RESEARCH PAPER

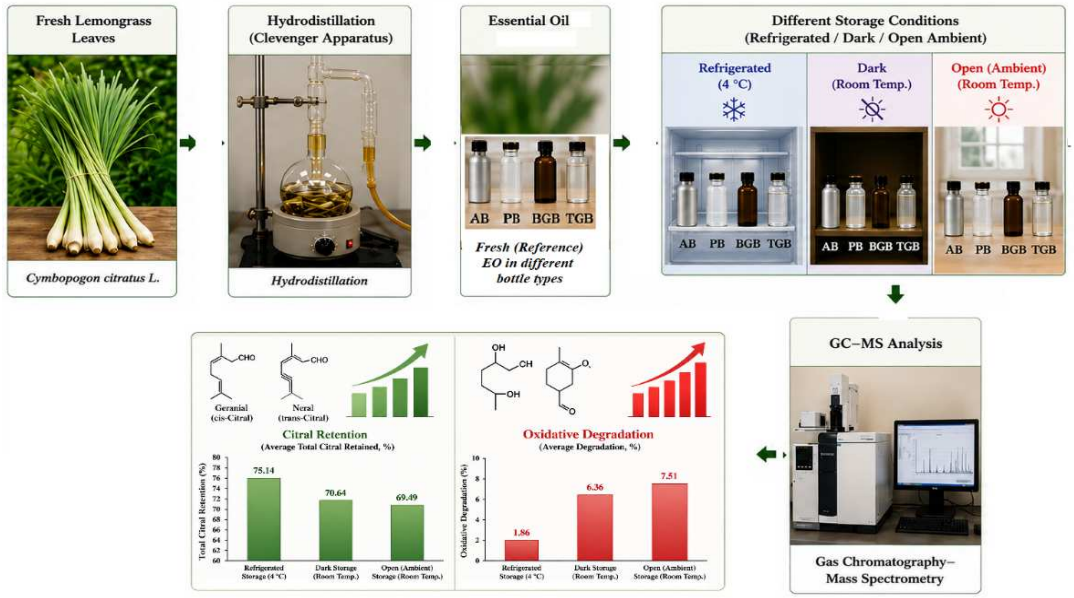
Stability Assessment of Lemongrass *(Cymbopogon citratus L.)* Essential Oil under Different Storage Environments and Packaging Materials

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ABSTRACT:
The present study investigated the influence of storage conditions and packaging materials on the physicochemical properties and chemical stability of Cymbopogon citratus essential oil during twelve months of storage. Fresh essential oil was extracted by hydrodistillation using a Clevenger-type apparatus and stored under refrigerated (4 °C), dark, and open (ambient) conditions in aluminum bottles (AB), plastic bottles (PB), brown glass bottles (BGB), and transparent glass bottles (TGB). Physicochemical properties and total citral content were periodically evaluated by standard analytical methods and gas chromatography. Refrigerated storage exhibited the highest stability, with total citral remaining between 73.28 and 74.38% after twelve months, corresponding to approximately 94–95% retention of the initial citral content. Dark storage resulted in moderate citral degradation (66.61–70.02%), while open (ambient) storage produced the greatest loss (65.80–69.98%). Brown glass bottles consistently showed the highest citral retention, followed by transparent glass, aluminum, and plastic bottles. Physicochemical analysis revealed only minor changes during storage, with gradual increases in refractive index, specific gravity, and acid value, accompanied by increases in optical rotation indicating progressive oxidative deterioration. The findings demonstrate that storage temperature and packaging material act synergistically to preserve citral stability and essential oil quality. Refrigerated storage in brown glass bottles was identified as the most effective condition for minimizing oxidative degradation, extending shelf life, and maintaining the commercial, aromatic, and therapeutic quality of citral-rich lemongrass essential oil.

