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Review on: Genetic insights into lemongrass (*Cymbopogon flexuosus* Steud): Traditional uses to modern applications

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Abstract
Lemongrass (*Cymbopogon flexuosus* Steud) is a tropical aromatic herb renowned for its culinary, medicinal, and aromatic properties. This plant has gained substantial attention in recent years within the field of genetics and plant breeding due to its potential for sustainable agriculture, essential oil production, and pharmacological applications. This abstract provides an overview of the current state of research on lemongrass genetics and plant breeding. Genetic studies have unveiled the genetic diversity present within lemongrass populations, with a focus on its complex phytochemical profile, yield potential, and adaptability to various environmental conditions. Advances in molecular genetics have allowed for the identification of key genes involved in essential oil biosynthesis, disease resistance, and stress tolerance in lemongrass. Plant breeding efforts in lemongrass have primarily targeted traits such as improved essential oil content, aroma quality, disease resistance, and enhanced adaptability. Traditional breeding techniques, as well as modern biotechnological approaches like marker-assisted breeding, have been employed to accelerate the development of superior lemongrass cultivars. However, lemongrass breeding faces several challenges, including the limited availability of genetic resources, long breeding cycles, and the need for comprehensive genomic resources. Furthermore, the potential impact of climate change on lemongrass cultivation necessitates the development of climate-resilient cultivars. In conclusion, future research endeavours should focus on expanding the genetic resources available for lemongrass, enhancing breeding methodologies, and addressing the challenges associated with sustainable lemongrass production. This pursuit not only contributes to the agricultural and pharmaceutical industries but also promotes the conservation of this valuable tropical herb.

Keywords: *Cymbopogon*, diversity, abiotic and biotic stress management, fingerprinting, biochemical properties

Introduction

Cymbopogon flexuosus, commonly called by lemongrass, is a tropical herb that is widely cultivated for both culinary and medical purposes. *Cymbopogon* (Poaceae family). This genus, which has between 102 and 104 species worldwide, is found in tropical and subtropical climates due to the variety of uses they have in the agriculture, culinary, cosmetics, and pharmaceutical industries. Large-scale cultivation of *Cymbopogon* grasses is common, particularly in tropical and subtropical regions (Akhila, 2010) [6]. It is native to Southeast Asia and is characterised by a distinctive blend of lemon and grassy overtones in both flavor and fragrance. It has a strong citrus aroma because to the high concentration of the aldehyde citral, which has two geometric isomers, geranial (citral a) and neral (citral b). In most cases, one isomer cannot exist without the other. In addition to citral, *Cymbopogon* species' essential oils also include trace amounts of geraniol, geranyl acetate, and mono terpene olefins like limonene and myrcene (in *C. flexuosus and C. citratus*, respectively) (Weiss, 1997) [92]. The most prized *Cymbopogon* species in terms of producing essential oils and having desirable phytochemical and pharmacological qualities are *Cymbopogon flexuosus* and *Cymbopogon citratus*. (Akhila, 2010) [6]. The tall, slender lemongrass plant can reach a height of 6 feet (1.8 meters), and its long, narrow, and green leaves resemble grass blades. The leaves have a saw-like edge and grow in clusters. The plant's bulbous base is frequently light or pale green in color. Lemongrass is well known for its powerful lemony scent, which is invigorating, zesty, and just a little bit sweet. When the leaves are chopped or crushed, the aroma is produced, making it a popular choice for aromatherapy.

Lemongrass is a common component in the cuisine of many Southeast Asian nations, including Thailand, Vietnam, Cambodia, Malaysia, Indonesia, and some regions of China and India. Lemongrass has historically been employed in herbal medicine due to its possible health advantages. Anti-inflammatory, antioxidant, and antibacterial activities are thought to exist in it. Lemongrass tea, which has relaxing and digestive benefits, is frequently made with it. The plant's essential oil, which has uplifting and stress-relieving properties, is extracted and utilized in aromatherapy. Due to its attractive aroma and potential skin advantages, it is often utilized in massage oils and skincare products. Lemongrass thrives in tropical and subtropical climates with well-drained soil and plenty of sunlight.

Chemical Evaluation of Lemongrass essential oil

The chemical makeup of the essential oils of several *Cymbopogon* species and its various plant portions have been widely researched. Geraniol and geranyl acetate are the two main components of *C. flexuosus* oil extracted from the leaves. During the growth of leaves, the ratio of geraniol and geranyl acetate changes noticeably. At day 10 following leaf emergence, the essential oil contained 59% and 33%, respectively, of geraniol and geranyl acetate. However, throughout the time of leaf growth from days 10 to 50, the amount of GA decreased from 59 to 3% while the level of G increased from 33 to 91%. (Wannissorn *et al*. 1996) [91]

