 2014, Datiles, 2022). The plant needs regular watering, but with careful care it can last for many years without needing to be replaced. As it is a perennial plant, occasional pruning may be necessary to maintain its health (Khalid et al., 2010).

3. Chemical composition of *Pelargonium odoratissimum*

3.1. Essential oils (EO)

From a molecular point of view, the main bioactive compounds of *P. odoratissimum* belong to the volatiles (see Fig. 1).

The results shown in Table 2 indicate that citronellol is the main constituent of commercially available essential oils with a content of over 25 % (Matusinsky et al., 2015; Benelli et al., 2018), followed by a high content of geraniol. Significant concentrations of methyl eugenol and isomenthone were described in the EOs from the seedlings obtained by hydrodistillation (Khalid et al., 2010, Khalid et al., 2009), while the EOs obtained by steam distillation were richer in limonene and isomenthone (Khalid et al., 2009). The dominance of methyl eugenol was confirmed in the EO samples from the leaves (content up to 96 %) (Andrade et al., 2011). In this context, Fig. 2 illustrates the bioactive molecules mechanism of action of *Pelargonium odoratissimum* depending on their organ.

3.2. Phenolic composition

Although this species has been extensively investigated for its essential oil composition, there are surprisingly only few studies on the phenolic composition of *P. odoratissimum*. According to the results of Fernandez-Soto et al. (2023), the methanolic extracts of *P. odoratissimum* contain high amounts of phenolic compounds (258.2± 14.4 mg GAE/g DW), including flavonoids whose content is only 31.0±1.4 mg CE/g DW. These authors compared the extracts of 21 medicinal plants commonly used in traditional medicine and only the extracts of *Cinnamomum* sp. and *Melissa officinalis* contained higher levels of phenolics than *P. odoratissimum*. The phenolics from *Cinnamomum* sp. and *P. odoratissimum* were also found to be the main contributors to the antibacterial activity of the medicinal drink from Ecuador, called Hordata. In the fingerprinting studies of this more polar extract, the authors identified a large number of gallic acid derivatives, catechins and several flavonoid glucosides of pharmacological importance (Table 2, Fig. 1).

Williams et al. (2000) conducted a systematic study of the phenolic compounds in the leaves of 58 *Pelargonium* species using thin

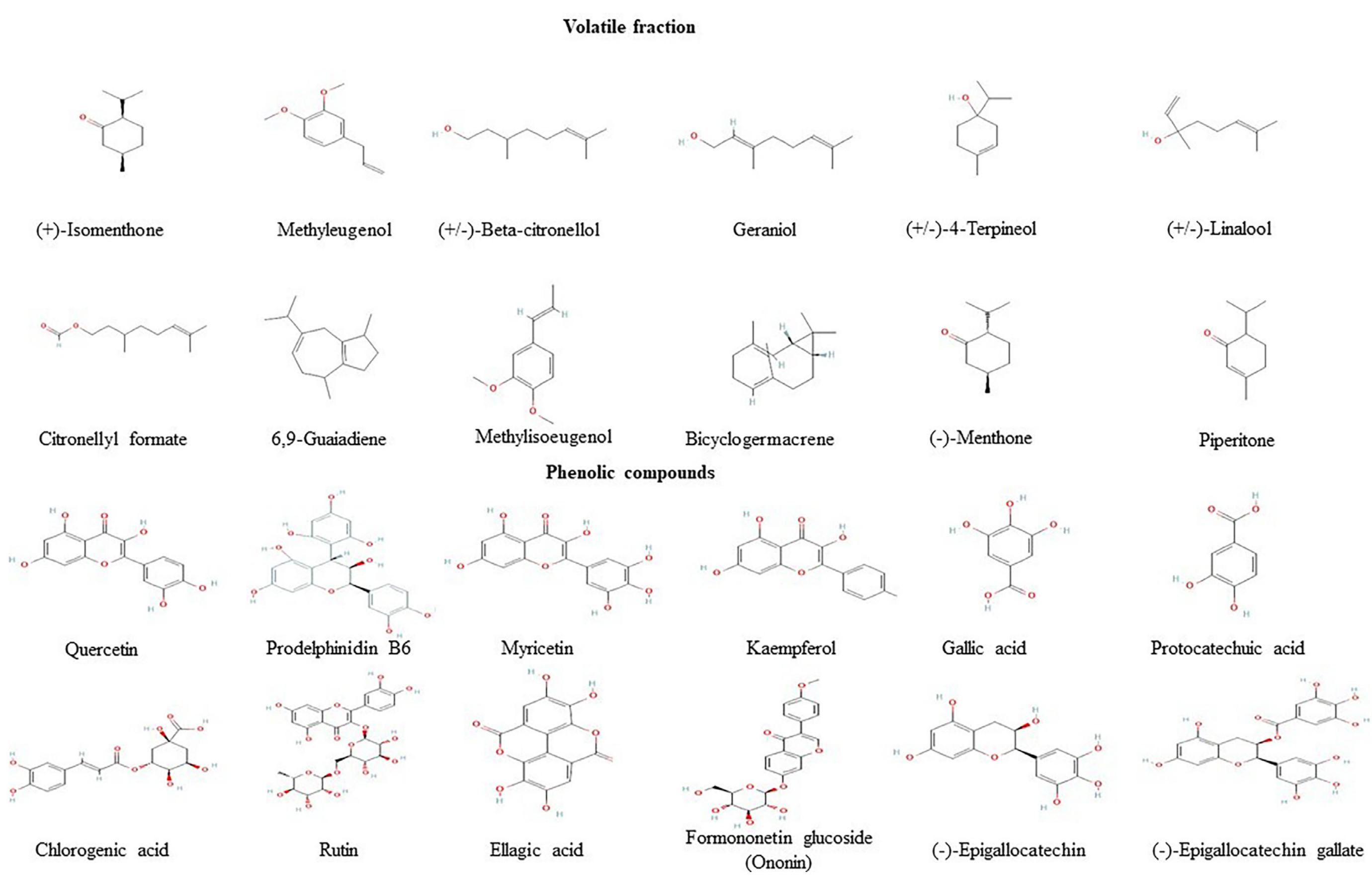

Fig. 1. The major secondary metabolites determined in *Pelargonium odoratissimum*Scientific papers give some evidence of the pharmacological potential of the valuable essential oil (EO) content of *P. odoratissimum*. The EOs are complex mixtures of volatile aromatic plant secondary metabolites with low-molecular-weight (Rehman et al., 2016). They mainly consisted of terpene compounds and their derivatives and are usually produced by hydro- or steam-distillation (da Silveira et al., 2015; Masango, 2005). The chemical composition of the EOs obtained from *P. odoratissimum* is reported in Table 2. The extraction methods, the harvest period of the plant and the part of the plant used (leaves, flowers, seedlings) as well as the percentage of the main constituents identified in each EO are also given.