Keywords: Lemongrass essential oil; Storage stability; Citral degradation; GLC-analysis; Oxidative stability.
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GRAPHICAL ABSTRACT:



INTRODUCTION

Essential oils are naturally occurring volatile substances extracted from aromatic plants and consist mainly of terpenes and oxygenated compounds such as alcohols, aldehydes, ketones, esters, and phenolic compounds. These oils are commonly obtained from leaves, flowers, stems, roots, seeds, and bark through extraction methods including steam distillation, hydrodistillation, and cold pressing [1]. Due to the presence of biologically active constituents, essential oils exhibit significant antimicrobial, antioxidant, medicinal, and preservative properties [2]. The chemical composition and bioactivity of natural products are influenced by several factors, including plant species, geographical origin, climatic and environmental conditions, harvesting stage, and extraction technique. [3–4]

In recent years, essential oils have gained considerable attention in food, pharmaceutical, and cosmetic industries because of the increasing demand for natural and eco-friendly products [4]. They are particularly valued for their antimicrobial properties, which are associated with their ability to interact with and disrupt microbial cell membranes, inhibit bacterial enzymes, and interfere with DNA synthesis. Furthermore, chemical functionalization or derivatization of phenolic compounds can enhance their antimicrobial activity and improve their therapeutic potential [5]. The biological activities of essential oils strongly depend on their chemical profile and the concentration of active constituents.

Among aromatic plants, lemongrass (Cymbopogon citratus and Cymbopogon flexuosus) is widely recognized for its characteristic lemon-like fragrance and therapeutic importance. Lemongrass essential oil is rich in citral, which mainly consists of α-citral and β-citral and contributes significantly to its aroma and biological activity [8]. Other important constituents include myrcene, linalool, geraniol, and geranyl acetate. Citral-rich lemongrass oil has demonstrated strong antioxidant and antibacterial properties against various pathogenic microorganisms. In addition, studies have shown that citral may improve the effectiveness of certain antibiotics against multidrug-resistant bacteria, highlighting its potential role in combating antibiotic resistance [8].

Traditionally, it has been used for the treatment of wounds, skin infections, fever, and common cold symptoms [9]. During storage and transportation, oxidation reactions may occur, resulting in the formation of hydroperoxides and other degradation products that reduce the oil's aromatic quality and biological effectiveness [10]. Lemongrass essential oil has also been reported to possess insecticidal, repellent, medicinal, and therapeutic properties [11, 12]. Environmental factors such as storage temperature, light exposure, and container type significantly influence the chemical stability and shelf life of essential oils [13].

Furthermore, its eco-friendly nature and pleasant aroma have promoted its application in integrated pest management systems as an alternative to synthetic chemical pesticides [14,15].

Despite these valuable properties, the practical application of lemongrass essential oil is limited due to its high volatility, low water solubility, and sensitivity to environmental conditions such as oxygen, light, heat, and moisture [16]. To improve the stability and functionality of essential oils, encapsulation techniques have been widely investigated [17]. Encapsulation involves incorporating essential oil droplets within polymeric or emulsifying matrices that act as protective barriers against oxidation, evaporation, and environmental degradation [18]. This approach enhances the stability, controlled release behavior, and overall performance of essential oils in different applications. Additionally, the lipophilic constituents of lemongrass oil can interact with microbial membranes, causing membrane disruption and increased permeability, thereby contributing to its antimicrobial effectiveness [19–20].

Although several studies have investigated the chemical composition, bioactivity, and storage stability of lemongrass (*Cymbopogon citratus*) essential oil, the combined effects of storage environment, packaging material, and prolonged storage duration on citral stability have received comparatively limited attention.

Previous studies have demonstrated that storage conditions can alter the chemical composition and stability of *C. citratus* essential oil. Tran et al. [21] investigated changes in the chemical composition of lemongrass essential oil under different storage conditions over four months, demonstrating the influence of storage environment on its volatile constituents. More recently, Kumar et al. [22] evaluated the effects of aluminum, transparent glass, and HDPE plastic containers on the chemical degradation and antibacterial activity of lemongrass essential oil during one year of storage. However, a comprehensive comparison integrating different storage environments with commercially relevant packaging materials over an extended 12-month period, together with systematic monitoring of citral retention and physicochemical quality parameters, remains comparatively limited. Such an integrated assessment is important because citral, comprising geranial and neral, is the principal aroma and bioactive constituent of lemongrass essential oil and is closely associated with its commercial quality and functional properties. Therefore, the present study aimed to systematically evaluate the effects of storage