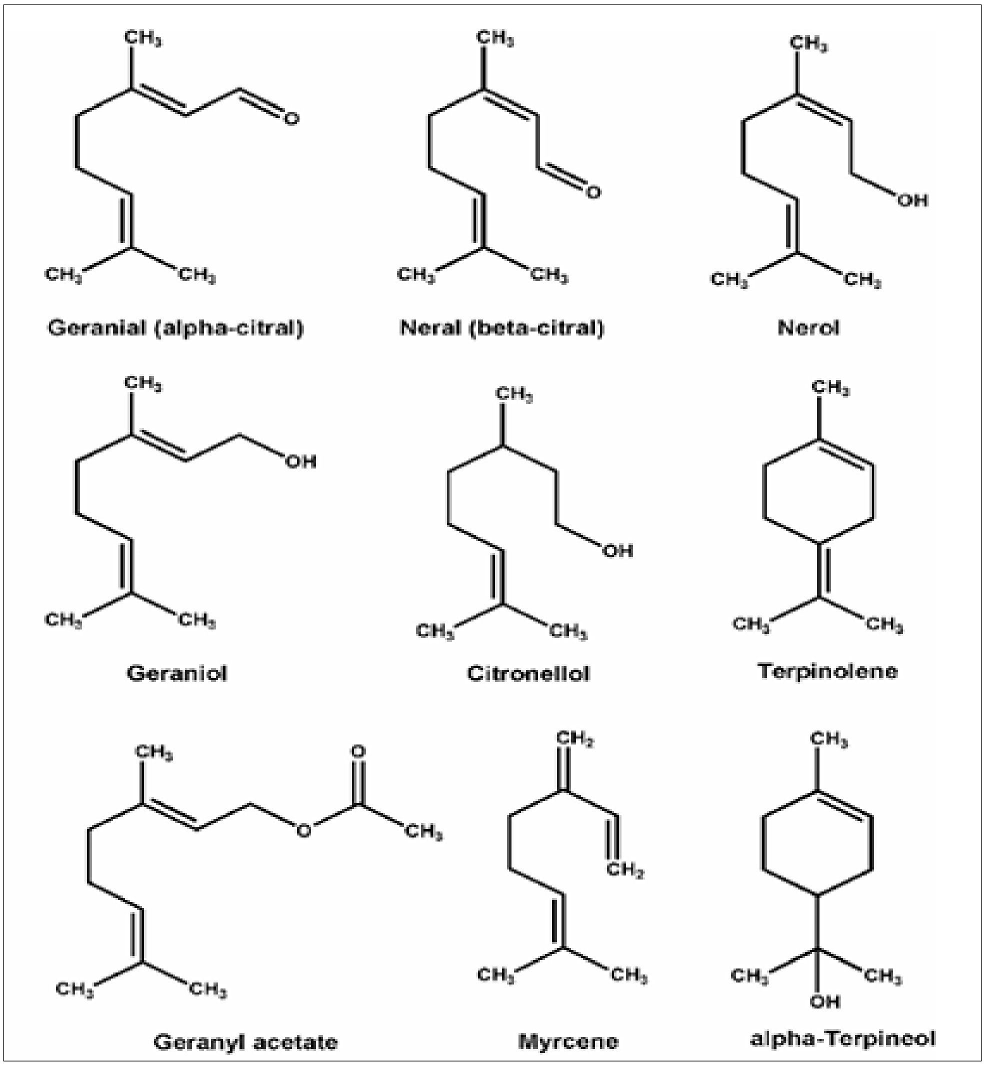


Fig 1: 'Chemical structure of major constituents in Lemongrass essential oil

Lemongrass composition, qualities, and uses

Lemongrass's composition, characteristics, and uses are based on three main ingredients: cellulose, hemicellulose, and lignin (Kaur and Dutt 2013; Bekele *et al*. 2017) [46, 10]. Table 1 is a list of the chemical components of the lemon grass plant. From a structural perspective, lemon grass is a hydrocarbon mostly made up of carbon and oxygen. Table 1 also lists the elemental makeup of lemongrass (ash excluded). Whereas hemicellulose is mostly composed of amorphous parts interspersed with crystalline sections, cellulose is a three-dimensional linear molecular structure that comprises both crystalline and amorphous regions. The degree of polymerization, which can range from 100 to 10,000 for cellulose and less than 200 for hemicellulose, is another fundamental distinction between cellulose and hemicellulose (Yang 2008) [93]. Cellulosic components are bound together by lignin, an amorphous heterogeneous three-dimensional nonlinear polymer (Bajpai 2016) [9]. 1,4 b-gluco-pyranose units make up cellulose, xylose, galactose, arabinose, and mannose subunits make up hemicellulose, and p-hydroxyphenyl, guaiacyl, and syringyl units make up the majority of lignin (Pierson *et al*. 2013) [72]. Figure 3 displays the architectures of cellulose, hemicellulose, and lignin. In addition, the oil content of lemongrass varies according to its genetic makeup, growing environment, culture, and agronomic practices. Typically, 1-2 percent of the entire dry weight is recovered as essential oil (EO) (Carlson *et al*. 2001) [18]. Nonetheless, the composition may change depending on the drying process. Compared to sun- or shade-drying techniques, oven-drying leaves can yield more essential oil (EO); however, oil obtained through shade-drying has a higher citral concentration, which is used to determine the oil's quality (Hanaa *et al*. 2012) [38]

Chemical constituents	Amount %	Elemnets	Amount % (excluding ash)
Cellulose	39.5	Carbon	39.34
Hemicellulose	22.6	Oxygen	53.3.
Lignin	28.5	Hydrogen	5.81
Ash	1.5	Nitrogen	1.54
Moisture	6.8	Sulphur	0.01

The chemical constitutes and elemental composition of lemongrass (Bekele *et al.* 2017; Madhu *et al.* 2017) [10, 55]

According to Sarer *et al*. (1983 [96]; Rauber *et al*. 2005) [76], citral is primarily composed of two stereo-isomeric mono-terpene aldehydes: neral and geranial, or trans-citral and cis-citral. Citral makes up more than 45% of lemongrass oil on average, however species-to-species variations may be significant. Citral content in East Indian lemongrass (C. *citratus*) typically ranges from 30 to 94% (Moore-Neibel *et al*. 2012) [61]. According to reports, the composition of EO also includes several hydrocarbons, including terpenes, alcohols, ketones, and esters (Abegaz *et al*. 1983; Evans 2009) [2, 28]. Along with flavonoids, alkaloids, anthraquinones, phenols, tannins, and saponins, C. *citratus* is also rich in phytochemicals. Furthermore, a number of studies have shown trace amounts of myrcene, elemicin, nerol, geraniol, borneol, citronellol, limonene, a-terpineol catechol, luteolin, apigenin, quercetin, kaempferol, glycosides, chlorogenic acid, caffeic acid, and geranyl acetate, in addition to methyl heptenone, isovaleric aldehyde, fumesol, L-linalool, furfurol, isopulegol, decyclic aldehyde, p-coumaric acid, and terpinene (Akhila 2010) [6]. Further investigations have shown that phytochemicals such isoscoparin, orientin, and swertiajaponin are present in lemongrass (Cheel *et al*. 2005; Bharti *et al*. 2013b) [20, 13].

According to Saleem *et al*.'s studies, the amount of major constituents of lemongrass EO is shown in Fig. 4. This indicates that trans-citral (geranial) and cis-citral (neral) are more prevalent, while nerol, geraniol, citronellol, terpinolene, geranyl acetate, myrcene, and other components are more reduced (Saleem *et al*. 2003a, b) [81, 82]. Lemongrass has a wide range of applications due to scientific research showing its effectiveness as an antifungal, antibacterial, and anti-protozoal agent (Kishore *et al*. 1993; Mishra and Dubey 1994 [60]; Wannissorn *et al*. 1996) [49, 91]. Several research have also demonstrated lemongrass's anti-nociceptive and anti-inflammatory properties (Viana *et al*. 2000; Wannissorn *et al*. 2005; Boukhatem *et al*. 2014) [90, 95, 91]