Table 2
Chemical composition of *Pelargonium odoratissimum* essential oil and extracts.

Origin	Sample/Extraction method	Harvest period	Plant tissue	Main components identified	Reference
Shanghai, China	Essential oil obtained by hydro-distillation	During 2007 and 2008	Seedlings	isomenthone (from 26.44 to 36.92 %), methyleugenol (from 30.40 to 37.05 %),	(Khalid et al., 2010)
Czech Republic	Commercial essential oil	Not available	Not available	β-citronellol (24.86 %), geraniol (12.50 %), terpinene-4-ol (6.19 %), linalool (4.73 %)	(Matusinsky et al., 2015)
Italy	Not available	June 2016	Aerial parts	isomenthone (16.2 %), citronellol (30.1 %), citronellyl formate (9.1 %), 6,9-guaiadiene (5.7 %)	
Poland	Commercial essential oil	Not available	Not available	citronellol (29.77 %), citronellyl formate (9.22 %), geraniol (6.51 %), isomenthone (3.34 %), linalool (2.45 %).	(Benelli et al., 2018)
Brazil	Essential oil obtained by steam distillation	June 2007	Leaves	methyl eugenol (96.8 %), methyl isoeugenol (1.7 %), bicyclogermacrene (0.9 %), germacrene B (0.3 %)	(Andrade et al., 2011)
Pebworth-UK	Essential oil obtained by steam distillation for 1 h	July 2000	Leaves	methyl eugenol (from 31.2 to 79.8 % %), isomenthone (from 4.6 to 16.9 %); L-menchone(from 2.5 to 7.9 %); piperitone (from 1.4 to 8.8 %)	(Lis-Balchin and Roth 2000)
Shanghai, China	Essential oils obtained by hydro-steam and steam distillation	During 2007 and 2008	Seedlings	Hydrodistillation: methyl eugenol (30.4 and 25.9 %), isomenthone (26.4 and 26.9 %). Hydro-steam distillation: limonene (30.5 and 32.4 %), isomenthone (20.8 and 19.2 %) and methyl eugenol (21.3 and 16.2 %). Steam distillation: limonene (49.4 and 38.8 %), isomenthone (15.1 and 19.3 %), methyl eugenol (12.2 and 14.4 %)	(Khalid et al., 2009)
Ecuador	Methanolic extract	March 2022	Leaves	Epigallocatechin, gallocatechin polymers, epigallocatechin gallate, luteolin glucosides, tri-*O*-galloylglucose, rutoside, quercetin hexoside, naringenin glucoside, kampferol neohesperidoside, trifolin, myricetin galactoside, quercetin, gallic acid, galloylglucose, geraniin, granatin B, ellagic acid, formononetin glucoside	(Fernandez-Soto et al., 2023)
UK	Methanolic extract	Not available	Leaves	Quercetin, prodelphinidin, myricetin, kaempferol, gallic acid and protocatechuic acid	(Williams et al., 2000)
Egypt	Aqueous extract	March 2021	Leaves	Gallic acid, chlorogenic acid, syringic acid, ferulic acid, rutin, naringenin	(Abdelbaky et al. 2022)

layer chromatography (TLC) and found that the leaves of *P. odoratissiumum* contain significant amounts of the flavonoid quercetin and the proanthocyanidin prodelphinidin. The flavonoids myricetin and kaempherol as well as some simple phenolic acids such as gallic acid and protocatechuic acids were also found to be present in significant quantities.

Abdelbaky et al. (2022) also analyzed the composition of an aqueous extract of *P. odoratissimum* leaves using HPLC-DAD and quantified several phenolic compounds in it. Their results were in agreement with those of Fernandez-Soto et al. (2023), in which the highest amounts of gallic acid, chlorogenic acid, syringic acid, and ferulic acid were detected in the investigated samples, while rutin and naringenin were the most abundant representatives of flavonoids, however their combined contents were significantly lower than those of phenolic acids.

As explained in the following sections, *P. odoratissimum* has been used for the treatment of various remedies and has a significant pharmacological potential, possibly due to the presence of important secondary metabolites from the groups of terpenes and polyphenols (flavonoids and phenolic acids). As studies on the composition of the plant are not very numerous, further research is needed on this subject.

4. Pharmacological activity of *Pelargonium* spp

Pelargonium species, their chemistry and biological activities are the subject of numerous studies and review articles. Products from *Pelargonium* species have been used in the past to cure fevers, neuralgia, wounds, tumors, diarrhea, and dysentery. Among them, *P. graveolens* is one of the best-known representatives. Various authors describe the importance of its volatiles and its use as an antioxidant, antidiabetic, dermatoprotective, anti-inflammatory and antibacterial (Al-Mijalli et al., 2022; Moutaouafiq et al., 2019; Ćavar and Maksimović, 2012), antifungal, anticancer (Fahmy et al., 2023), repellent, and contact fumigant (Abouelatta et al., 2020) agent. The most important indications of the bioactivity of the different *Pelargonium* species are listed in Table 3.

Although knowledge about *P. odoratissimum* is relatively limited, several authors emphasise its strong pharmacological potential and its importance in phytotherapeutic treatment. Various biological activities of this particular plant species are discussed below. They range from its antibacterial and antifungal activity, which are the best described in the scientific literature, to its anti-inflammatory properties and free radical scavenging activity.

4.1. Antibacterial properties of Pelargonium spp

Antibacterial activity is a complex process involving living organisms in which the survival rate can be affected by the presence of toxic substances (Ben Akacha et al., 2023; Ben Hsouna et al., 2023). The antimicrobial properties are the best-studied properties of *Pelargonium* spp.

