

ORIGINAL RESEARCH ARTICLE

From Lab to Market - A Critical Review of Pharmacological Properties, Bioavailability, Formulation, and Commercialization Challenges of *Cymbopogon citratus* (Lemongrass)

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ABSTRACT

The aromatic grass *Cymbopogon citratus*, commonly known as Lemongrass, has traditionally been used for its medicinal properties and is now receiving heightened scientific and commercial attention for its applications in therapeutics, food flavoring, cosmetics, and agro-industrial products. This review synthesizes data from over 30 studies that focused on four critical aspects: (i) the pharmacological properties of *C. citratus*, (ii) the bioavailability and pharmacokinetics of its active constituents, (iii) formulation strategies to address stability, delivery, and utility challenges, and (iv) commercialization obstacles such as production, regulation, and market acceptance. The report indicates that *C. citratus* exhibited potent antimicrobial activity with MIC values ranging from 12.5 µg/mL to 100 mg/mL, antioxidant activity with IC₅₀ values from 15.13 µg/mL to 4.05 mg/mL, and anti-inflammatory activity with IC₅₀ values ranging from 50µg to 750 mg/Kg. These pharmacological properties are attributed to the major bioactive compounds *C. citratus*, including citral, caryophyllene, and myrcene. Pharmacokinetic studies indicate that citral and myrcene undergo rapid absorption, significant metabolism, and are eliminated through urine and other bodily fluids. Research in formulation has focused on enhancing the bioactive compounds in *C. citratus* essential oils (EOs) through the application of microencapsulation, solid lipid nanoparticles, and nanoemulsions to improve stability. While the plant has shown promising efficacy, the path to commercialization faces several challenges, including variable raw material quality, regulatory scrutiny, and competition from synthetic alternatives. This review concludes with an examination of the potential of *C. citratus* in both therapeutic and commercial sectors. Despite promising pre-clinical data, a significant lack of clinical trials and in-depth mechanistic studies remains the primary barrier to therapeutic application.

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INTRODUCTION

The most substantial and safest drugs since sundry have been medicinal plants, which play a remarkable role in health care systems (Isah et al., 2022; Oladeji et al., 2020). Medicinal herbs are indispensable therapeutic agents in the healthcare system for maintaining exceptional well-being and optimal health (Bensabah et al., 2015). The ethnopharmacological knowledge of medicinal herbs could well be traced back to the Stone Age (Bello et al., 2019). Recently, unexpected advancements have been observed in the use of herbs in primary healthcare systems across Asia (Isah et al., 2025), Africa, America, and other parts of the world (Lawal et al., 2017). Over two-thirds of the world's population relies on medicinal plants as therapeutic drugs; this upsurge may be due to the acceptability, compatibility, and adaptability of these natural remedies to the human body (Balakrishnan et al.,

2014). In the past, an increasing number of consumers have been looking for new herbal products with unique features that offer acceptable moments, fewer side effects, and sufficient health benefits (Asioli et al., 2017; Yasmeeen et al., 2017).

Furthermore, herbal drugs were produced through scientific or systematic studies of bioactive constituents, ethnopharmacology, or indigenous knowledge of medicinal herbs (Román et al., 2017). This forms the bedrock of the advancement in phytochemistry (McCarthy & Liu, 2017). In recent times, almost 10,000 medicinal herbs have been documented, and about 4500 have been examined for bioactive components and pharmacological properties (Oladeji et al., 2020). One of

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the medicinal herbs with immeasurable pharmacological activities is *C. citratus*.

Lemongrass is a perennial grass that is evenly dispersed and found in tropical regions (Francisco et al., 2011).. It is widely used in South and Central America for its pleasant taste and therapeutic properties (Bensabah et al., 2015; Coelho et al., 2016). The name *Cymbopogon* originates from the Greek words "kymbe-pogon," meaning boat-beard (due to its flower spike configuration), and "citratus" (Latin), meaning lemon-scented leaves (Shah et al., 2011). It is part of the Poaceae (formerly Gramineae) family (Figure 1). Findings have reported more than 55 species. Out of which *C. citratus* (West Indian grass), *C. flexuosus* (East Indian or Malabar grass), and *C. pendulus* (Jammu grass) are the most widely distributed species (Chowdury et al., 2015; Clement et al., 2015). The pharmacological activities of *C. citratus* have an outstanding record in the folk and Ayurvedic medicine (Tarkang et al., 2012). Scientific investigations have reported the antifungal, antibacterial, antiprotozoal, anti-inflammatory, anti-carcinogenic, antioxidant, anti-rheumatic, and cardio-protective properties of *C. citratus* (Ajayi et al., 2016; Avoseh et al., 2015). It has also been known to restrain platelet composition, cure diabetes, gastrointestinal infections, anxiety or depression, malaria, and pneumonia (Costa et al., 2016). Industrially, it serves as additives, flavor, and insecticides (Bossou et al., 2013) and preservatives in beverages, baked foods, and cuisines (Avoseh et al., 2015). However, the information obtained from these studies is highly fragmented, and there is limited documentation regarding the plant's bioavailability, formulation strategies, and commercialization. Consequently, an in-depth literature review of *C. citratus* will undoubtedly provide the information necessary to understand the knowledge gaps and stimulate future research opportunities. Hence, this review aims to critically synthesize this fragmented data, identify consistent trends and contradictions in bioactivity, and establish a solid foundation for future research.