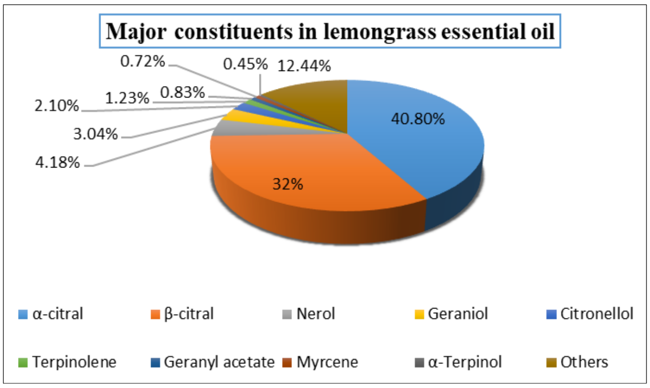


Fig 2: Major component in lemongrass essential oil

The Bioactive Substances in Lemon Grass and its oil

There are already a plethora of ethnopharmacological uses for lemon grass. Its ability to restore health may be attributed to the variety of secondary metabolites it generates. Fats, proteins, carbs, fiber, minerals, and a number of other beneficial substances were found in the grass, according to an analysis (Table 1-3). These fall into several types, including tannins, phenols, alkaloids, terpenoids, and flavanoids. Lemon grass has also been reported to contain anthraquinones, steroids, phlobotannins, and cardiac glycosides.

Table 1: Nutritional Content of Lemongrass

S.no.	Nutritional component	Quantity
1.	Carbohydrates	55.00%
2.	Crude fat	5.10%
3.	Crude protein	4.56%
4.	Crude fiber	9.28%
5.	Energy	360.55 al/100g

Source: Ranade and Thiagarajan 2015 [74]

Table 2: Mineral Content of Lemongrass

S. No.	Mineral	Qunatity (mg/100g)
1.	Na	54.8
2.	K	59.5
3.	Ca	39.5
4.	Mg	70
5.	Fe	0.024
6.	Mn	0.952
7.	Zn	121
8.	P	89.3
9.	Phytate	11860

Source: Ranade and Thiagarajan 2015 [74]

Table 3: Bioactive components of Lemon grass oil

S. No.	Chemical Constituent	S. No.	Chemical Constituent	S. No.	Chemical Constituent
1.	Citral	17.	Geranial	33.	Valencene
2.	Burneol	18.	Nerol	34.	Viridiflorol
3.	α-terpineol	19.	Citronellol	35.	α-Selinene
4.	ß-Myrcene	20.	Methyl-n-nonyl-ketone	36.	Humulene
5.	ß-O-Cimene	21.	Dextro-carvone	37.	α-Guaiene
6.	Allo-o-cimene	22.	Geranic-acid	38.	t-Cadinol
7.	α-Pinene oxide	23.	α-Bergamotene	39.	ß-Eudesm
8.	Myrcenol	24.	Isolongifolene-4-5-9-10-dehydro Levo-ß-elemene	40.	(E,E)-Farnesal pimelyl dihydrazide
9.	t-Muurolol	25.	γ-Muurolene	41.	Di-n-octylphthalate
10.	Linalool	26.	α-Gurjunene	42.	Geranyl-acetate
11.	1-Octyn-3-ol trans-	27.	α-Muurolene		
12.	Chrysanthemal	28.	a-Amorphene ß-Sesquiphellandrene		
13.	3-Undecyne,3-carvomenthenone	29.	α-Farnesene		
14.	Citronellal	30.	α-Elemol		
15.	Neral	31.	d-Cadinene		
16.	trans-(-)-Carveol	32.	Germacrene-D		

Source: Ranade and Thiagarajan 2015 [74]

Table 4: Biological activity of lemongrass

Biological activity	Components	References
Analgesic	Essential oil, Flavonoids, alkaloids	Lorenzetti *et al*. 1991 Bone and Mills 2013 [97, 98]
Anti-diabetic	Essential oil	Souza *et al*. 1991 [97]
Anti-carcinogenic	Essential oil, flavonoids	Bone and Mills 2013 [98]
Anti-inflammatory	Essential oil, tannins, saponins, flavonoids	Bone and Mills 2013 [98]
Anti-microbial	Essential oil, tannins, flavonoids	Kishore *et al* 1993 [50], Mishra and Dubet 1994 [61] and Bone and Mills 2013 [98]
Anti-nociceptive	Essential oil	Lorenzetti *et al*. 1991 [97]
Antioxidant	Essential oil, tannin, vitamins, flavonoids, phenols	Bone and Mills 2013 [98]
Antipyretic	Flavonoids, alkaloids	Bone and Mills 2013, Ekepenyong *et al*. 2015 [98, 21]
Astringent	tannins, saponins, alkaloids	Bone and Mills 2013 [98]
Aromatherapy	Essential oil	Buchbauer and Jirovets 1994, Bone and Mills 2013 [99, 98]
Cardio-protective	vitamins	Ekepenyong *et al*. 2015 [21]
Cell signalling and transport	Minerals	Ekepenyong *et al*. 2015 [21]
Diuretic	Essential oil	Bone and Mills 2013 [98]
Hematologocal	Essential oil	Ekepenyong *et al*. 2015 [21]
Hemodynamic	Minerals	Ekepenyong *et al*. 2015 [21]
Hypocholestrolemic	Essential oil, saponins, flavonoids	Bone and Mills 2013 [98]
Hypoglycemic	Essential oil, tannins	Ekepenyong *et al*. 2015 [21]
Hypotensive	Essential oil	Ekepenyong *et al*. 2015 [21]
Insecticidal repelling	Essential oil	Lima *et al* 2009 [100]
Neuropharmacological	Essential oil, alkaloids, minerals	Koo *et al*. 2003, Bone and Mills 2013 [, 98]

Studies on karyomorphology: *C. flexuosus* underwent screening and was specifically selected for both morphological and karyomorphological analyses. The species showcases significant heterogeneity in its morphology, chemotype, and genotype, as highlighted in Lavania's research in 1987. Through karyomorphological studies, it was revealed that the natural population of *C. flexuosus* comprises diverse ploidy levels, including diploid, tetraploid, and hexaploid races. This variation in ploidy levels is widespread across different variants of *Cymbopogon* species in the natural environment, contributing to their complex chemotaxonomy.

The presence of different ploidy levels among *Cymbopogon* species is significant, as polyploidization has the potential to augment the production of secondary metabolites and enhance DNA methylation. Notably, within the Cymbopogon genus, C. flexuosus stands out with the highest ploidy level and the most advanced karyotype type. This serves as a testament to the evolutionary progress within the genus, underscoring the advanced characteristics and completion of its evolutionary lineage (Narayan 1966; Marigowda *et al.* 2016) [64, 57].