conditions and packaging materials on the physicochemical properties and citral retention of lemongrass essential oil during twelve months of storage using gas chromatography, and to relate the observed changes to potential degradation pathways. The findings provide practical information for optimizing storage conditions and packaging strategies to improve the shelf life and preserve the quality of lemongrass essential oil for aroma, flavour, cosmetic, pharmaceutical, and food applications.

MATERIALS AND METHODS

Collection of Plant material :

Fresh lemongrass (*Cymbopogon citratus* L.) leaves were collected from the botanical garden of VSSD College, Kanpur, India, in the morning hours (5:00–6:00 a.m.). The collected plant material was thoroughly washed with distilled water to remove adhering dust and other impurities. After cleaning, the leaves were air-dried under ambient laboratory conditions and stored in the Chemistry Laboratory at a controlled temperature of 27–30 °C prior to further experimental analysis.

Extraction of essential oil:

Fresh leaves of lemongrass (*Cymbopogon citratus* L.) were carefully weighed and transferred into a round-bottom flask connected to a Clevenger-type apparatus for essential oil extraction. Hydrodistillation was carried out for approximately 5–6 h to ensure efficient recovery of volatile constituents from the plant material. During the distillation process, steam passed through the plant matrix, facilitating the release of aromatic compounds, which were subsequently condensed and collected in the graduated receiver of the apparatus.

After completion of the extraction process, the essential oil layer was carefully separated from the aqueous distillate. The collected oil was then treated with anhydrous sodium sulfate to remove residual moisture and obtain a clear, water-free essential oil sample. The purified lemongrass essential oil was subsequently transferred into clean airtight glass vials to minimize contamination, oxidation, and volatilization losses during storage.

$$\text{Essential oil Yield (\%)} = \frac{\text{weight of oil collected(gm)}}{\text{Weight of sample (gm)}} \times 100$$

To evaluate the influence of storage conditions on the chemical stability and compositional integrity of the oil, freshly extracted samples stored in glass vials were maintained under three different environmental conditions, namely refrigerated storage, dark storage, and open storage conditions at room temperature. Four commercially available packaging materials were selected to evaluate their effect on the storage stability of *Cymbopogon citratus* essential oil: aluminum bottles (AB), plastic bottles (PB; HDPE), brown glass bottles (BGB), and transparent glass bottles (TGB). Each 100 mL bottle was filled with 100 mL of freshly extracted essential oil and sealed with airtight polypropylene screw caps (Fig.1).



Fig.1 Storage containers (100 mL) used in the storage stability study of Cymbopogon citratus essential oil. AB = aluminum bottle; PB = transparent plastic bottle; BGB = brown glass bottle; TGB = transparent glass bottle.

The average wall thickness was approximately 1.0 mm (AB), 1.2 mm (PB), and 2.0 mm (BGB and TGB). These packaging materials differ in their oxygen and light barrier properties and are widely used in the aroma, cosmetic, pharmaceutical, and essential oil industries. Brown glass and aluminum provide superior protection against light and oxygen, whereas HDPE exhibits comparatively higher oxygen permeability. For each storage condition (refrigerated, dark, and ambient), three independent bottles of each packaging type were used (n = 3). All physicochemical and GC analyses were performed in triplicate, and the results are expressed as mean ± standard deviation.

PHYSICOCHEMICAL PROPERTIES:

Freshly extracted and de-moisturized lemongrass essential oil samples were transferred into clean glass vials and stored under three different conditions for twelve months: open condition at room temperature (27 ± 3 °C), refrigerated condition, and dark condition protected from light exposure. Equal volumes of oil (100 mL) were filled into the glass vials up to the neck level to minimize air space and were tightly sealed with inner and outer caps throughout the storage period.