Figure 1: *Cymbopogon citratus* (Lemongrass) (Cortes-torres et al., 2023)

Traditional uses of *C. citratus*

Many people use plant-based medicines today as part of traditional medicine to treat a wide range of illnesses (Manzoor et al., 2019). It has been reported that the use of traditional medicine improves the socioeconomic standing and overall health of human populations in developing nations (van Wyk & Prinsloo, 2020). *C. citratus* is one of the most used medicinal plants by various populations from ancient times. The medicinal uses of this plant are diverse, depending on factors such as the illness being treated, the parts of the plant used, and the geographic area of the population. All the traditional uses of the plant are based on the richness of *C. citratus*, which contains a wide range of bioactive compounds with potential health-beneficial effects (Avoseh et al., 2015). *C. citratus* and its derivatives are used differently to manage various diseases in the North, West, South, and East of Africa (Hacke et al., 2020). In Ethiopia, the plant and its parts are used to treat stomach aches. They administer the plant's roots orally to patients with digestive problems (Tazi et al., 2024). The plant is widely used by the Moroccan, Algerian, and Tunisian populations in folk medicine for the treatment of various diseases (Chaachouay et al., 2022; Miara et al., 2018, 2019). In Tunisia, the local population uses the infusion and extract of *C. citratus* to manage diuretic and intestinal abnormalities (Tazi et al., 2024). In Egypt, Madi et al. (2021) reported the use of the EOs from the *C. citratus* as an anticholinesterase agent. In South Africa, *C. citratus* is widely used by local people to treat stomach and gut problems, high fever, and headaches. Meanwhile, Ntonga et al. (2014) reported the use of *C. citratus* extracts, EOs, and infusions against malaria and other fevers in Cameroon. In Asia, the plant is traditionally used as a digestive aid, a pain reliever, and for the management of colds and flu (Kurnia Supandi et al., 2024).

METHODOLOGY

Research papers

The methodology used in this review paper was based on a literature review of publications focusing on the pharmacological properties and bioactive constituents of *C. citratus*. In this context, various search engines and databases, including Google Scholar, Scopus, ScienceDirect, and PubMed, were used to collect valuable information for the current review. The keywords for the search include *C. citratus*, Lemongrass, antimicrobial activity, antioxidant potential, anti-inflammatory properties, anticancer activity, enzyme inhibitory activity, bioactive compounds, and phytoconstituents. Only original research articles published in English from 2015 to 2025 were incorporated into the table synthesis.

Research articles from various databases were screened, harmonised, and de-duplicated. Titles and abstracts were screened to remove any records that contained inaccuracies in subject matter or outcomes pertinent to this review. Finally, the complete text articles were scrutinized to eliminate any irrelevant data, as illustrated in Figure 2.

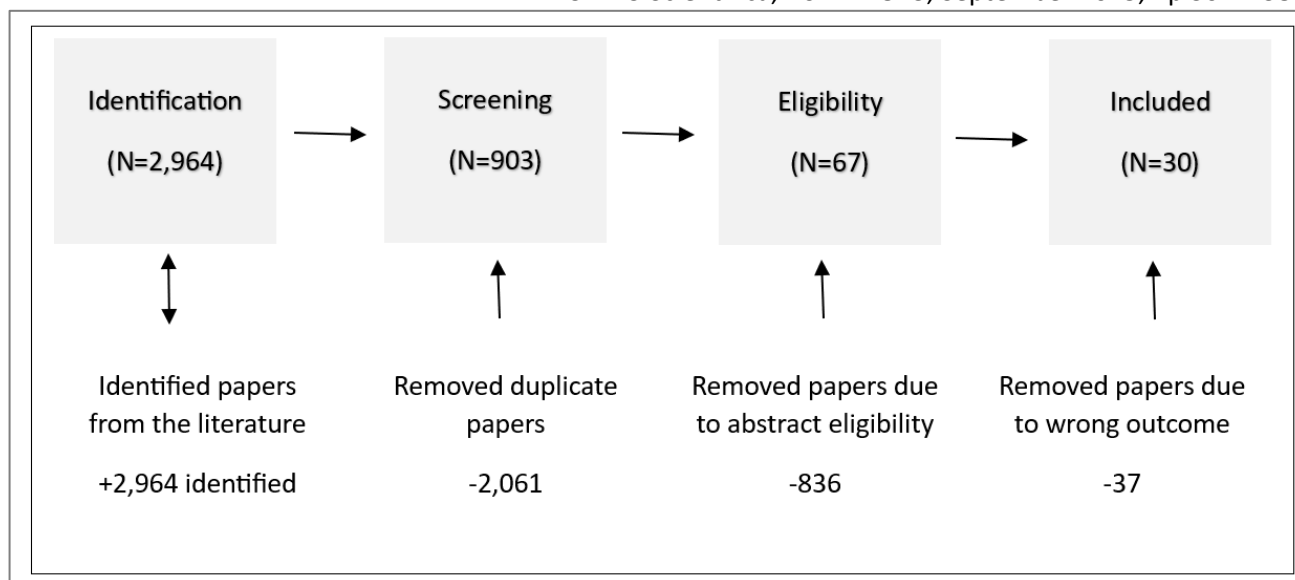


Figure 2: Flow diagram of the literature search and selection process.

3.2 Data recordings

Relevant data on studies of *C. citratus* bioactive compounds and their pharmacological properties were recorded. The information obtained consisted of various parts of the plant, such as leaves, roots, stems, and EOs. The extraction solvent/methods, pharmacological properties, principal bioactive constituent, findings, country of study, and references regarding *C. citratus* are summarised in Table 1.

RESULTS AND DISCUSSION

Collection, Reporting, and Summary of the Review Outcomes

All findings were recorded and summarized in Table 1. The research gaps were identified to establish a roadmap for future research, providing knowledge on novel drug discoveries from *C. citratus*.