Karyotype analysis: Karyotyping using digital calipers enabled the measurement of chromosomes, presented in micrometers. Various characteristics were considered for comparison, including satellite number and positioning within chromosomes, centromere location, basic chromosome count, absolute and relative sizes. The assessment also involved examining heterochromatin area distribution during mitotic prophase and pro-metaphase. Chromosomes were categorized based on arm ratios, identifying six regions denoted as M (middle), T (ends), m (median), sm (sub median), t (terminal), and st (sub-

terminal) following the classification proposed by Levan, Fredga, and Sandberg in 1964.
The nomenclature used 'm', 'sm', 't', and 'st' to indicate halves of the chromosome's length from the centromere. Secondary constrictions were observed in two forms on the karyotype. The first type featured a long, fiber-like structure with a small satellite on the short arm, termed a genuine satellite chromosome. The second type displayed a small gap in the satellite chromosome with a larger satellite, representing a minor secondary constriction or secondary constriction chromosome. Relative chromosome length was determined by the proportion each chromosome contributed to the total chromosomal length. Chromosomes were further classified into three types, M, m, and sm, based on their centromeric positions, and within each group, they were ordered in decreasing length.

Table 2: Karyo-morphological data of diploid race (2n=20) of *C. flexuosus*

Chromosome pair	Short arm (sa) (µm)	Long arm (la) (µm)	Ratio (la/sa)	Total chromosome length	Relative length	Chromosome type
1	1.065	1.065	1.0	2.13	9.44	M
2	1.3	1.47	1.13	2.77	12.27	m
3	0.86	1.0+0.43(sat)	1.66	2.30	10.19	m
4	0.93	1.15	1.23	2.08	9.21	m
5	0.83	1.13	1.36	1.96	8.68	m
6	0.86	1.75	2.01	2.60	11.52	sm
7	0.83	1.53	1.84	2.36	10.46	sm
8	0.76+0.2(sat)	1.33	1.75	2.30	10.19	sm
9	0.75	1.31	1.75	2.06	9.13	sm
10	0.73	1.26	1.73	2.00	5.58	sm

Source: Marigowda *et al*. 2016 [57]
Total chromatin length: 22.56 µm
Karyotype formula: 1M+4m+5sm
Karyotype asymmetry: 2A

Table 3: Karyo-morphological data of tetraploid race (2n=40) of *C. flexuosus*

Chromosome pair	Short arm (sa) (µm)	Long arm (la) (µm)	Ratio (la/sa)	Total chromosome length (µm)	Relative length	Chromosome type
1	1.38	1.38	1.0	2.76	6.46	M
2	1.10	1.10	1.0	2.20	5.15	M
3	1.03	1.03	1.0	2.06	4.82	M
4	0.95	0.95	1.0	1.90	4.45	M
5	0.91	0.91	1.0	1.83	4.28	M
6	0.83+0.15(sat)	0.83	1.0	1.81	4.24	M
7	1.2	1.56	1.30	2.76	6.46	m
8	0.98	1.51	1.54	2.50	5.85	m
9	1.0	1.43	1.43	2.43	5.69	m
10	1.03	1.30	1.26	2.33	5.45	m
11	0.86	1.33	1.55	2.20	5.15	m
12	0.86	1.25	1.45	2.11	4.94	m
13	0.86	1.16	1.35	2.03	4.75	m
14	0.78	1.21	1.55	2.00	4.68	m
15	0.83	0.5+0.5(sat)	1.20	1.83	4.28	m
16	0.73	1.1	1.50	1.83	4.28	m
17	0.66	1.0	1.51	1.66	3.89	m
18	0.8	1.4	1.75	2.20	5.15	sm
19	0.76+0.1(sat)	1.33	1.75	2.20	5.15	sm
20	0.76	1.31	1.73	2.08	4.87	sm

Source: Marigowda *et al*. 2016 [57]
Total chromatin length: 22.56 µm
Karyotype formula: 6M+11m+3sm
Karyotype asymmetry: 1A

Table 4: Karyo-morphological data of hexaploid race (2n=60) of *C. flexuosus*

Chromosome pair	Short arm (sa) (µm)	Long arm (la) (µm)	Ratio (la/sa)	Total chromosome length (µm)	Relative length	Chromosome type
1	1.53	1.53	1.0	3.06	5.07	M
2	1.40	1.40	1.0	2.80	4.64	M
3	1.25	1.25	1.0	2.50	4.14	M
4	1.10	1.10	1.0	2.20	3.64	M
5	0.86	0.86	1.0	1.73	2.87	M
6	0.80	0.80	1.0	1.60	2.65	M
7	0.66	0.66	1.0	1.33	2.20	M
8	0.63	0.63	1.0	1.26	2.08	M
9	1.43	1.0+0.76(sat)	1.23	3.20	5.31	m
10	1.16	1.56	1.35	2.73	4.53	m
11	1.0	1.66	1.66	2.66	4.41	m
12	0.93+0.16(sat)	1.33	1.43	2.42	4.01	m
13	1.13	1.26	1.12	2.40	3.98	m
14	0.93	1.33	1.43	2.26	3.75	m
15	0.96	1.20	1.25	2.16	3.58	m
16	0.86	1.16	1.35	2.03	3.37	m
17	0.76	1.23	1.62	2.00	3.32	m
18	0.73	1.13	1.55	1.86	3.08	m
19	0.73	1.06	1.46	1.80	2.98	m
20	0.53+0.36(sat)	0.76	1.44	1.66	2.75	m
21	0.73	0.93	1.27	1.66	2.75	m
22	0.66	1.0	1.51	1.66	2.75	m
23	0.66	1.0	1.51	1.66	2.75	m
24	0.73	0.90	1.23	1.63	2.70	m
25	0.70	0.80	1.14	1.50	2.49	m
26	0.56	0.90	1.60	1.46	2.42	m
27	0.80	1.43	1.79	2.23	3.69	sm
28	0.60	1.30	2.16	1.90	3.15	sm
29	0.56	0.96	1.72	1.53	2.54	sm
30	0.48	0.95	1.97	1.43	2.37	sm

Source: Marigowda *et al*. 2016 [57]
Total chromatin length: 60.32µm:
Karyotype formula: 8M+18m+4sm;
Karyotype asymmetry: 2B

Breeding objective of lemongrass: A widely grown crop among fragrant and therapeutic plants is lemongrass. Enhancing quality, productivity, and essential oil content is the goal of lemongrass breeding. Additionally, disease resistance and environmental adaptability are prioritized. Resilience against drought, resilience to pests, and attractive flavor profiles are critical components of sustainable farming. Other factors to take into account include modifying development patterns, increasing shelf life, and lowering allergenic substances. With a focus on lowering environmental impact and improving market appeal, these goals provide consistent, high-quality lemongrass production for a range of industries and uses. They also cater to the needs of consumers and farmers. To accomplish these objectives, cooperation between breeders, researchers, and farmers is essential.