After twelve months of storage, the physicochemical properties of the lemongrass oil samples were evaluated and compared with freshly distilled oil, as presented in Table 1. Parameters including optical rotation, refractive index, specific gravity, solubility in ethanol, acid value, ester value, and ester value after acetylation were determined according to the standard methods prescribed by the Bureau of Indian Standards (BIS) for essential oil analysis [23-29]. Optical rotation was measured using Rajdhani RSP3 Polarimeter, while refractive index was determined using a Abbe Refractometer. All analyses were

performed in triplicate, and the results are expressed as mean ± standard deviation.

Table 1. Results of different storage conditions in glass vials on the physicochemical properties of lemongrass essential oil after twelve months of storage.

Physiochemical Properties	Freshly distilled oil	Brown Glass Bottle (BGB)-Stored Lemongrass Essential Oil After Twelve Months		
		Refrigerator	Dark	Open
Color	Dark yellow	Dark yellow	Dark yellow,	Pale yellow,
Odor	lemon-like	lemon-like	lemon-like	lemon-like
Optical rotation	- 2.74°± 0.02	- 2.72°± 0.02	- 2.69°± 0.02	- 2.65°± 0.02
Refractive index	1.4775 ±0.0002	1.4779 ±0.0002	1.4782 ±0.0002	1.4787 ±0.0002
Specific gravity	0.8912 ±0.0002	0.8918 ±0.0002	0.8924 ±0.0002	0.8929 ±0.0002
Solubility (70% EtOH)	2 vol.	2 vol.	2 vol.	2 vol.
Acid value % by mass	2.72%± 0.02	2.90 ± 0.02	3.26 ± 0.03	4.74 ± 0.03

Gas Chromatography Analysis of Lemongrass Essential Oil:

The chemical composition of lemongrass essential oil was analyzed using Gas Chromatography equipped with an Agilent 789013 gas chromatograph. Separation of volatile constituents was achieved using a fused silica capillary column HP-INNOWAX (30 m × 0.25 mm internal diameter × 0.25 µm film thickness). Nitrogen was used as the carrier gas at a constant flow rate of 1.5 mL min^{-1}, while *n*-hexane was used as the solvent. The injection volume of the oil sample was 0.2 µL, and the GC interface temperature was maintained at 250 °C. The oven temperature program was initially set at 60 °C and increased to 200 °C at a rate of 6 °C min^{-1}, followed by heating from 200 °C to 275 °C at 8 °C min^{-1}, and finally from 275 °C to 280 °C at 5 °C min^{-1}.

A built-in data-handling programme for the gas chromatograph, provided by the manufacturer, was used for all quantification. The relative % composition of each component was calculated based on GC peak areas without applying a correction factor.

RESULTS AND DISCUSSION

Physical Properties

The physical properties of freshly distilled lemongrass (*Cymbopogon citratus* L.) essential oil and samples stored in brown glass bottles (BGB) under refrigerated, dark, and open (ambient) conditions for twelve months are presented in Table 1 and Fig. 2. Only minor physicochemical changes were observed during storage, although the extent of change varied with storage conditions. Refrigerated storage showed the highest preservation of oil quality, whereas open (ambient) storage resulted in comparatively greater physicochemical changes.

Freshly distilled lemongrass essential oil exhibited a characteristic dark yellow color with a strong lemon-like odor, reflecting its high citral content. After twelve months, the oils stored under refrigerated and dark conditions largely retained their original dark yellow appearance, whereas the sample stored under open (ambient) conditions gradually changed to pale yellow, indicating pigment degradation due to oxidation and prolonged exposure to atmospheric oxygen. Similar color changes have been reported during long-term storage of citral-rich essential oils owing to oxidative degradation of monoterpenoids and naturally occurring pigments.

The characteristic lemon-like aroma remained unchanged under all storage conditions, suggesting that the principal volatile constituents responsible for the fragrance were largely preserved throughout storage. Although gradual oxidation occurred, the changes were insufficient to produce noticeable sensory deterioration.