Table 1: Summary of pharmacological properties and bioactive compounds of *C. citratus*

S/N	Plant parts	Extraction solvent/method	Pharmacological properties	Major Bioactive constituent	Findings	Country	References
1.	Leaves	Ethanol/maceration	Antibacterial Activity	Alkaloids, flavonoids, saponins, tannins, and phenols.	<i>C. citratus</i> extract inhibits the growth of <i>Fusobacterium nucleatum</i> bacteria at a minimum inhibitory concentration (MIC) of 0.78% and at a percentage inhibition of 55.7%.	Indonesia	(Kurnia Supandi et al., 2024)
2.	Leaves	Methanol, chloroform, and n-hexane/maceration	Anti-inflammatory activity	Mono(2-ethylhexyl) phthalate, caryophyllene, and 1,30-triacontanediol	All extracts demonstrated significant dose-dependent reductions in paw swelling, with effectiveness observed at doses up to 750 mg/kg body weight. The methanolic extract was particularly potent.	Pakistan	(Muhammad et al., 2021)
3.	Leaves (EO)	Hydrodistillation	Antioxidant activity and CNS-related therapies.	E-geranial, Z-geranial, and myrcene.	Antioxidant activity, as determined by the 2,2-Diphenyl-1-picrylhydrazyl (DPPH) assay, exhibited a significant radical scavenging effect with an EC ₅₀ of 48.5 µL/mL. In silico studies indicated that Z-geranial had a stronger binding affinity for muscarinic receptors (M1 and M2) than standard drugs. β-pinene and myrcene also showed affinity for multiple muscarinic receptor subtypes (M1, M2, M4), suggesting potential therapeutic implications for neuroprotection, cardiovascular regulation, and disorders	Mexico	(Cortés-torres et al., 2023)
4.	Leaves (EO)	Hydrodistillation	Antioxidant, antifungal, and antibiofilm properties	Geranial, neral, and myrcene.	Antioxidant activity was assessed using DPPH and β-carotene bleaching assays, with the essential oil (EO) demonstrating a DPPH IC ₅₀ of 19.25 µg/mL, suggesting potent free radical scavenging. The EO inhibited <i>Candida</i> biofilm formation by up to 91.2%, with MIC values ranging from	Tunisia	(Rhimi et al., 2022)

					0.25 to 1 $\mu\text{L}/\text{mL}$. Scanning Electron Microscopy (SEM) confirmed structural disruption of fungal cells.		
5.	Leaves (EO)	Hydrodistillation	Antioxidant and anti-inflammatory activities	Citral and β -myrcene.	The EO showed antioxidant activity in vitro and reduced reactive oxygen species (ROS) in vivo. The inflammatory response was evaluated by inducing edema in the zebrafish yolk sac, and treatment with EO significantly reduced edema in a dose-dependent manner. Concentrations above 50 $\mu\text{g}/\text{mL}$ showed a notable anti-inflammatory effect without causing mortality or malformations, indicating low toxicity.	Brazil	(Kiara et al., 2024)
6.	Leaves (EO)	Hydrodistillation	Antioxidant and anti-inflammatory activities	Citral, limonene, α -pinene, and caryophyllene oxide.	The EO exhibited promising antioxidant capacity (DPPH IC_{50} of 91.0 $\mu\text{g}/\text{mL}$) and anti-inflammatory activity (as determined by the protein denaturation method; IC_{50} of 397.11 $\mu\text{g}/\text{mL}$). In silico docking confirmed strong interactions between key constituents and COX-2, lipoxygenase, and antioxidant enzymes.	India	(Salaria et al., 2020)
7.	Leaves	Aqueous/maceration	Multi-biological activity.	Tannins, phenols, saponins, polysaccharides, and flavonoids	The extract showed vigorous antioxidant activity ($\text{IC}_{50} = 15.13 \mu\text{g}/\text{mL}$), anti- α -amylase ($\text{IC}_{50} = 101.14 \mu\text{g}/\text{mL}$), lipase inhibition, and antimicrobial effects. It also demonstrated cytotoxicity against Hep3B liver cancer cells ($\text{IC}_{50} = 144.35 \mu\text{g}/\text{mL}$) while sparing normal LX-2 cells. Electrophysiological studies confirmed modulatory effects on AMPA receptor subunits, with a significant impact on GluA2 kinetics, which supports the neuroprotective potential of this mechanism.	Palestine	(Rahhal et al., 2024)
8.	Dried Leave	Water and Ethanol/maceration	Enzyme Inhibitory Activity	Nil	The ethanol extract of <i>C. citratus</i> was observed to exert higher inhibitory activities on sucrase ($\text{IC}_{50} = 8.74 \text{ mg}/\text{mL}$) and Maltase ($\text{IC}_{50} = 18.93 \text{ mg}/\text{mL}$).	Indonesia	(Tirtanin gtyas Gunawan-Puteri et al., 2020)
9.	Leaves (EO)	Soxhlet extraction	Antimicrobial Activity	Tannins, flavonoids, volatile oils, phenols, saponins, and terpenoids	<i>C. citratus</i> EO exhibited antimicrobial activity against <i>E. coli</i> , <i>Klebsiella pneumoniae</i> , <i>C. albicans</i> , <i>Microsporium gypseum</i> , and <i>Trichophyton mentagrophyte</i> at MIC values ranging from 25 mg/mL to 100 mg/mL .	Nigeria	(Olaitan et al., 2023)
10.	Leaves	Aqueous/maceration	Antiviral and Antibacterial	Nil	The <i>C. citratus</i> extract exhibits potent antiviral activity, with a half-maximal inhibitory concentration (IC_{50}) of 500 $\mu\text{g}/\text{mL}$. Antibacterial potency against <i>S. aureus</i> and <i>K. pneumoniae</i> with a mean inhibition zone of 10.7 mm to 16.4 mm > at 50 μL .	Iraq	(Salih et al., 2022)
11.	Pseudostems and leaves (EO)	Hydrodistillation	Antioxidant, Antimicrobial, and Cytotoxic effects.	Geranial, neral, citral, and β -myrcene	In DPPH and hydroxyl scavenging assays, the Lemongrass EO exhibited potent antioxidant activities, with IC_{50} values of 2.58 and 4.05 mg/mL , respectively. Antimicrobial efficacy against <i>E. coli</i> , <i>Cutibacterium acnes</i> , <i>Streptococcus agalactiae</i> , and <i>S. aureus</i> was observed at concentrations of 8 $\mu\text{g}/\text{mL}$ to 10 $\mu\text{g}/\text{mL}$. 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) experiment demonstrated that the EO resulted in low cell viability (3%) at doses ranging from 200 to 400 $\mu\text{g}/\text{mL}$, with IC_{50} values of 23.11 $\mu\text{g}/\text{mL}$ and 82.46 $\mu\text{g}/\text{mL}$.	Thailand	(Vijitra et al., 2024)
12.	Leaves (EO)	Hydrodistillation	Antioxidant and	Phenolic and flavonoid	<i>C. citratus</i> EO showed iron-reducing power, DPPH radical scavenging,	Nigeria.	(Olaiya et al., 2016)