Among the various bacterial strains susceptible to *Pelargonium* essential oils and extracts are those that cause food spoilage, plant pathogens and the infectious strains that can cause dysfunctions of the human urogenital system, respiratory tract,dermatoses or inflammatory conditions. According to certain studies (Christodoulakis et al., 2013; Lis-Balchin et al., 1997; Nozaki et al., 2001), *Pelargonium* oils have both antibacterial and antifungal properties.

P. odoratissimum EO has been shown to have a strong antimicrobial action. Lis-Balchin et al. (1996) focused on the development of antibacterial activities of the plant against *S. aureus* ATCC 25923 and *Escherichia coli* ATCC25 992. The authors demonstrated a visible inhibition of their growth after the administration of 100 μL/mL and 500 μL/mL of *P. odoratissimum* essential oil, respectively. These results were confirmed by Andrade et al. (2011), although the impact of *P. odoratissimum* EOs was weaker.

A green synthesis and characterization of ZnO nanoparticles (NPs) using the aqueous leaf extract of *P. odoratissimum* was the subject of the work of Abdelbaky et al. (2022). The antibacterial activity against

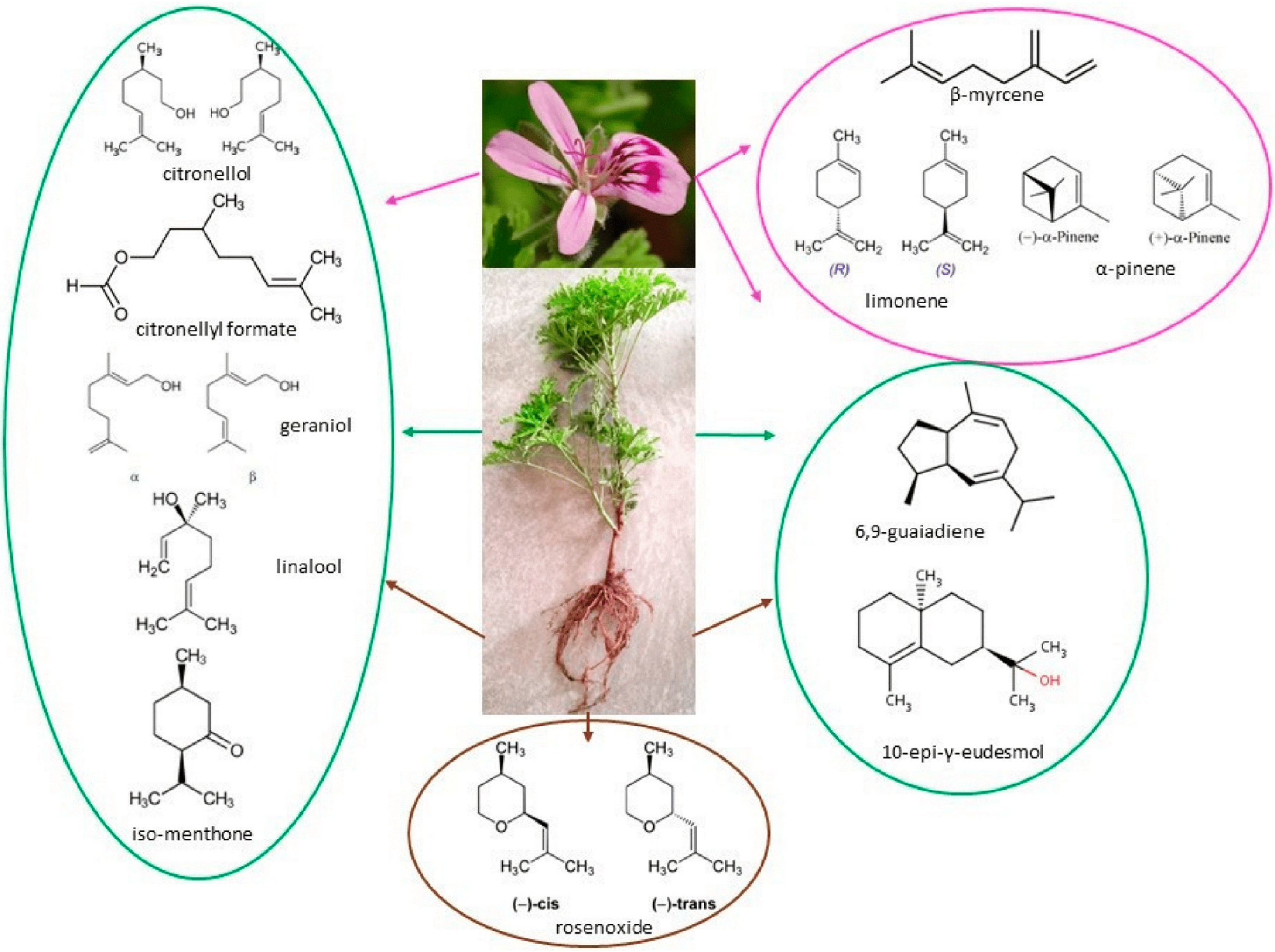

Fig. 2. Bioactive molecules mechanism of action of *Pelargonium odoratissimum* depending on their organ.

foodborne pathogenic bacterial strains was investigated using the disc-diffusion assay for both – the nanoparticles with *P. odoratissimum* extract (10, 20 and 30 μg/mL) and the *P. odoratissimum* extract alone (20 μg/mL), and it was found that *S. aureus* (ATCC 8095), *Pseudomonas aeruginosa* (ATCC 10662), and *E. coli* (ATCC 25922) had inhibition zones between 28 and 16 mm. The ZnO NPs had a stronger effect than the extract itself, acted on both Gram-positive and Gram- negative bacteria and interestingly showed a higher or equal inhibitory potential as gentamycin used as a positive control at the same dose. This study denotes that the biosynthesized ZnO NPs can be used as safe alternatives to synthetic compounds and as potential candidates for medical and pharmaceutical applications.

In further studies by Lis-Balchin and Roth (2000) it was also found that methyl eugenol is the main contributor to the antimicrobial activity, efficacy, and bioactivity of the EO of *P. odoratissimum* against *S. aureus, S. epidermidis, Proteus vulgaris,* and *Bacillus cereus*.