Only slight variations in optical rotation were observed during storage (Fig. 2a). The freshly distilled oil exhibited an optical rotation of −2.74 ± 0.02°, while refrigerated storage showed the smallest deviation (−2.72 ± 0.02°). The values gradually shifted to −2.69 ± 0.02° under dark storage and −2.65 ± 0.02° under open (ambient) storage, indicating minor compositional changes associated with slow oxidation and structural modification of terpenoid constituents.

A gradual increase in refractive index was observed during storage (Fig. 2b). The refractive index increased from 1.4775 ± 0.0002 in freshly distilled oil

to 1.4779 ± 0.0002 after refrigerated storage, 1.4782 ± 0.0002 after dark storage, and 1.4787 ± 0.0002 after open (ambient) storage. This increase may be attributed to the gradual formation of oxygenated compounds and oxidation products that slightly alter the optical properties of the oil.

Specific gravity also increased slightly during storage (Fig. 2c), rising from 0.8912 ± 0.0002 in freshly distilled oil to 0.8918 ± 0.0002, 0.8924 ± 0.0002, and 0.8929 ± 0.0002 under refrigerated, dark, and open storage conditions, respectively. The smaller increase under refrigerated storage indicates better preservation of the original composition, whereas the greater increase under open storage suggests enhanced oxidation and formation of higher molecular weight oxygenated compounds.

No change was observed in the solubility of the oil in 70% ethanol, as all samples remained completely soluble in two volumes of ethanol throughout the storage period. This result indicates that prolonged storage under the investigated conditions did not significantly affect the overall polarity of lemongrass essential oil.

Overall, refrigerated storage in brown glass bottles provided the highest physical stability of lemongrass essential oil during twelve months of storage, whereas open (ambient) storage caused the greatest deterioration. The higher citral retention and lower oxidative degradation under refrigerated conditions confirm that low-temperature storage in brown glass bottles is the most suitable method for preserving essential oil quality.

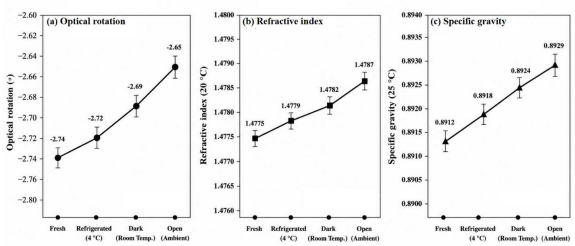
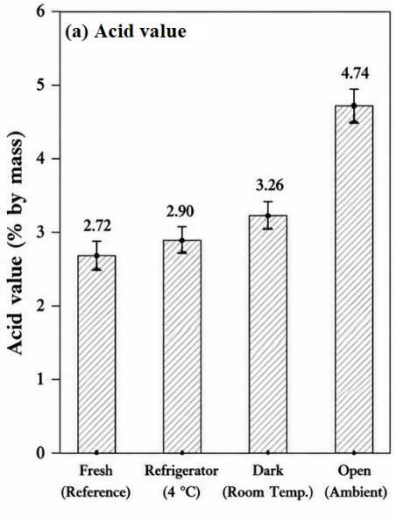


Fig. 2. Changes in the physicochemical properties of Brown Glass Bottle (BGB)-stored lemongrass essential oil after 12 months under different storage conditions: (a) optical rotation, (b) refractive and (c) specific gravity (values are mean ± SD, n = 3).

Chemical Properties:

The changes in the chemical quality parameters of Brown Glass Bottle (BGB)-stored lemongrass essential oil after 12 months under different storage conditions are presented in Table 1 and Fig. 3. Storage conditions influenced the chemical stability of the essential oil, particularly the acid value.

The acid value increased from 2.72 ± 0.02% in freshly distilled oil to 2.90 ± 0.02%, 3.26 ± 0.03%, and 4.74 ± 0.03% under refrigerated, dark, and open (ambient) storage, respectively (Fig. 3). The lower acid value under refrigerated storage indicates reduced oxidation and hydrolysis, whereas the highest value under open storage reflects greater oxidative deterioration due to prolonged exposure to oxygen and ambient conditions.