			Antibacterial Activities		hydrogen peroxide scavenging, and metal chelating activity at 10 to 40%. <i>C. citratus</i> EO exhibited antibacterial activity against <i>S. epidermidis</i> and <i>S. aureus</i> at MIC values of 212.5 mg/mL and <106.25 mg/mL, respectively.		
13.	Leaves (EO)	Hydrodistillation	Antimicrobial	Citral, neral, and β -myrcene	The antimicrobial activity of Lemongrass EO against <i>E. coli</i> , <i>S. aureus</i> , <i>Salmonella typhi</i> , <i>K. pneumoniae</i> , <i>Aspergillus niger</i> , and <i>C. albicans</i> was documented, with zone diameters ranging from 19 mm to 38 mm at a concentration of 100 mg/mL.	Sudan	(Mohamed Ali, 2017)
14.	Leaves (EO)	Hydrodistillation	Antimicrobial Activity	Isothymol, thymol, trans-caryophyllene, and cymene	<i>C. citratus</i> EO had an MIC value of 0.1% against <i>Listeria monocytogenes</i> , <i>E. coli</i> O157:H7, <i>Salmonella typhimurium</i> , <i>S. aureus</i> , and <i>B. subtilis</i>	Iran	(Lone, 2017)
15.	Leaves	Methanol/maceration	Antioxidant and Antimicrobial Activities	Phenolic and flavonoid	The methanol extract demonstrated notable antioxidant activity, with DPPH and FRAP values of $26.03 \pm 1.60 \mu\text{M}$ and $922.43 \mu\text{M}$ trolox/100 g, respectively. A 35 mm zone of inhibition was observed with the methanol extract at 150 mg/mL against <i>B. subtilis</i> .	Egypt.	(Hanaa et al., 2021)
16.	Leaves (EO)	Steam distillation	Antioxidant Activity	Nil	The IC ₅₀ values recorded for the DPPH and Nitric Oxide scavenging assays were 0.5 mg/mL and 2 mg/mL, respectively.	India	(Lawrence et al., 2015)
17.	Leaves	Ethanol, water, and methanol/reflux and steam distillation	Antifungal activity	Tannins, flavonoids, and alkaloids	The methanolic extract of Lemongrass exhibited the most significant zone of inhibition against <i>Aspergillus niger</i> (ranging from 10.20 to 10.99 mm) and <i>Colletotrichum musae</i> (ranging from 9.20 to 9.50 mm) at a concentration of 1000 ppm.	India	(Nyamath & Karthikeyan, 2018)
18.	Leaves	Ethanol, chloroform, and acetone/maceration	Antimicrobial Effect	Flavonoids, tannins, alkaloids, steroids, and phytosteroids	The ethanol leaf extract exhibited the most potent antimicrobial activity against <i>E. coli</i> , <i>S. aureus</i> , and <i>Salmonella typhi</i> , with MICs ranging from 50 to 100 mg/mL.	Nigeria	(Umar et al., 2016)
19.	Leaves (EO)	Hydro-distillation	Antimicrobial activities	Citral, α -citral, and citral diethyl acetal	The antibacterial activity of the EO ranges from 25% to 100% against <i>E. coli</i> , <i>B. cereus</i> , and <i>S. aureus</i> .	Colombo	(Prematilake et al., 2018)
20.	Leaves	Methanol and aqueous/Solvent extraction	Antimicrobial Activities	Cyclohexane-1-3,5-trione & 2-phenyl-1,4-benzopyrone.	Methanolic extract of <i>C. citratus</i> exhibits activity against <i>E. coli</i> and <i>P. aeruginosa</i> at MIC values of 12.5 $\mu\text{g}/\text{mL}$. In contrast, the aqueous extract was only active against <i>P. aeruginosa</i> at a concentration of 12.5 $\mu\text{g}/\text{mL}$.	Nigeria.	(Hassan et al., 2021)
21.	Fresh stalk	Ethanol/maceration	Antioxidant activity	Phenolic compounds	The highest antioxidant activity of 14.14% was achieved by microencapsulating 25% <i>C. citratus</i> extract with β -cyclodextrin.	Indonesia	(Erminawati et al., 2019)
22.	Leaves	Ethanol and acetone/maceration	Antioxidant activity	Phenolic compounds	The ethanol extract exhibited a scavenging activity of 73.8 $\mu\text{g}/\text{mL}$ in the DPPH assay, whereas the acetone extract exhibited a scavenging activity of 67.9 $\mu\text{g}/\text{mL}$.	Pakistan	(Irfan et al., 2022)
23.	Fresh and dried leaves	Aqueous and methanol/maceration	Antioxidant Activity	Phenolic compounds	The DPPH radical scavenging assay of <i>C. citratus</i> demonstrated antioxidant activities for the dried leaves (71.15 ± 0.14 to $89.79 \pm 0.16 \mu\text{g}/\text{mL}$) and fresh leaves (71.65 ± 0.45 to $81.94 \pm 0.84 \mu\text{g}/\text{mL}$).	Nigeria	(Adeyemo et al., 2018)
24.	Leaves (EO)	Hydro-distillation	Antifungal Activities	Geraniol, neral, myrcene, and geraniol.	<i>C. citratus</i> EO exhibits antifungal activity against <i>A. obovatus</i> , <i>A. oryzae</i> , <i>A. fumigatus</i> , and <i>A. parasiticus</i> at MIC values of 1.0 $\mu\text{L}/\text{mL}$.	Benin Republic	(Dègnon et al., 2019)
25.	Stalk and leaves	Water, ethanol, and methanol/reflux and steam distillation	Antibacterial activity	Tannins, flavonoids, and alkaloids	At a concentration of 1000 ppm, the ethanol leaf extract exhibited the highest zone of inhibition against <i>S. aureus</i> , measuring 12.30 mm.	India.	(Karthikeyan & Nyamath, 2018)
26.	Fresh leaves	Ethanol and methanol/maceration	Antibacterial activity	Alkaloids, flavonoids, saponins,	The ethanolic and methanolic leaf extracts had MIC values of 6.125 mg/mL and 12.5	Nigeria.	(Chibuzo et al., 2025)