The plant is traditionally consumed in horchata, a traditional herbal infusion drink from Ecuador. Fernandez-Soto et al. (2023) investigated the impact of the individual components of this herbal mixture on antimicrobial potential. In their studies the plant extracts were tested against *Enterococcus faecium, Enterococcus faecalis, S. aureus, Klebsiella pneumoniae, Acinetobacter baumannii, Acinetobacter baumannii, Pseudomonas aeruginosa, Enterobacter cloacae, E. coli* and resistant species such as methicillin-resistant *S. aureus, K. pneumoniae* carbapenemase, vancomycin-resistant *E. faecalis*, serine-β-lactamase and metallo-β-lactamase *E. coli*, and *E. coli* extended-spectrum β-lactamases. The authors indicated a great antibacterial potential of *P. odoratissimum* herb against *S. aureus* with a MIC value of 500 μg/mL and a MBC of 500 μg/mL. In addition, the tested extract showed partial inhibition of biofilm formation of these bacteria, including resistant MRSA strains.

In view of the above information, it can be concluded that *P. odoratissimum* EO or extracts possess strong antimicrobial properties. *P. odoratissimum* has been found to be a rich source of EO and polyphenolics which may affect its antimicrobial activity. Based on the information gathered, it can be concluded that this species contains similar constituents to other *Pelargonium* species and its antimicrobial activity is similar in strength to that of other geraniums. There are many examples in the scientific literature of the antimicrobial activity of other, more commonly cultivated species. Their antimicrobial properties are induced by the presence of the same metabolites that are present in *P. odoratissimum*. Previous reports have documented the potential of *Pelargonium* spp. and their constituents against various bacterial pathogens (Mativandlela et al., 2006), such as *S. aureus, Proteus vulgaris, Bacillus cereus*, and *Staphylococcus epidermidis*. The results indicate considerable antibacterial activity with an inhibition halo of 0.8 cm for *S. aureus* at a concentration of 20 % of the oil in methanol, suggesting that *Pelargonium* EOs could be used as new antibacterial agents for food, pharmaceuticals or cosmetics. Methanolic and petroleum extracts showed higher antibacterial activity than the steam-distilled volatile samples.

Table 3
The examples of the major pharmacological applications of *Pelargonium* species.

Indication	Species and samples	Study type	Major findings	References
Cancer	*Pelargonium graveolens* EO	*In vitro*; promyelocytic leukemia cell lines: NB4 and HL-60	EO with citronellol, geraniol, 10-epi-γ-eudesmol, isomenthone, and linalool as the leading components showed anticancer properties with LC_{50} values of 62.5 and 86.5 μg/mL respectively	
	Pelargonium graveolens	*In vitro* Fibrosarcoma-Wehi 164 cell line	Silver nanoparticles inhibited the growth of tumor cells by 50 % at 2.6 μg/mL.	Safaepour et al., 2009)
Free radicals	*Pelargonium* EO	*In vitro* studies with egg yolk, chicken liver and muscle tissue	The antioxidant index of EO was calculated as IC50 of 100 ppm.	
Hypertension and stress	*Pelargonium graveolens* EO	Clinical study in (14 patients with hypertension and 8 patients with stress-induced problems)	Improvement after 2 months of oral administration of 45 mL EO/day (citronellol 8 %, geraniol 9.0 %, geranyl acetate 27.4 %, citronellyl formate 6.6 %, linalool 5.5 %, α-pinene 2.6 %, α-phellandrene 1.7 %, *cis-rose* oxide 1.2 %)	(Nozaki et al., 2001)
Bacterial and fungal infections	*Pelargonium graveolens EO*	*In vitro* dilution method	Strong activity against Gram positive bacteria, and origin-dependent activity against Gram-negative bacteria (*B. subtilis, Enterobacter faecalis, E. aerogenes, S. aureus, S epidermidis, Mycobacterium smegmatis, Streptococcus mutans, E. coli, Yersina enterociltica, K pneumoniae, P. aeruginosa. Salmonella typhi*)	(Aggarwal et al., 2000)
Inflammatory conditions	*Pelargonium graveolens EO*	*In vivo* Rat model of inflammation	Essential oil was administered at doses 100, 200 or 400 mg/kg to rats suffering from carrageenan-induced paw edema. The oil showed an anti-inflammatory activity.	
Scrub typhus	*Pelargonium graveolens*	*In vitro* Repelling properties	Undiluted essential oil repelled the 57 % of larvae	
Seborrheic dermatitis	*Pelargonium graveolens*	*In vivo*	A shampoo and cream containing *Pelargonium graveolens, Cymbopogon martinii, Laurus nobilis, Tanacetum annum* and *Lavandula latifolia* applied twice daily cured the disease, which did not recur.	(Kim et al., 2014)
Spasmolytic conditions	*Pelargonium* EO	*In vitro* Isolated guinea pig ileum	Diluted EO exerted cAMP-mediated spasmolytic properties with postsynaptic mechanism of action (IC50 between 6.03×10^{-7} g/mL to 4.83×10^{-5} g/mL)	(Lis-Balchin et al., 1998; Lis-Balchin et al., 1997)
Vaginal infections	*Pelargonium roseum*	*In vitro*	*Pelargonium* essence-controlled *Trichomonas vaginitis* with a strength comparable with metronidazol	

In the study on the antimicrobial properties of Gerniums, the oil of *P. radula* (Cav.) L'Hérit, which has been shown to be an active inhibitor of fourteen (Pepeljnjak et al., 2005), and extracts of *P. sidoides* and *P. reniforme* are listed as inhibitors of Gram-positive and Gram-negative bacterial strains (Mativandlela et al., 2006).

As proved above, *P. odoratissimum* extracts and EOs are more efficient in the treatment of disorders caused by the presence of Gram-positive bacteria. However, their effect on Gram negative bacteria, especially after changing the formulation or applying samples growing in certain regions, can be significant and even comparable to the strength of an antibiotic. The strength of *P. odoratissimum* is comparable to other geraniums due to a similar composition containing citronellol and geraniol. These constituents have been shown to act synergistically against several bacteria when combined with the antibiotics norfloxacin, ciprofloxacin, erythromycin, and/or oxacillin (Shin et al., 2007), and gentamycin (Mostafa et al., 2018) and are effective against *Bacillus cereus, Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa* and *Salmonella typhi*.

Table 4 shows the results of the antimicrobial studies conducted on *P. odoratissimum* and other *Pelargonium* spp.