Potential applications of Lemongrass

Adsorption of metal ions and dyes: Lemongrass, known for its excellent adsorption properties owing to its cellulosic nature, has been utilized as a bio-absorbent material for various metal ions and dyes. Studies have shown that *Cymbopogon citratus* demonstrates effective adsorption of Cu^{2+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, and Zn^{2+} (Lee *et al*. 2014; Sobh *et al*. 2014) [102, 103]. On the other hand, the West Indian lemongrass, *Cymbopogon flexuosus*, has been found effective in removing As^{3+} and Cr^{4+} from aqueous solutions (Jha and Kumar 2017) [104]. In many cases, lemongrass has been dried, pulverized into powder, and utilized as an absorbent material for metal ion absorption (Lee *et al*. 2014; Sobh *et al*. 2014) [102, 103].

Moreover, some instances have explored the inclusion of the whole lemongrass plant in the adsorption process (Jha and Kumar 2017) [104]. Creating smaller particles has been found to enhance the adsorption capacity, with reports suggesting a significant 93% ion removal using the powdered form of lemongrass (Sobh *et al*. 2014) [103]. In a study on dye adsorption, waste lemongrass was obtained from the lemongrass oil distillation unit and transformed into ash to assess its capacity to absorb methylene blue dye. The lemongrass ash efficiently absorbed nearly half of the dyes from the solution within the first 90 minutes, with around 40% being adsorbed within the initial 40 minutes. The adsorption of dyes was observed to increase with higher doses of lemongrass adsorbent, adjusted pH levels, and prolonged contact time. Similar to the behaviour observed in metal ion adsorption, a higher initial concentration of dyes led to increased adsorption due to the availability of absorbent sites.

Production of paper pulp: Paper pulp production: A number of grass species have already been investigated for their potential to be pulped and used to make paper (Madakadze *et al*. 2010) [101]. The cellulose-rich lemongrass has demonstrated its promise as a raw material for the paper industry. Before delignification, lemongrass is chopped into chips (15–25 mm), just like other raw materials used to make pulp. It has been reported that the lemon grass chips were cooked for one to three hours at 130–170 degrees Celsius when anthraquinone and alkali were present. Before being put through rollers to create sheets,the prepared substance was cleaned, put through a vibratory flat screen with a pore size of 0.15 mm, and then beaten. (Kaur and Dutt 2013) [47]. Both lemongrass *Cymbopogon flexuosus* and Sofia grass, a *Cymbopogon* species recognized as *Cymbopogon Martinii* and the origin of palmarosa oil, exhibited excellent mechanical strength qualities in the production of chemical-grade pulp (Kaur and Dutt 2013) [47].

Utilization as a composite substance: 'The most recent usage of lemongrass has been documented in the field of composites, where it was applied as a thermoplastic composite's reinforcing material. In their 2017 study, Bekele *et al*. presented lemongrass composite powder, which was made from lemongrass flour with a particle size range of 150–850 in l minute. The powder was combined with high density polyethylene (HDPE) and maleic anhydride grafted polypropylene (MA-g-PP) as a coupling agent. Lemongrass essential oil (EO) has also been utilized in the sol-gel mixture to create bio composite films together with chitosan and starch. Moreover, mixing, casting, and aging were steps in that procedure. The homogenous surface structure was identified by the SEM pictures of the biofilm that was formed. Given that the film's tensile strength was not disclosed (Pandharipande and Katekhaye 2017) [105].'

Generation of silica and bioenergy: A few studies have looked explored using lemongrass to produce bioenergy. *Cymbopogon flexuosus* was dried, crushed, and then put through a pyrolysis chamber in a fluidized bed reactor with a nitrogen environment in order to produce bio oil (Madhu *et al*. 2017) [56]. There have been reports on the use of lemongrass to produce silica (Firdaus *et al*. 2015, 2016) [33]. These reports describe two distinct processes, one of which includes the treatment of acid leaching while the other produces silica directly by calcination.

Application in food preservation: There is ample evidence of lemongrass essential oil's antibacterial properties against microorganisms. Interestingly, revealed that lemongrass essential oil had more advantageous action than other essential oils against 12 significant bacterial species. Figure 14 illustrates the likely antibacterial action of lemongrass essential oil (EO) on cytoplasmic cells by showing that the EO causes cytoplasmic coagulation, which results in the production of spheroplasts and inhibits the formation of septa. It flushes out the intracellular hydrogen ions, which causes the bacterial cell to become immobile and die (Ekpenyong and Akpan 2017) [106]. Lemongrass has been shown to be effective against a variety of bacteria, including Salmonella Enteritidis and E. coli, as well as fungus (Mishra and Dubey 1994; Paranagama *et al*. 2003) [61, 71]. (Moore-Neibel *et al*. 2012) [62, 61]. According to this EO has apparently prevented the germination of a number of important postharvest diseases, including *Rhizopus stolonifer*, *Botrytis cinerea*, *Cladosporium herbarum*, and *Colletotrichum coccodes*. A few entries with high oil and citral content are selected for their in vitro antifungal efficacy.