				tannins, glycosides, reducing sugar, oils, and steroids	mg/mL, respectively, against <i>Streptococcus pyogenes</i> and <i>S. aureus</i> .		
27.	Leaves (EO)	Steam distillation	Antimicrobial, antibiofilm, antioxidant, and anticancer activities	D-limonene	<i>C. citratus</i> EO exhibited significant antimicrobial, antibiofilm, antioxidant, and anticancer properties. It showed inhibition zones for various microorganisms and demonstrated vigorous antioxidant activity. It also exhibited anticancer activity against prostate and liver cancer cells, with IC ₅₀ values of 170.09 and 105.06 μM, respectively.	Egypt	(Selim et al., 2025)
28.	Leaves (EO)	Hydrodistillation	Antimicrobial, anticancer, and antioxidant activities	Citral, isoneral, geraniol, geranyl acetate, citronellal	<i>C. citratus</i> EO has a broad spectrum of activities, including antimicrobial, antifungal, and anticancer effects, mainly attributed to its citral content. The oil has potential for use in the pharmaceutical, cosmetic, and food preservation industries.	India	(Mukarram et al., 2022)
29.	Leaves	Ethanol/maceration	Antioxidant and anticancer activities	Flavonoids	<i>C. citratus</i> extract demonstrated antioxidant activity by protecting cells from oxidative stress caused by rotenone. It also showed anticancer effects by decreasing cell viability and increasing oxidative stress in cervical cancer cells.	Brazil	(Pan et al., 2021)
30.	Leaves	Ethanol/maceration	Anticancer	Citral, elemicin, methyl isoeugenol, and lonicerin	<i>C. citratus</i> extract induced apoptosis in colon cancer cells and enhanced the efficacy of the FOLFOX chemotherapy regimen, improving tumor suppression while mitigating chemotherapy-induced weight loss.	Canada	(Ruvino et al., 2019)

Major Bioactive Compounds and EO Extraction Method of *C. citratus*

Hydrodistillation was the predominant method for EO extraction (67% of studies). The method is widely used for EO extraction because it is simple, cost-effective, and well established, and it can efficiently extract oils from a variety of medicinal and aromatic plants (Kaur et al., 2021). This technique uses water or steam to break down plant material, allowing volatile compounds to be released and collected, thereby preserving the natural composition of the oils and avoiding the use of chemical solvents that could alter their properties (Nguyen et al., 2021). *C. citratus* contains numerous bioactive compounds, including caryophyllene, citral, myrcene, α-pinene, phenols, and flavonoids, which are crucial for its therapeutic potential (Irfan et al., 2022; Lahyaoui et al., 2025; Vijitra et al., 2024). Bioactive compounds, such as citral, caryophyllene, and phenolics, contribute significantly to its antioxidant, anti-inflammatory, antimicrobial, and anticancer properties (Salaria et al., 2021; Salih et al., 2022). Studies highlight the broad antimicrobial spectrum of these compounds, especially against multidrug-resistant strains of *S. aureus* and *C. albicans*, which showcase their potential as natural therapeutic agents for combating microbial infections (Chibuzo et al., 2025; Rhimi et al., 2022). The high concentration of antioxidant compounds, such as flavonoids, helps neutralize reactive oxygen species (ROS), which are involved in oxidative stress that causes cardiovascular diseases, neurodegenerative disorders, and

cancer (Onyedikachi et al., 2021). Figure 3 depicts the structures of the most often reported bioactive compounds in *C. citratus*.

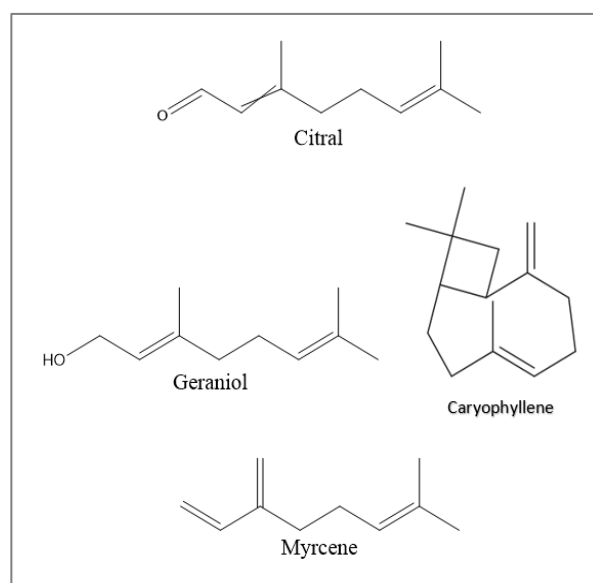


Figure 3: Chemical structures of the major bioactive compounds reported in *C. citratus*

Pharmacological Properties of *C. citratus*

The number of studies regarding the pharmacological properties of *C. citratus* is shown in the Figure 4. Most studies focused on antimicrobial activity, followed by

antioxidant, anticancer, anti-inflammatory, and enzyme inhibitory activities. However, some studies assess multiple bioactivities.