4.2. Antifungal activity of Pelargonium odoratissimum

As already mentioned, the antibacterial and antifungal properties of *Pelargonium* spp. have been extensively studied. The spectrum of antifungal properties of geranium oils included plant pathogens, honeybee chalkboard illness, and HIV/AIDS. According to some reports, the fungicides nystatin, amphotericin B and ketoconazole in combination with *Pelargonium* oil or its constituents, citronellol and geraniol, had additive or synergistic effects in inhibiting the growth of *Candida* species (Rosato et al., 2008), *Trichophyton choenleinii, T. soudanense, Aspergillus niger*, and *A. flavus*. Of these essential oil constituents with high antifungal activity, citronellol (24.86 %), geraniol (12.50 %), citronellyl formate (7.72 %), isomenthones (6.19 %), and eudesmol (5.95 %) were the most effective. The pathogenic species tested in these studies are among the most serious cereal pathogens. These results suggest that EOs have great potential for the safe and environmentally friendly treatment of fungal plant diseases and could be a modern and effective alternative to chemical pesticides.

In the search for a replacement of synthetic preservatives against storage moulds by natural agents, *P. odoratissimum* EO was shown to significantly inhibit mycelial growth and aflatoxin B1 production in a dose-dependent manner. It proved to be non-phytotoxic with a germination rate of 100 % in chickpeas. Due to its antifungal and anti-aflatoxigenic potential and its *in vivo* efficacy, *P. odoratissimum* EO has been recommended as a herbal food preservative (Szutt et al., 2019). In another study (Lis-Balchin et al., 1996), the essential oil of *P. odoratissimum* was effective against three fungi: *Aspergillus flavus* CML 1816, *Aspergillus carbonarius* CML 1815, and *Aspergillus parasiticus* CMLA 817. For all three toxigenic fungi, a significant inhibition of mycelial growth was observed with increasing EO dosage. The inhibitory activity against the same three fungi (*A. flavus, A. carbonarius and A. parasiticus*) was confirmed by Andrade et al. (2011) in a publication in which the authors reported a strong activity of EO against fungi (100 % inhibition) and a low effect on bacteria.

In addition, Prakash et al. (2016) studied the antifungal and anti-aflatoxin efficiency of the EO of *P. odoratissimum* extracted from the leaves of the plant by hydrodistillation. The free radical-scavenging activity was tested against 2,2-diphenyl-1-picryl-hydrazyl radicals (DPPH) while the antifungal activity was investigated against 14 food-borne mold species. The oil showed moderate antifungal activity with minimum inhibitory concentrations of 3 to 5 μL/mL, compared to other EOs tested. In addition, the EO inhibited mycelial growth and aflatoxin B 1 production in a dose-dependent manner.

The antifungal effect of *P. odoratissimum* EO against five pathogenic fungi (*Oculimacula yallundae, Microdochium nivale, Zymoseptoria tritici, Pyrenophora teres*, and *Fusarium culmorum*) was also investigated by Matusinsky et al. (2015). In their study, the radial

Table 4
Antibacterial activity of *Pelargonium* spp. essential oils and extracts.

Study design	Species	Sample	Bacterial species	Major findings	References
In vitro	*Pelargonium odoratissimum*	Methanolic extract	*Staphylococcus aureus, Klebsiella pneumoniae, Escherichia coli*	Methanolic extract from *P. odoratissimum* was the second strongest antimicrobial extract from the traditionally used drink Horchata	(Fernandez-Soto et al., 2023)
In vitro	*Pelargonium odoratissimum* nanoparticles	Aqueous leaf extract in ZnO nanoparticles	*Staphylococcus aureus, Bacillus cereus, Escherichia coli*	Increased antimicrobial action when in the form of nanoparticles, comparable with gentamycin	(Abdelbaky et al., 2022)
In vitro	*P. glutinosum* Eeden ex Hoffmanns, *P. filicifolium* and cultivars	Essential oil	*Saccharomyces ludwigii, Zygosaccharomyces bailii, Salmonella enteritidis, Listeria inocua*	Eight essential oils reduced the bacterial population in broccoli soup.	(Lis-Balchin et al., 1998)
In vitro	*Pelargonium* spp.	*-Commercial EO*	*Staphylococcus aureus, S. Epidermidis, Proteus vulgaris, Bacillus cereus*	Citronellol and geraniol exhibited antibacterial activity.	(Lis-Balchin et al., 1996)
In vitro	*Pelargonium graveolens* L.	Essential oil obtained from the leaves by hydrodistillation	*B. subtilis, Enterobacter faecalis, E. aerogenes, S. aureus, S epidermidis, Mycobacterium smegmatis, Streptococcus mutans, E. coli, Yersina enterociltica, K pneumoniae, P. aeruginosa. Salmonella typhi*	Strong activity against Gram- positive bacteria, variable activity against Gram-negative bacteria that is dependent on the origin of the leaves	(Aggarwal et al., 2000)
In vitro	*Pelargonium graveolens* L.	Essential oil obtained from the leaves by hydrodistillation	*K. pneumoniae, P. Vulgaris, S. Aureus, Enterococcus faecalis, E. Coli, P. Aeruginosa*	The EO inhibited growth at a concentration of 0.2-2.0 % or 60-600 ppm.	(Jirovetz et al., 2006; Hammer et al., 1999)
In vitro	*Pelargonium graveolens* L.	Essential oil obtained from the leaves by hydrodistillation	*S. aureus, E. Coli, P. Vulgaris*	Combination of thyme and *P. graveolens* oil inhibited growth of both Gram-positive and Gram- negative bacteria.	(Ghaly, 2006)
In vitro	*Pelargonium graveolens* L.	Essential oil obtained from the leaves by hydrodistillation	*E. coli, K. Pneumoniae, P. Vulgaris, B. Subtilis, S aureus, P. Aeruginosa*	*P. graveolens* oil (MIC 6.7-12.8 mg/mL) inhibited Gram-positive and Gram-negative bacteria.	(Prabuseenivasan et al., 2006)
In vitro	*Pelargonium graveolens* L.	Essential oil obtained from the leaves by hydrodistillation	*Lactobacillus acidophilus, L. casei, Atopobium vaginae, Bacteroides vulgaris, Gardnerella vaginalis, Streptococcus agalactiae*	The species isolated from vaginal samples of women with bacterial vaginosis were susceptible to oil (citronellol 24.9 %, geraniol 17.5 %, linalool 12.9 %)	
In vitro	*Pelargonium graveolens* L.	Essential oil obtained from the leaves by hydrodistillation	*E. coli, S. Aureus. K. Pneumoniae, p. Aeruginosa. Proteus mirabilis*	Bacteria isolated from urine samples of patients with urinary tract infection were susceptible to *P. graveolans* oil (18.6-27.5 mm inhibition zone, MIC 8.9-35.9 mg/mL)	
In vitro	*Pelargonium graveolens* L.	Leaf ethanolic extract	*Listeria monocytogenes, S aureus, E. coli, Enterobacter cloacae, Acinetobacter baumanii*	These spoilage bacteria were found sensitive to the extract which can be used to extend shelf-life of processed foods.	(Bayoub et al., 2010)
In vitro	*Pelargonium graveolens* L. Herit. Ex Ait.	Leaf extract	*S. aureus, E. coli*	Cotton fabric treated with microencapsulated extract retained 50-60/ aroma after 10 washes. The extract was effective against both bacteria, with *S. aureus* (Gram-positive) being more sensitive.	(Thilagavathi and Kannaian, 2010)
In vitro	*Pelargonium graveolens* L.	Essential oil obtained from the leaves by hydrodistillation	*Lasisiplodia thebromae, Colleotrichum musae*	Banana fruits treated with *P.* EO were not affected by crown rot disease.	(Sangeetha et al., 2010)
In vitro	*Pelargonium graveolens* L.	Acetone flower extract	*S. aprophyticus, Micrococcus luteus*	The extract inhibited bacterial growth at varied concentrations.	(Mostafa et al., 2018)
In vitro	*Pelargonium graveolens* L. Herit	Essential oil obtained from the leaves by hydrodistillation	25 bacterial strains	The EO was more active against Gram-positive bacteria. No inhibition was observed against *Escherichia coli, Aeromonas hydrophila, Alkaligenes faecalis, Erwinia carotovora, Enterobacter aerogenes, Proteus vulgaris* or *Moraxella sp.*	