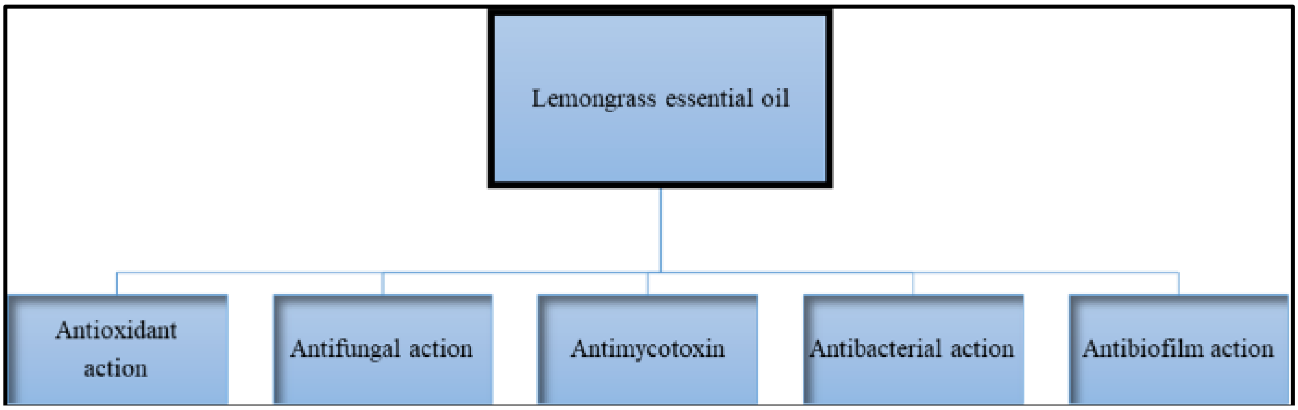


Fig 3: Lemongrass essential oil

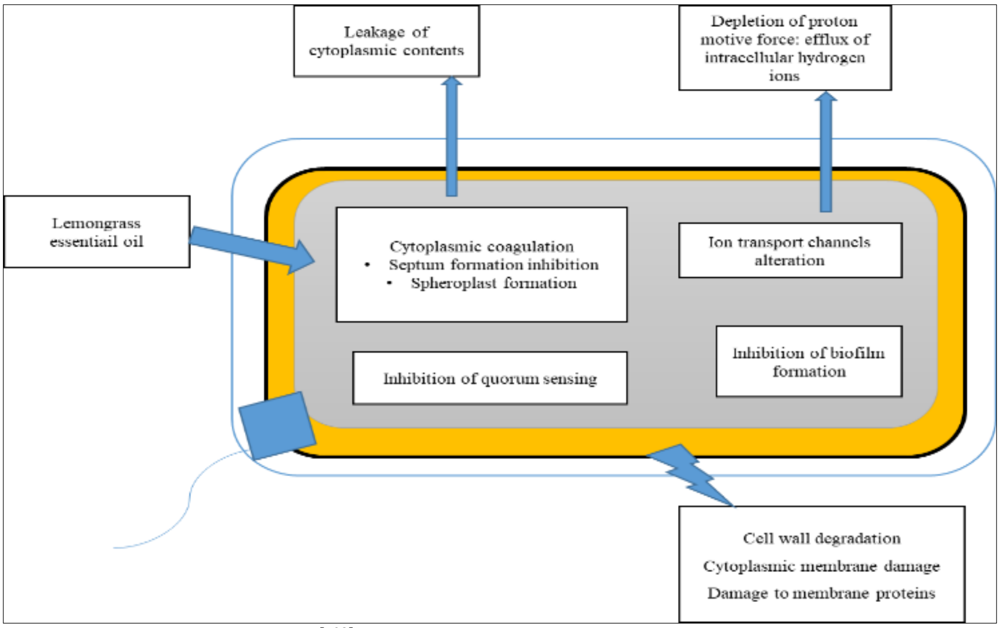
Application in cosmetics confectioneries: The biological activities of the ingredients in lemongrass are crucial for uses in cosmetics as well as in the fields of food science and medicine. The primary ingredient in lemongrass oil, citral, is thought to produce b-ionone, which has a low concentration of rose scent and is thus important for use in the perfumery industry. In the cosmetics industry, there are several lemongrass products with proprietary formulae that include glycerol and lemon balm oil.

Genetic Markers and Genomic Tools: Molecular markers in lemongrass, such as DNA-based markers, have revolutionized plant breeding programs by offering precise tools for selection and improvement. Lemongrass (*Cymbopogon sp*) is a popular herb known for its culinary and medicinal uses, and its genetic diversity plays a crucial role in developing improved varieties with enhanced traits. Here's why lemongrass molecular markers are of significant importance in plant breeding:

Genetic Diversity Assessment: Molecular markers allow for a comprehensive evaluation of the genetic diversity within lemongrass populations. By studying the genetic makeup of different lemongrass varieties or accessions, breeders can identify unique traits, disease resistance, and other desirable characteristics that can be used in breeding programs. Marker-Assisted Selection (MAS) molecular markers enable breeders to select plants with specific traits at the DNA level. This is particularly valuable for traits that are difficult to assess through traditional methods, such as disease resistance or tolerance to abiotic stress. MAS accelerates the breeding process by reducing the need for time-consuming and resource-intensive phenotypic evaluations other than

this accelerated breeding programs, trait mapping, conservation of Genetic Resources, hybridization and gene introgression and precision breeding are the main pioneer of molecular breeding for improvement of lemongrass crop.
Assessing different varieties or germplasms based on morphological traits involves examining cultural characteristics at various stages, but this method lacks reliability due to the influence of complex genetic interactions on many traits. Molecular markers derived from DNA sequences, such as RAPD and ISSR, offer a more dependable means of identification compared to morphological traits (Adhikari *et al*. 2013; Khanuja *et al*. 2005) [4, 48]. These DNA markers, renowned for providing extensive polymorphism at the genetic level, are instrumental in distinguishing closely related genotypes, aiding in the assessment of genetic diversity. RAPD and ISSR markers have been effectively utilized in studying various medicinal and aromatic crops (Bharmauria *et al*. 2009, Kasaian 2011, Khan *et al*. 2010) [12, 45, 48]. Similar to RAPD markers, ISSR markers are widely employed for individual fingerprinting. The ISSR technique stands out for its efficiency, speed, simplicity, reproducibility, and cost-effectiveness in assessing genetic diversity or identifying closely related cultivars in numerous plant species (Gonzalez *et al*. 2002; Bhau *et al*. 2009) [36, 14].
The study aimed to evaluate genotypic and phenotypic variations among 12 different genotypes of *Cymbopogon flexuosus*, a valuable medicinal plant, using three marker systems: morphological, biochemical, and molecular markers, including Random Amplified Polymorphic DNA (RAPD) and Inter-simple sequence repeat (ISSR). This comprehensive analysis seeks to establish relationships among the germplasm by correlating genotypic and phenotypic data to enhance the quality and quantity of essential oils.
The generated UPGMA dendrogram, which incorporated ISSR and RAPD analysis, revealed notable dissimilarity between genotype RLJ-M3 and RLJ-M10 (0.57), whereas the highest similarity was observed between genotype RLJ-M7 and RLJ-M9 (0.90) (Saikia *et al*. 2015) [78].