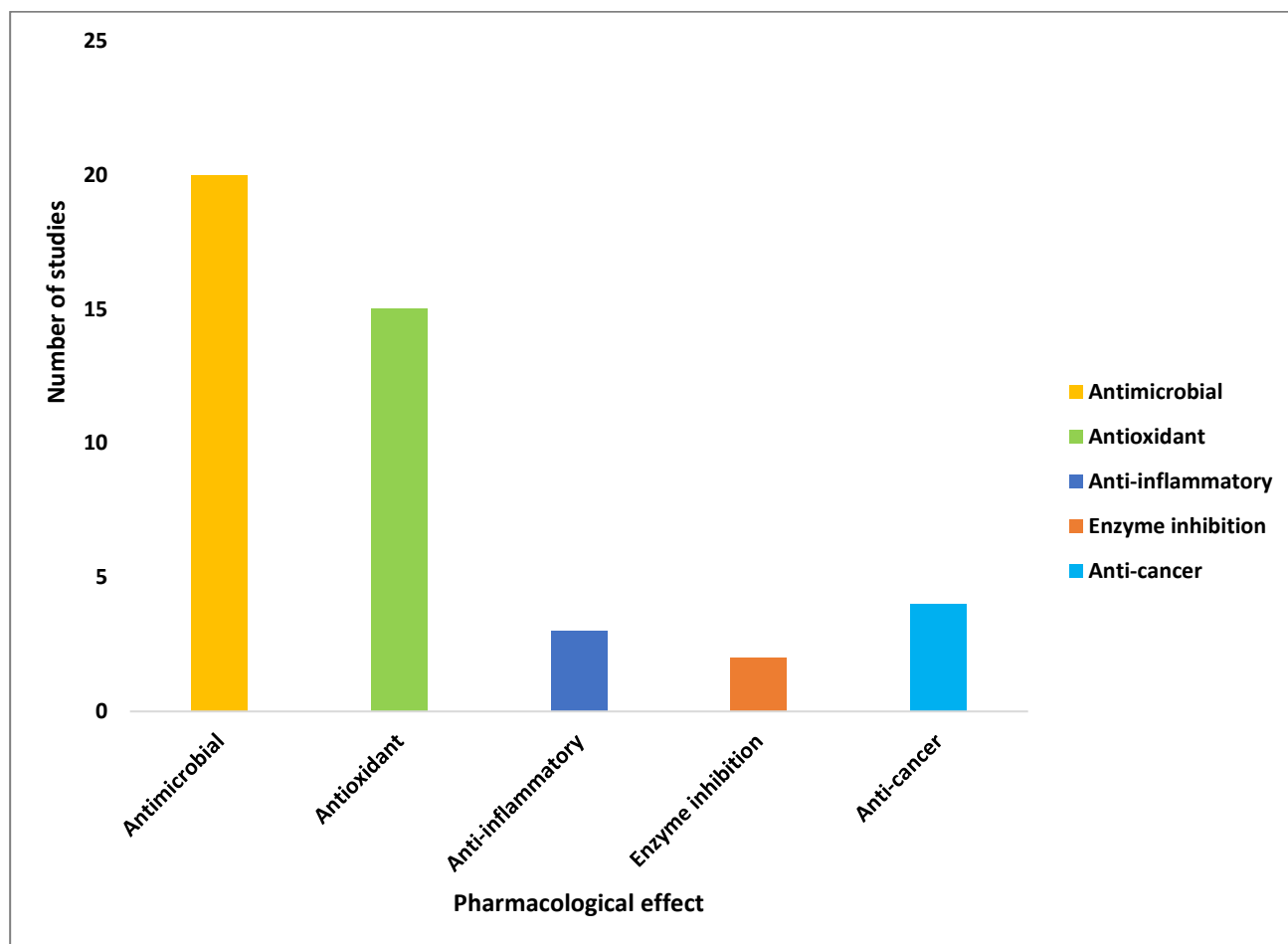


Figure 4: Number of studies regarding the different pharmacological properties of *C. citratus*

C. citratus extracts demonstrate notable antimicrobial efficacy against Gram-positive and Gram-negative bacteria, especially *Bacillus* spp., *K. pneumoniae*, *S. aureus*, *Streptococcus pyogenes*, *P. aeruginosa*, and *E. coli*. Furthermore, it exhibits potent antifungal activity, particularly on *Candida* and *Aspergillus* species (Olaitan et al., 2023; Subramaniam et al., 2020). Studies also suggest that flavonoids disrupt bacterial cell membranes and inhibit biofilm formation, thereby contributing to the plant's antimicrobial efficacy (Kieltyka-Dadasiewicz et al., 2024; Rhimi et al., 2022). Moreover, when combined with antibiotics, lemongrass extracts enhance antimicrobial activity, offering a promising approach to combat multidrug-resistant microorganisms (Aparna et al., 2019). The report indicates that *C. citratus* exhibited potent antimicrobial activity, with MIC values ranging from 12.5 µg/mL to 100 mg/mL against bacteria and fungal isolates.

Similarly, leaf and EOs from *C. citratus* have been shown to possess potent antioxidant properties. The plant's phenolic compounds play a significant role in scavenging free radicals, which are known to cause cellular damage and contribute to various diseases (Adeyemo et al., 2018). In vitro assays, such as the DPPH radical scavenging, nitric oxide scavenging, FRAP, and metal chelating assays, have confirmed the strong antioxidant potential of *C. citratus* extracts at IC₅₀ values ranging from 15.13 µg/mL

to 4.05 mg/mL, making it a valuable candidate for preventing oxidative stress-related conditions like cardiovascular diseases, neurodegenerative disorders, and cancer (Kiara et al., 2024; Olaiya et al., 2016).

Furthermore, *C. citratus* has been documented to possess significant anti-inflammatory activity with IC₅₀ values ranging from 50 µg to 750 mg/Kg. This efficacy has been attributed to its active constituents, such as citral, myrcene, and caryophyllene (Kiara et al., 2024; Salaria et al., 2021). These compounds have been found to inhibit pro-inflammatory pathways by suppressing the production of inflammatory cytokines and reducing swelling in animal models (Onyedikachi et al., 2021). This makes Lemongrass a potential therapeutic agent for managing inflammatory diseases such as arthritis and inflammatory bowel disease (Muhammad et al., 2021).