Table 5
Antifungal properties of *Pelargonium* spp.

Study design	Species	Preparation method	Fungus species	Outcomes	References
In vitro	*Pelargonium odoratissimum*	Essential oil	Aspergillus flavus, Aspergillus carbonarius, and Aspergillus parasiticus	Inhibition of mycelial growth and aflatoxin B1 production was observed with an increasing dosage of the EO	(Andrade et al. 2011)
In vitro	*Pelargonium odoratissimum*	Essential oil from the leaves	14 food-borne mold species	Moderate antifungal activity with minimal inhibitory concentrations of 3 to 5 μL/mL	(Prakash et al. 2016)
In vitro	*Pelargonium odoratissimum*	Essential oil	*Oculimacula yallundae, Microdochium nivale, Zymoseptoria tritici, Pyrenophora teres, Fusarium culmorum*	EO from PO showed good results with an effective dose against most species below 1 μL/mL	(Matusinsky et al. 2015).
In vitro	*Pelargonium graveolens*	Essential oil	*Aspergillus niger, A. flavus, A. nidulans, A. fumigatus, Rhizopus nodulens, Fusarium oxysporum* (plant pathogen)	*P. graveolens* oil at 0.25-2.5 mL/L showed concentration dependent antifungal activity (11-89 mm inhibition zone)	
In vitro	-	Individual terpenes	*Colletotrichum gloeosporioides* (*Glomerella cingulate*) (causes anthracnose of mango, citrus, and papaya fruits)	Citronellol and geraniol were more active (100 % inhibition) than geraniol (60 % inhition) and linalool (8 % inhibition) at 250 ppm in the tertiary group.	(Su et al., 2010)
In vitro	*Pelargonium graveolens*	Essential oil	*Candida albicans* (causing candidiasis), *Cryptococcus neoformans* (causing cryptococosis)	The oil of *P. graveolens* L., its six constituents and their mixture in equal proportions of all compounds were fungicidal for both fungi. The MIC values were: 7.8-31.2 μL/mL for geranium oil; 7.8 μL/mL for geraniol and isomenthone; 15.6 μl/mL for the compound mixture. The activity was independent from temperature. Oil and constituents were better than fungicides clorimazole, traconazole, gruseofulvin, nystatin, fluconazole and amphotericin B.	(Rath et al., 2005)
In vitro	*Pelargonium graveolens*	Essential oil	*A. flavus* 2 strains	*P. graveolens* oil at 0.75 g/L was fungitoxic and was better than synthetic fungicides. At 0.5 g/L it stopped production of aflatoxin B_1 by the fungal strains.	(Singh et al., 2008)
In vitro	*Pelargonium graveolens*	Essential oil	*A. niger, A. flavus, A. fumigatus, Mucor spp., Rhizopus spp.*	Geranium oil at a dilution of 1:1000 displayed mycosporicidal activity against fungi isolated from HIV-positive individuals.	
In vitro	*Pelargonium graveolens*	Essential oil	*Malassezia* species	Three *M.* species isolated from patients with pityriasis versicolor were susceptible to *P. graveolens* (geraniol 22.1 %, citronellol 28.2 % essential oil (26.1 mL inhibition zone)	(Naeini et al., 2009)

mycelial growth of the fungi was tested by agar dilution method and the EO of *P. odoratissimum* showed good results with an effective dose against most species below 1 μL/mL.

Considering the above information, it can be concluded that *P. odoratissimum* EO or extracts possess significant antifungal properties.

In the scientific literature there are many examples of the use of application of other geraniums as antifungal agents against *Fusarium, Malassezia, Aspergillus, Rhizopus, Collototrichum, Vericillum, Candida, Cryptococcus, Phomopsis* and other species. Table 5 shows the findings on the antifungal properties of the representatives of the genus. Among the other species shown to have antifungal activity, the ethanolic extracts of *P. radula* (Cav.) L'Hérit were mentioned as active against fifteen fungi (Pepeljnjak et al., 2005), the EOs from *P. graveolens* inhibited dermatophytes even when administered as vapors, and the ethanolic extracts of *P. reniforme* and *P. sidoides* inhibited the growth of *Fusarium oxysporum, Aspergillus niger* and *Rhizopus stolonifera.*

Similar to the results on the antimicrobial activity of *P. odoratissimum*, the scientific investigations confirmed moderate to strong potential of the plant in the inhibition of fungi. As previously demonstrated, citronellol and geraniol are probably responsible for this activity (Su et al., 2010). The active concentration of different *Pelargonium* species including *P. odoratissimum* is a few micrograms (or microliters) per mL, demonstrating their strong inhibitory properties.