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Fig 3. Changes in chemical properties of Brown Glass Bottle (BGB)-stored lemongrass essential oil after 12 months under different storage conditions: acid value (% by mass),

Overall, storage conditions influenced the chemical stability of lemongrass essential oil during the Twelve-month storage period. Refrigerated storage showed the least change, with the lowest acid value (2.90 ± 0.02%), These results indicate that refrigerated storage in brown glass bottles is the most suitable condition for maintaining the chemical quality of lemongrass essential oil during long-term storage.

GC Analysis of Lemongrass Essential Oil :

(i) Refrigerated Storage

The effect of refrigerated storage on the total citral content of Cymbopogon citratus essential oil packaged in aluminum bottles (AB), plastic bottles (PB), brown glass bottles (BGB), and transparent glass bottles (TGB) is presented in Table 2(i) and Fig. 4. Refrigerated storage effectively maintained citral stability throughout the 12-month storage period, indicating that low temperature significantly retarded chemical deterioration of the essential oil. Fresh oil contained 77.92% total citral, which decreased only slightly after three months to 75.92% (AB), 75.91% (PB), 76.50% (BGB), and 75.99% (TGB). The consistently higher citral retention in BGB, followed by TGB, AB, and PB, demonstrates that packaging material played a complementary role in preserving essential oil quality under refrigerated conditions. Similar observations have been reported for citral-rich essential oils, where low-temperature storage

effectively reduced oxidation and volatilization of monoterpenoids while maintaining aroma quality [13]. A gradual decline in total citral content was observed with increasing storage duration in all bottle types; however, the reduction remained relatively small. After 6 months, citral contents were 75.93% (BGB), 75.90% (TGB), 74.68% (AB), and 74.60% (PB). After 9 months, the values decreased to 74.68% (BGB), 74.63% (TGB), 74.63% (AB), and 73.38% (PB), respectively. At the end of 12 months, BGB and TGB retained the highest citral content (74.38% each), followed by AB (73.66%) and PB (73.28%). Overall, the reduction in citral from the fresh reference value of 77.92% was 3.54 percentage points in BGB and TGB, 4.26 percentage points in AB, and 4.64 percentage points in PB, corresponding to retention of approximately 95.46%, 95.46%, 94.53%, and 94.05%, respectively. These results demonstrate that refrigerated storage preserved more than 94% of the initial total citral content over the 12-month period. The superior stability of citral under refrigerated storage can be attributed to the suppression of oxidation, isomerization, and volatilization reactions at lower temperatures. According to the Arrhenius principle, decreasing storage temperature reduces reaction rates and limits the formation of oxidation products from geranial and neral, thereby preserving total citral [30].

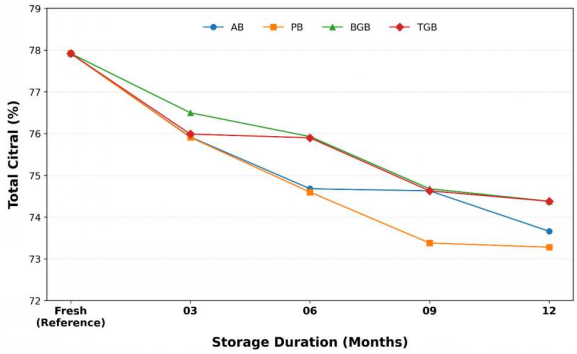


Fig. 4. Changes in total citral (%) of lemongrass essential oil stored in AB, PB, BGB, and TGB under refrigerated conditions (twelve months).

Brown glass bottles further enhanced citral retention because they effectively blocked ultraviolet radiation and provided an excellent barrier against atmospheric oxygen, reducing photooxidation and oxidative degradation. Transparent glass bottles also performed well owing to their low oxygen permeability but allowed greater light transmission, whereas aluminum bottles showed slightly lower stability. Plastic bottles consistently exhibited the greatest citral loss, which may be attributed to their comparatively higher oxygen permeability and possible interaction of volatile compounds with the polymer matrix during prolonged storage [22, 30].