C. citratus extracts also demonstrated enzyme inhibitory activity against sucrase and maltase enzymes, which are involved in carbohydrate digestion (Tirtaningtyas Gunawan-Puteri et al., 2020). The enzyme-inhibitory activity of plant's extracts, particularly those from the leaves, plays a crucial role in regulating postprandial blood glucose levels, making them beneficial for managing diabetes (Tirtaningtyas Gunawan-Puteri et al., 2020). Additionally, the extracts have shown potential inhibition

of lipase activity, which could aid in weight management and the prevention of obesity (Rahhal et al., 2024).

Likewise, numerous studies highlight the ability of Lemongrass extracts to combat oxidative stress, which is crucial for cancer prevention, and their potent anticancer effects, through the induction of apoptosis in human cancer cells, including colon (HT-29) and cervical (SiHa) cancer cells. LEO enhances the efficacy of chemotherapy drugs, such as 5-fluorouracil (5-FU), as demonstrated by in vitro and in vivo studies that show its ability to reduce cell viability, promote apoptosis, and inhibit tumor growth (Pan et al., 2021; Ruvinov et al., 2019). Additionally, lemongrass extract has shown promise in reducing chemotherapy side effects, such as weight loss, and in preventing intestinal tumors in transgenic mice, suggesting its potential as a complementary treatment for colorectal cancer (Ruvinov et al., 2019). These findings indicate that LEO has a promising role in cancer treatment and prevention, warranting further investigation (Kieltyka-Dadasiewicz et al., 2024; Mukarram et al., 2022).

BIOAVAILABILITY AND PHARMACOKINETICS

Absorption, Distribution, Metabolism, and Excretion

Investigations into the pharmacokinetics of *C. citratus* are scarce, especially with human subjects (Ozjoiofor et al., 2021). Nevertheless, animal and in vitro studies have offered valuable insights into the absorption and metabolism of its bioactive constituents, notably citral, a principal monoterpene alcohol (Tak & Isman, 2016). Studies suggest that these compounds are rapidly absorbed following oral administration and extensively metabolized through oxidation, glucuronidation, and sulphation (Lan et al., 2013). Citral, being highly lipophilic, exhibits high tissue distribution but is metabolized quickly in the liver. Its half-life is relatively short, and it is excreted primarily through urine and expired air (Li et al., 2017). This rapid metabolism limits systemic bioavailability, but it supports the potential therapeutic application of short-acting formulations (Lan et al., 2013; Tak & Isman, 2016).

Phytochemicals and Implications for Bioavailability

Citral, comprising approximately 60–80% of lemongrass oil, is the most extensively studied bioactive molecule due to its potent anti-inflammatory, antibacterial, and anticancer properties (Aly et al., 2025; Sharma et al., 2021). Its bioavailability is limited by its low aqueous solubility and volatility (Aytac et al., 2018). Consequently, oral bioavailability is frequently diminished, especially when delivered as an EO. Research on its pharmacokinetics indicates significant first-pass metabolism, resulting in rapid elimination from the body (Mishra et al., 2019; Sharma et al., 2021). Enhancing the bioavailability of citral is essential to improve its therapeutic efficacy, especially for formulations designed for prolonged therapeutic effects (Ekpenyong et al., 2015). Synergistic interactions among phytochemicals may improve absorption and efficacy (Zhao et al., 2020).

FORMULATION STRATEGIES

Due to the volatile nature and limited water solubility of Lemongrass EO, various formulation techniques have been designed to improve its stability, delivery, and bioavailability.

Microencapsulation via Spray Drying

Microencapsulation has been identified as a promising technique to mitigate the instability and degradation of EOs during processing (Mostafa & Mohammad, 2020). A previous study demonstrated that spray drying with maltodextrin as the wall material achieved an encapsulation efficiency of approximately 85%, successfully preserving the EO and improving its retention during storage. The microencapsulated formulations exhibited potent antibacterial and antioxidant activities, suggesting potential uses in the food and pharmaceutical sectors (Alencar et al., 2022). Similarly, another study highlighted the use of a maltodextrin-gelatin combination for microencapsulating Lemongrass EO, demonstrating that microencapsulation can protect the oil from oxidation and degradation of its bioactive components (Nguyen et al., 2021).

Solid Lipid Nanoparticles (SLNs) and Nanoemulsions

Recent advancements in nanotechnology have resulted in the development of self-nanoemulsifying drug delivery systems (SNEDDS) and nanoemulsions for the effective delivery of *C. citratus* oil (Ujilestari et al., 2018). Ali et al. (2023) investigated the application of solid lipid nanoparticles (SLNs) for encapsulating lemongrass oil, demonstrating improved stability and regulated release of its active components, notably citral. The SLNs were shown to enhance the antibacterial and anticancer efficacy of lemongrass oil, suggesting that this formulation could expand its medicinal applications. Additionally, nanoemulsions and chitosan-coated nanoemulsions have been investigated as carriers for lemongrass oil in food packaging applications (Silva et al., 2025). Nanoemulsions offer improved dispersion in aqueous systems and enhanced retention of volatile compounds (Ashaq et al., 2025).

Food Ingredient/Nutritional Formulations

Research on formulation has investigated *C. citratus* EO and extracts inside food matrices. A study by Santoso et al. (2018) examined the potential of lemongrass extract in ice cream and yogurt. The outcome indicated that lemongrass-based products had favorable consumer acceptance, exhibiting no notable sensory deterrents, suggesting that lemongrass active constituents can be effectively integrated into food compositions. Moreover, its antioxidant properties make it a viable additive for extending the shelf life of food products (Kiara et al., 2024; Naufalin et al., 2019; Rhimi et al., 2022). A study on soy lecithin-stabilized lemongrass essential oil (LGEO) nanoemulsions revealed that their incorporation into orange juice enhanced its shelf life. The ideal formulation (6% LGEO, 6% lecithin) markedly enhanced antioxidant

activity and decreased bacterial count. Sensory evaluations indicated that the juice had a better flavor and scent, especially at a concentration of 0.2% (Nouraddini et al., 2025).