4.3. Effects on diabetes

Diabetes mellitus (DM) is diagnosed on the basis of elevated blood glucose concentrations (Benlarbi et al., 2022). Hyperglycemia associated with diabetes results from insulin deficiency on an immunological basis, as in type 1 diabetes, or from impaired insulin action or insulin resistance, as in type 2 diabetes (Galicia-Garcia et al., 2020). Secondary forms of diabetes can occur after insulin deficiency due to conditions such as pancreatitis/pancreatectomy or insulin resistance as in Cushing's syndrome or acromegaly. Complications can occur with any type of diabetes. Diabetes is the leading cause of blindness, end-stage renal failure, and non-traumatic amputations. Diabetes increases the risk of atherosclerotic vascular disease by a factor of two to five. Currently, 285 million adults are affected by this disease. Unfortunately, this number will rise to 439 million by 2030 (Reed et al., 2021).

Current treatment for diabetes includes synthetic medication or insulin. Both treatments have proven to be effective in controlling the disease over time. However, both solutions also create new problems. Adverse events in patients treated with either or both therapies include drug resistance, hypoglycemia, edema, and weight gain. These symptoms are obviously counterproductive to the intended goal and can be difficult to deal with when trying to improve one's health (Johns et al., 2006). Geranium, traditionally used as an antidiabetic agent, has come under criticism. Previous studies have shown that the ethanolic extract of *P. odoratissimum* (Ahamad and Uthirapathy, 2021), especially at doses of 600 and 1000 mg/L, significantly lowered glucose levels from the second hour to the third and fourth hours after injection, and this effect was dose-dependent. The effect of the extract at a dose of 1000 mg/L was similar to that of glibenclamide. However, the hypoglycemic effect of the extract was clearly recognizable.

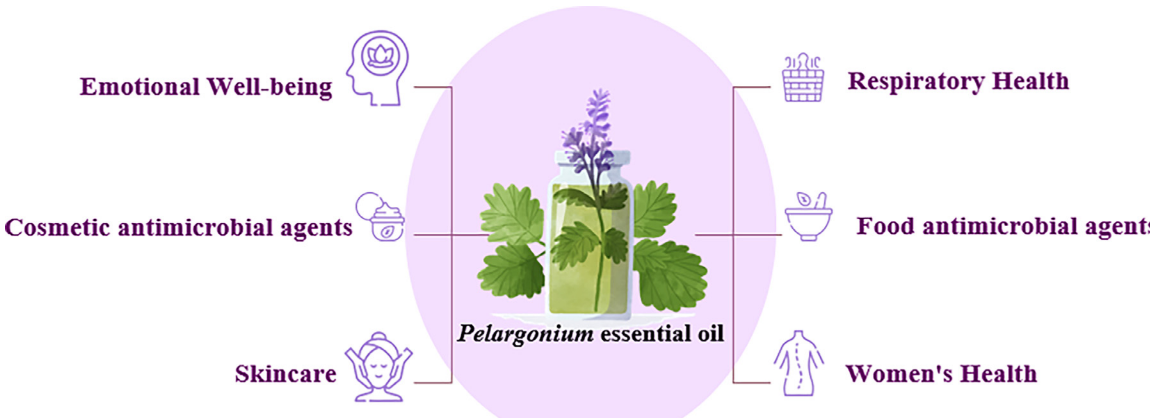

Fig. 3. Illustration of the diverse benefits of *Pelargonium* essential oil.

A stronger potential has been demonstrated for other representatives of the genus. In a study by Boukhris et al. (2012), *P. graveolens* EO was tested at a dose of 150 mg/kg body weight on alloxan-induced diabetic rats and proved to be more effective in the treatment of diabetes mellitus. After administration of the oil, the diabetic rats showed a significant blood glucose lowering effect. After treatment with rose geranium EO, TBARS levels in the liver and kidneys decreased significantly, demonstrating the anti-oxidative properties of the oil, which inhibits the development of diabetes by reducing oxidative stress and preventing the formation of free radicals.

4.4. Versatile aromatics and therapeutic potency of Pelargonium essential oils

Pelargonium essential oil is known for its many uses. With its robust rose aroma underlined by a refreshing menthol note, geranium oil has a soft, fresh, and long-lasting fragrance, that makes it an aroma used in perfumery,aromatherapy, as a calming agent and as a remedy for nervous tension, anxiety, fear, exhaustion, depression, in the treatment of bronchitis, laryngitis, and menopausal symptoms, for conditions such as eczema, as a cleansing, balancing, astringent, and moderate skin tonic, for athlete's foot, and for respiratory well-being (Naeini et al., 2011; Moyo et al., 2013). Traditionally, EO has been considered as a potential aphrodisiac agent. At this point, it should be noted that the EO of *Pelargonium odoratissimum* has a similar fingerprint to other geranium oils and can be expected to show similar effects to those described above.

A summary of the major beneficial properties of *Pelargonium* essential oil are presented in the Fig. 3.

4.5. Other applications of Pelargonium odoratissimum

In the previously mentioned study by Abdelbaky et al. (2022), ZnO NPs synthesized using an aqueous leaf extract of *P. odoratissimum* exhibited antioxidant activity, the ability to improve membrane stability of lysosome cells, and no hemolytic activity.

The antioxidant potential of EO from the leaves of *P. odoratissimum* was also observed by Prakash et al. (2016). The radical-scavenging activity was tested against 2,2-diphenyl-1-picryl hydrazyl radicals (DPPH) and the oil showed weak antiradical activity with an IC_{50} value of 96.63 μL/mL.

The biological effects of *Pelargonium odoratissimum* are summarized in Fig. 4.