(ii) Dark Storage

The influence of dark storage on the total citral content of Cymbopogon citratus essential oil stored in aluminum bottles (AB), plastic bottles (PB), brown glass bottles (BGB), and transparent glass bottles (TGB) is presented in Table 2(ii) and Fig. 5. Although storage in darkness eliminated direct photooxidation, a progressive decline in total citral was observed throughout the 12-month storage period, indicating that oxidative degradation continued under ambient temperature. After three months, BGB retained the highest citral content (74.33%), followed by TGB (72.40%), AB (71.37%), and PB (70.87%). Compared with refrigerated storage, all bottle types exhibited lower citral retention, suggesting that temperature plays a more decisive role than light exclusion in preserving citral-rich essential oils [13, 21, 22]. As increases storage duration, total citral gradually decreased in all packaging materials. At six months, citral content declined to 72.59% (BGB), 71.87% (TGB), 71.19% (AB), and 70.76% (PB), while after nine months the corresponding values further decreased to 72.40% (BGB), 71.58% (TGB), 70.30% (AB), and 69.91% (PB), respectively. Brown glass bottles consistently exhibited the highest citral retention, whereas plastic bottles showed the greatest reduction. This behavior can be attributed to the superior oxygen and light barrier properties of brown glass, which restrict oxygen diffusion and minimize residual light-induced oxidation. In contrast, the higher oxygen permeability of plastic packaging facilitates oxidative conversion of citral into secondary oxygenated compounds, thereby accelerating quality deterioration during storage [13, 21].

After twelve months, the total citral content decreased to 70.02% (BGB), 69.69% (TGB), 68.56% (AB), and 66.61% (PB), corresponding to reductions of 10.14%, 10.57%, 12.00%, and 14.52%, respectively, compared with fresh oil. The greater losses observed under dark storage compared with refrigerated storage indicate that elimination of light alone is insufficient to preserve citral if storage temperature remains moderate. Thermal oxidation, autoxidation, and gradual degradation of geranial and neral continue during prolonged storage, leading to progressive depletion of total citral. Overall, the order of citral stability remained BGB > TGB > AB > PB, confirming that brown glass bottles provide the most effective protection under dark storage conditions.

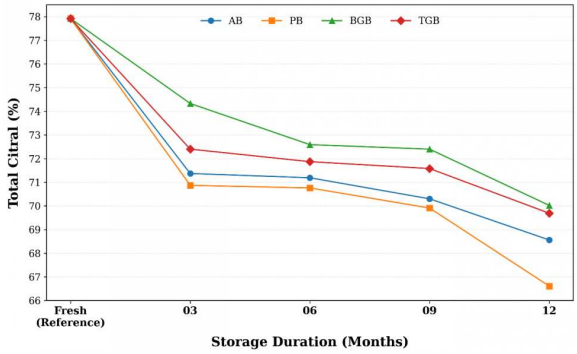


Fig. 5. Changes in total citral (%) of lemongrass essential oil stored in AB, PB, BGB, and TGB during twelve months of dark storage.

(iii) Open (Ambient) Storage

The effect of open (ambient) storage on the total citral content of *Cymbopogon citratus* essential oil is presented in Table 2(iii) and Fig. 6. Open storage resulted in the greatest reduction in citral among all storage conditions, demonstrating the combined adverse effects of ambient temperature, atmospheric oxygen, and intermittent light exposure on essential oil stability. After three months**,** total citral ranged from 70.76% (PB) to 73.88% (BGB), while AB and TGB retained 71.25% and 72.13%, respectively. Even at this early stage, citral retention was lower than that observed under refrigerated and dark storage, indicating accelerated degradation under ambient conditions [21, 22]. The decline became more pronounced with increasing storage duration. At six months**,** total citral decreased to 70.50% (BGB), 69.91% (TGB), 69.54% (AB), and 66.69% (PB). Further
reductions were observed after nine months**,** reaching 70.02%, 68.94%, 66.94%, and 66.61%, respectively. Brown glass bottles consistently maintained the highest citral content, whereas plastic bottles exhibited the most rapid deterioration. These results indicate that packaging materials with superior oxygen barrier properties significantly delay oxidation, whereas plastic containers allow greater oxygen ingress, thereby promoting degradation of geranial and neral during long-term
storage.