Water stress effect on lemongrass: Given that environmental pressures have a direct impact on crop growth, development, yield, and quality, they represent the biggest threat to food security (Crisp *et al*. 2016) [22]. Heat stress, drought, floods, salinity, and an excess or shortage of nutrients are examples of environmental stressors. Of these, dryness continues to be the primary constraint on plant growth and production globally, with over 50% of agricultural land located in arid and semi-arid regions. Furthermore, it is anticipated that the phenomena of global warming would exacerbate the drought crisis (Dai 2013) [23]. According to Saikia *et al*. (2018) [79], one of the most important environmental pressures affecting sustainable production is drought. Drought drastically inhibits plant development and growth (Bhargava and Sawank 2013; Rahadari and Hoseini 2012) [11, 75]. Moreover, during drought stress, crop quality and production suffer (Nezhadahmadi *et al*. 2013; Zlatev and Lidon 2012) [65, 94]. Cell division, elongation, and differentiation are essential for plant growth and development. Turgor loss, disruption of enzyme activity, and a reduction in photosynthesis-derived energy are all consequences of drought (Ding *et al*. 2013; Osakabe *et al*. 2014) [107, 68]. Lemongrass was susceptible to dehydration. Relative greenness and other aspects of plant development are negatively impacted by water deficiency, although the proportion of essential oils was favourably impacted. Conditions of water deficiency led to a rise in proline content, reflecting the protein's critical involvement in such stressful situations. In addition, the main compounds of essential oil geranial and neral- increased under severe water deficit compared to low water deficit. Given the difficulties with water scarcity, particularly in dry and semi-arid regions, it is advised to extend irrigation intervals to 10 days in order to reduce water usage and preserve slight drops in the output of oilseeds and herbs. Economically, the high-quality oil under stress will make up for the yield reductions by selling for a premium. It is also advised to carry out more research to improve lemongrass growth and quality in these stressful environments (Ahmoud *et al.* 2022) [56].



Source: Christopher *et al*. 2015 [109]

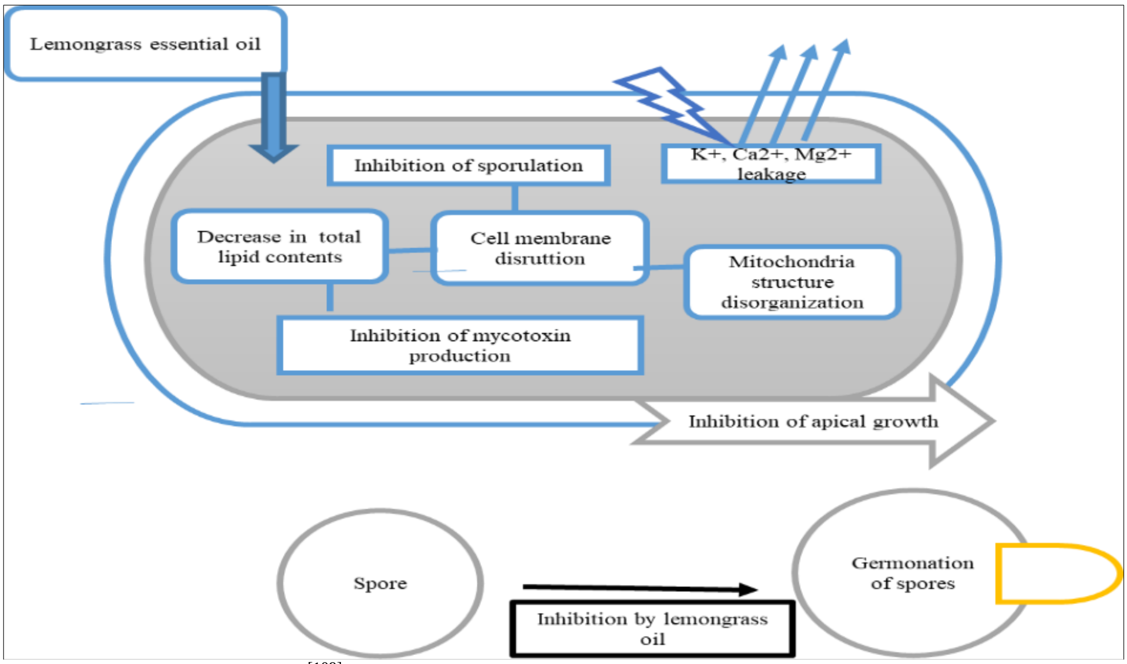
Fig 4: Possible antibacterial mechanism of action of lemongrass essential oil

Lemongrass essential oil's antibacterial properties: Numerous research have used both Gram-positive and Gram-negative microorganisms to evaluate the essential properties of lemomgrass experimentally. While some of these bacteria are susceptible to the antibacterial properties of essential oils, others are not. *Salmonella choleraesuis, Bacillus cereus, Bacillus subtilis, E. coli, K. pneumoniae, Pseudomonas aeruginosa, S. aureus, L. monocytogenes,* and *Pseudomonas fluorescens* are among the organisms (Adegoke and Odesola, 1998; Naik *et al*., 2010; Falcao *et al.*, 2012; Singh *et al.*, 2011; De Oliveira *et al.*, 2010; Soares *et al*., 2013) [3, 62, 30, 86, 24, 87]. Gram-positive bacteria are more heavily impacted by EOs than Gram-negative bacteria, according to the majority of research. Although essential oils are lipophilic/hydrophobic, the hydrophilic lipopolysaccharides on the outer membrane of Gram-negative bacteria may contribute to their higher resistance (Poole, 2002; Nakaido, 2003; Saha *et al*., 2008) [73, 63, 78]. This could result in an impermeable barrier. According to EOs added to other antibiotic vehicles, such as phenoxyethanol and stannous chloride, are effective against the majority of multidrug-resistant bacterial strains, including *P. aeruginosa, S. aureus*, and *E. coli*. Numerous recent investigations have sought to clarify the mechanism behind the antibacterial properties of essential oils (EOs) and the essential components accountable for these effects. These antibacterial activities occur together with cytotoxic activity, indicating a shared mechanism of action that is obviously membrane-based. Numerous studies link the terpenoid components of essential oils (EOs) to their antibacterial properties; specifically, citral, geranial (α-citral), and neral (β-citral) are effective (Onawunmi *et al*., 1984; Millezi *et al*., 2013) [67, 59]. Onawunmi *et al*. (1984) [67] found that myrcene did not show any observable activity on its own, but rather when combined with geranial and neral, it increased their activities. Other compounds that are likewise isolatable from C. *citratus* that have antibacterial properties include 1,8-cineole, eugenol, cinnamaldehyde, and linalool (Gill and Holley, 2004; Millezi *et al*., 2013) [35, 59].