5. Conclusions and future perspectives

Pelargonium, a member of the botanical family Geraniaceae, is a genus of aromatic plants with several species whose beneficial biological properties have been scientifically documented. Among the well-studied representatives of the genus, *Pelargonium odoratissimum* occupies an important place. This specie, whose extracts are rich in terpenes and polyphenolics is widespread in South Africa and South America. *Pelargonium odoratissimum* has been found to be a strong antimicrobial and antifungal agent. Both the extract from the aerial parts of the plant and the essential oil have been shown to inhibit the growth of bacteria and fungi. The proven antimicrobial activity of the plant is influenced by the presence of geraniol and citronellol in the oil, but is also enhanced by phenolic components of the plant, namely flavonoids and phenolic acids which complement the overall antimicrobial effect. Other indicated properties, like glucose lowering properties, antioxidant action, or calming properties are of secondary importance.

The aim of this review was to draw attention to this less studied species, which is used in traditional remedies and herbal drinks and exhibits therapeutic potential against a variety of diseases of inflammatory or free radical origin, caused by fungal or bacterial infections. The information on *P. odoratissimum,* derived from a series of *in vitro* studies, was combined with data on other *Pelargonium* species to show the potential of this less investigated species. Although various

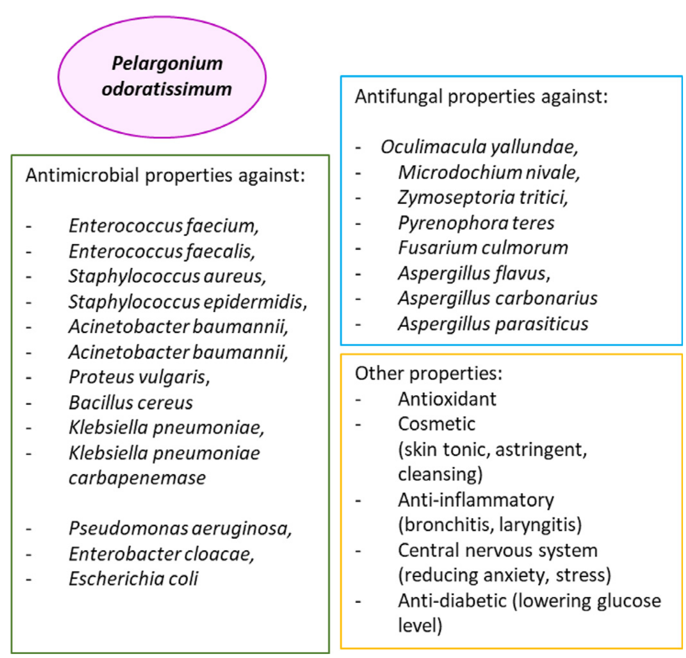

Fig. 4. Pharmacological effects of *Pelargonium odoratissimum*

biological activities of *Pelargonium* have been explored, their evaluation was mainly limited to *in vitro* models.

Despite its potential efficacy, there is a lack of sufficiently reliable information on the efficacy and safety of this species due to a lack of rigorous clinical research and standardization. The aforementioned studies should be further developed to demonstrate the beneficial properties of the essential oil or extracts. As mentioned in the review, *P. odoratissimum* EO was found to have strong antimicrobial properties and moderate antifungal activity and has been successfully used in aromatherapy to regulate central nervous system functions, bronchitis, and dermatologic inflammations. The recently discovered potential of the plant for therapeutic and industrial applications should prompt further studies.

Regarding the future perspectives for the development of *P. odoratissimum* as a commercially available plant material, the genetic and metabolic engineering of *Pelargonium* spp. opens many doors for the future industrial application of *P. odoratissimum*.

Members of the genus *Pelargonium* have been the subject of numerous studies in the field of genetic and metabolic engineering (Swaroop Verma et al., 2016). These investigations aimed to improve the quality of EO produced by *Pelargonium* species. In a study by Saxena et al. (2008), two transgenic plants, LZ-3 and 14TG, were developed that resulted in increased concentrations of geraniol and geranyl esters. These findings indicate an improvement in oil quality, particularly with regard to the ratio of citronellol/geraniol.

Another research group, Kulkarni et al. (2014, 2012), successfully produced some clones with varying amounts of citronellol, geraniol, isomenthone, or 10-epi-γ-eudesmol, resulting in oil yields that were 38 to 137 % higher than unmodified plants. These promising results show that the production of EO in *Pelargonium* can be increased by genetic modification.

In a previous study by Hamama et al. (2012), overexpression of rose DELLA homologous genes, which act as repressors of the gibberellic acid signaling pathway, resulted in remarkable changes in *Pelargonium* plants. Flowering was either blocked or delayed, root formation was impaired, overall growth was reduced, and the number of nodes and branches increased. These observations emphasize the role of DELLA genes in regulating various aspects of plant development.

In addition, overexpression of GrDXS, a gene related to isoprenoid biosynthesis, led to increased production of terpenoids by *P. graveolens*. This genetic modification resulted in an increased content of geraniol and citronellol, as well as a higher yield of linalool. The transformed lines exhibited a 15-20 % increased content of 10-epi-γ-eudesmol compared to the normal content in the EO.

To overcome the challenges of stress tolerance, expressed ACC deaminase from *Achromobacter xylosoxidans* in *P. graveolens*. The resulting transgenic lines showed a 20 to 23 % increase in height, an 18 to 60 % increase in biomass, and higher oil yields. In addition, these plants showed increased resistance to salt and drought stress, highlighting the potential benefits of genetic engineering to improve stress tolerance in *Pelargonium* species.

Genetic engineering strategies were not limited to the improvement of EO properties. Somaclonal variation strategies were used to obtain disease-resistant callus cultures of *P. graveolens* cv. Hemanti, resulting in the production of plants resistant to *Alternaria alternata* (Saxena et al., 2008).

In addition to the improvements mentioned above, genetic engineering has also been used to produce long-lived *Pelargonium* plants. Transgenic plants expressing a senescence-specific gene promoter (pSAG12) from *Arabidopsis thaliana* showed delayed leaf senescence, increased branching, and reduced internodal length (García-Sogo et al., 2012). These modifications offer the possibility of extending the lifespan of *Pelargonium* plants and increasing their ornamental and economic value. This approach demonstrates the potential of genetic manipulation for the development of disease-resistant varieties, a higher yield of plant material and its better quality. Further research in this field with the *P. odoratissimum* promises the development of better plant material in larger quantities with improved properties and benefits for medicinal, agricultural and ornamental purposes.

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Data availability

Not applicable

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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