Formulation Challenges

Notwithstanding progress, numerous hurdles remain in formulating lemongrass oil-based products. A significant concern is the volatility of EOs, which may lead to the degradation of active compounds during processing and storage (Ashaq et al., 2025; Nouraddini et al., 2025). Microencapsulation techniques, while efficacious, may lead to a gradual degradation of the bioactive constituents over time. Moreover, transitioning nano-formulations from laboratory settings to industrial production poses obstacles, especially regarding maintaining product quality consistency and achieving cost-effective manufacturing (Alencar et al., 2022; Mostafa & Mohammad, 2020; Nguyen et al., 2021).

COMMERCIALIZATION CHALLENGES

Supply Chain, Raw Material Variability, and Quality Issues

C. citratus is a valuable aromatic and medicinal plant with considerable industrial potential, particularly due to its citral-rich EO (Lahyaoui et al., 2025; Mukarram et al., 2022). Despite its increasing demand in the food, pharmaceutical, and cosmetic industries, the commercialization of Lemongrass faces persistent challenges across production, processing, and marketing (Mukarram et al., 2022). The barriers include limited financial resources, lack of technical knowledge, inadequate processing facilities, post-harvest losses, ineffective marketing channels, and fluctuating market prices (Dewi et al., 2024; Singh et al., 2024). These challenges are compounded by environmental stresses, including soil salinity, and necessitate the development of enhanced agronomic methods and value-added practices to promote profitability and sustainability. A study in Kenya found considerable diversity in lemongrass oil composition, which may affect product consistency (Mwithiga et al., 2024). Additionally, the variability in raw material quality complicates compliance with regulatory standards for commercial products, particularly in the food, cosmetic, and pharmaceutical sectors (Irfan et al., 2022; Kiełtyka-Dadasiewicz et al., 2024). Furthermore, fragmented supply chains in key producing regions (e.g., Southeast Asia, Africa) complicate large-scale production (Aly et al., 2025).

Competition with Synthetic Alternatives and Other Species

The global market for Lemongrass faces intense competition from synthetic fragrances and flavoring agents, which are produced at a lower cost and offer more consistent quality (Balanay & Guinancias, 2025). Moreover, other *Cymbopogon* species, such as *C. nardus* and *C. winterianus*, predominate in specific industries, particularly in the manufacture of insect repellents, overshadowing *C. citratus*. These factors hinder *C. citratus*'s

competitive positioning in the market (Kaur et al., 2021; Munda & Lal, 2020).

Regulatory and Standardization Issues

Regulatory challenges remain a significant barrier to the commercialization of lemongrass oil. In many countries, EOs are subject to strict quality control measures regarding purity, safety, and stability (Faheem et al., 2022). The variability in oil content and the risk of contamination with pesticides or heavy metals complicates the approval process (Bhatnagar, 2018; Okpo & Edeh, 2022). Furthermore, establishing standardized extraction and formulation protocols is essential to ensuring regulatory compliance in international markets (Aly et al., 2025; Ujilestari et al., 2018).

Market Size and Growth Forecast

Despite these challenges, the market for lemongrass extract is projected to grow significantly. The global market for *C. citratus* is experiencing exponential growth, driven by its extensive use in the food, pharmaceutical, cosmetic, and biopesticide industries, with India leading as the largest producer and exporter (Kumoro et al., 2021; Solomon et al., 2019). Recent forecasts project the global lemongrass oil market to grow at a compound annual growth rate (CAGR) of 9.93% from 2021 to 2028, expanding from \$41.98 million to \$81.43 million, reflecting rising demand for natural products and the development of high-yielding cultivars (Channayya et al., 2023). This growth is driven by increasing demand across industries such as fragrance, culinary, pharmaceuticals, and cosmetics, as well as the oil's documented therapeutic properties (Ashaq et al., 2024; Mukarram et al., 2022). In India, the lemongrass oil export market has grown at a compound annual rate of 16.08% in quantity and 25.20% in value over the past two decades, underscoring strong international demand and a sustainable supply (Harendra et al., 2025). Advances in cultivation techniques and the introduction of high-yielding varieties, such as "CIM-Krishnapriya," are expected to further boost production and farmer income (Channayya et al., 2023). Additionally, advancements in extraction methods are enhancing oil yield and quality, thereby supporting the market's expansion (Ashaq et al., 2024; Mwithiga et al., 2024). The global lemongrass oil market is poised for significant growth, driven by technological innovations and expanding applications across various sectors (Ashaq et al., 2024; Channayya et al., 2023; Harendra et al., 2025).

CONTRIBUTION TO KNOWLEDGE AND RESEARCH GAPS

This review examines the therapeutic potential of *C. citratus*, focusing on its pharmacological properties, bioactive compounds, bioavailability, formulation strategies, and commercialization challenges, all of which are of increasing interest in current medical research. Despite these advancements in *C. citratus* research, there are still knowledge gaps, including limited clinical data on efficacy and safety, insufficient standardization of extraction, a lack of in-depth molecular mechanisms investigations and formulation methods, and a lack of

scalable, cost-effective delivery systems (Süntar, 2020; Ujilestari et al., 2018). There is also a need for more research on synergistic effects and long-term stability of formulated products (Aparna et al., 2019; Partovi et al., 2019).

CONCLUSION

This critical synthesis confirms the strong pre-clinical evidence for *C. citratus* as a source of antimicrobial, antioxidant, and anti-inflammatory agents, primarily driven by citral. Moreover, this review highlighted its bioavailability, formulation strategies, and commercialization potential. The review revealed that *C. citratus* is a promising natural source of bioactive compounds with multifaceted therapeutic and economic benefits. However, further research is essential to bridge the existing knowledge gaps, such as the lack of clinical trials and precise mechanistic data.

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