Antifungal Activity: Positive fungicidal and anti-aflatoxigenic effects against various food storage and spoilage molds and yeast are demonstrated by *Cymbopogon citratus* essential oil (Paranagama *et al*., 2003; Matasyoh *et al*., 2011; Farhang *et al* 2013) [71, 58, 31]. Tyagi and Malik (2010) [89] support the findings of Boukhatem *et al*. (2014) [17], who found that EOs had much greater antibacterial action when employed in their vapour phase as opposed to their liquid phase. The lipophilic molecules in the aqueous phase combine to form micelles, which inhibit the attachment of essential oils to the organisms; in contrast, the vapor phase permits free attachment, which might be the reason why the vapour phase is more effective (Inouye *et al*., 2001; Inouye *et al*., 2003) [41, 40]. The potential of essential oil vapours has been studied less, despite growing interest, as compared to the extensive literature that shows the usefulness of essential oils in the liquid phase. Lemongrass essential oil has better antifungal action than tea tree or lavender essential oil, according to Casella & Casella (2010) [19]. It was also effective against a variety of yeast species (i.e., *C. albicans, Candida oleophila, Hansenula anomala, S. cerevisiae, Schizosaccharomyces pombe, Saccharomyces uvarum,and Metschnikowia fructicola) and fungi (i.e., Alternaria alternata, Aspergillus spp., Fusarium oxysporum, Penicillium roqueforti, Phytophthora infestans, Phoma sorghina, Phaeoramularia angolensis, etc.*) that cause food spoilage (Irkin and Korukluoglu, 2009; Tchinda *et al*., 2013; Kabera, 2013; Bonzi *et al*., 2013) [42, 88, 44, 15].

The cell membrane may be the major site of action for these essential oils. The transfer of nutrients and ions, the membrane potential, and the general permeability of fungal cells may all be impacted by their actions on the membrane. Despite the ideal settings, this always causes the microorganism to potentially die. Furthermore, conidial germination is linked to a number of signal transduction pathways, including as the cAMP/PKA and ras/MAPK pathways, as well as calcium/cal modulin signaling (Osherov and May, 2006) [69]. Lemongrass essential oil disrupts plasma cells, disarrays the structure of the mitochondria, and decreases *Aspergillus flavus hyphal* diameter, according to Helal *et al*. (2007) [39] (Link). Ca2+, K+, and Mg2+ leaks are also seen in fumigated mycelia. Moreover, the amount of saturated and unsaturated fatty acids increases while the amount of total lipids decreases. Since the cell uses its energy for survival or repair rather than proliferation, the outflow of tiny ions is not always a sign of total membrane dysfunction, since it may be seen in viable cells with limited growth (Bouhhid *et al*., 2010) [16]. The transmission of signals across cell membranes and, eventually, conidial germination may be impacted indirectly by this ion loss. Fungal infections are said to become latent or inactive due to the fungistatic properties of lemongrass essential oil, which prevents fungal growth and reproduction without eliminating it. The main component of lemongrass essential oil, which has anti-bacterial and anti-fungal properties, is citral. Certain fungus cannot develop when lemongrass essential oil is present in minimal fungicidal concentrations. When compared to growth culture, an in vitro experiment using these essential oils shows that *Fusarium sp*., *Sclerotium sp*., and *Alterneria sp.* do not grow at all.

Insecticidal effect of essential oil: *Cymbopogon* essential oils and their main ingredients act as allelochemicals. Allelochemicals are secondary metabolites that are employed as biopesticides in biocontrol because they have the ability to impact insect biology and behavior (Ganjewala, 2009) [34]. Comparing *C. citratus* to other commercial insecticidal products (Olivero-Verbel *et al*., 2010) [66], a number of studies demonstrate that it has a relatively strong insecticidal and repellent action on various insects that hamper food storage (Samarasekera *et al*., 2011; Kumar *et al*., 2013) [108, 50], even at the larval stage (Labinas and Crocomo, 2002; Li *et al*., 2005) [51, 54]. The anti-insect qualities of various doses of lemongrass essential oil were evaluated by Sharaby (1988) against the Spodoptera exigua Hbn, a smaller cotton leaf worm. The findings indicate that lemongrass essential oil was insecticidal, decreased egg hatchability, prevented third-instar larvae from eating on treated leaf discs, and inhibited egg laying. Lemongrass essential oil therefore served as an ovicidal and larvicidal agent, effectively controlling *S. exigua.* In the study of the insecticidal efficacy of lemongrass essential oil against the khapra beetle (*Trogoderma granarium Everts*) was also investigated on stored groundnuts. The essential oil of lemongrass has insecticidal properties. As a result, the authors advise against storing groundnuts with *T. granarium* and instead suggest using lemongrass essential oil.



Source: Christopher *et al*. 2015 [109]

Fig 5: Anti-fungal mechanism by lemongrass essential oil

Future prespective of lemongrass: As we look to the future, Lemongrass (*Cymbopogon flexuosus*) holds several promising avenues for research and application. Some key areas for future exploration include:

Biomedical Research: Continued research into Lemongrass's potential health benefits and pharmacological properties may yield new insights and applications in the field of medicine. This could include the development of novel drugs or natural remedies.

Agriculture and Pest Management: Investigating Lemongrass's role as a natural pest repellent and its potential use in integrated pest management strategies could reduce the reliance on chemical pesticides, promoting more sustainable agriculture.

Biofuel Production: Exploring Lemongrass as a source of biofuel could contribute to the development of alternative, renewable energy sources, reducing our dependence on fossil fuels.

Cultivation and Sustainability: Research and development efforts can focus on improving Lemongrass cultivation techniques to increase yields and resource efficiency while minimizing environmental impacts.

Product Diversification: Developing new products and applications for Lemongrass beyond essential oils, such as cosmetics, herbal medicines, and culinary innovations, can open up new markets and economic opportunities.

Conservation: Conservation efforts may be needed to protect wild Lemongrass populations, as increased demand for this valuable plant could lead to overharvesting and habitat degradation.

Conclusion

In conclusion, Lemongrass (*Cymbopogon flexuosus*) is a remarkable plant with a wide range of applications and benefits. Its unique citrusy aroma and flavor have made it a popular ingredient in culinary dishes, teas, and aromatherapy. Additionally, Lemongrass possesses various medicinal properties, including anti-inflammatory, antimicrobial, and antioxidant effects, which have been studied and utilized in traditional and modern medicine. Furthermore, Lemongrass cultivation and essential oil extraction have created economic opportunities for farmers and entrepreneurs in many regions. The plant's sustainable growth and relatively low resource requirements make it an environmentally friendly choice for essential oil production. Its potential for biofuel production and pest-repellent properties also hold promise for agriculture and pest management. Lemongrass (*Cymbopogon flexuosus)* is a versatile plant with a rich history and a promising future. Continued research and sustainable practices can harness its potential for the benefit of agriculture, industry, and human well-being. This remarkable plant is a testament to the value of biodiversity and the potential for natural resources to drive innovation and sustainable development.

Conflict of Interest

The author shows no conflict of interest.

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