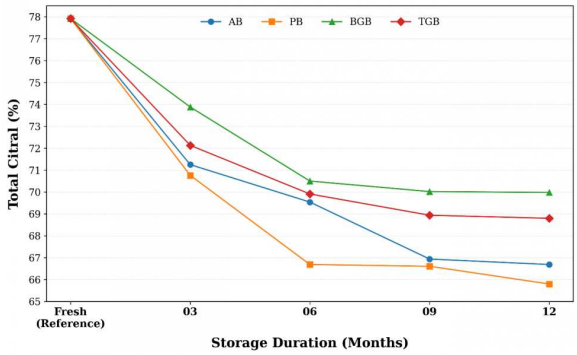


Fig. 6. Changes in total citral (%) of lemongrass essential oil stored in AB, PB, BGB, and TGB during twelve months of Open (Ambient) storage.

After twelve months, the total citral content declined to 69.98% (BGB), 68.80% (TGB), 66.69% (AB), and 65.80% (PB), corresponding to reductions of 10.19%, 11.70%, 14.41%, and 15.55%, respectively, relative to fresh oil. The substantial decrease observed under ambient storage reflects the combined effects of elevated temperature, oxygen exposure, volatilization, and oxidation, which accelerate the conversion of citral into secondary degradation products. Among all packaging materials, brown glass bottles provided the greatest protection by minimizing oxygen diffusion and light penetration, whereas plastic bottles exhibited the poorest performance because of their higher oxygen permeability and lower protective efficiency [21, 22].

Overall, ambient storage was the least suitable condition for preserving citral-rich lemongrass essential oil. The consistent order of citral retention (BGB > TGB > AB > PB) demonstrates that
storage temperature and packaging material act synergistically to influence chemical stability.

Therefore, long-term storage of lemongrass essential oil under ambient conditions, particularly in plastic containers, should be avoided to maintain its aroma quality, therapeutic value, and commercial shelf life [31]. Table 2. Combined effects of storage duration, storage condition, and
bottle type on the total citral content (%) of lemongrass (Cymbopogon citratus) essential oil.

Storage Duration (Months)	**Total Citral (%) in Different Bottle* Types**			
	AB	PB	BGB	TGB
Fresh (Reference)	77.92	77.92	77.92	77.92
(i) Refrigerated Storage				
03	75.92	75.91	76.50	75.99
06	74.68	74.60	75.93	75.90
09	74.63	73.38	74.68	74.63
12	73.66	73.28	74.38	74.38
(ii) Dark Storage				
03	71.37	70.87	74.33	72.40
06	71.19	70.76	72.59	71.87

09	70.30	69.91	72.40	71.58
12	68.56	66.61	70.02	69.69
(iii) Open (Ambient) Storage				
03	71.25	70.76	73.88	72.13
06	69.54	66.69	70.50	69.91
09	66.94	66.61	70.02	68.94
12	66.69	65.80	69.98	68.80

***Abbreviations:** AB = Aluminum Bottle; PB = Plastic Bottle; BGB = Brown Glass Bottle; TGB = Transparent Glass Bottle.*

Reaction mechanism of citral degradation

Citral, the major volatile constituent of lemongrass essential oil, consists mainly of geranial (α-citral) and neral (β-citral). Its α,β-unsaturated aldehyde structure makes it susceptible to oxidation, photooxidation, thermal degradation, and secondary rearrangement reactions during storage [32]. The proposed molecular pathways involved in these degradation processes are illustrated in Fig. 7(a). Accordingly, citral declined from 77.92% in fresh oil to 73.28–74.38% under refrigeration and to lower levels under dark and open ambient conditions.

Refrigeration provided the highest citral retention. In BGB, citral decreased from 77.92% to 74.38% after 12 months. The lower temperature suppresses thermally activated oxidation and other degradation reactions [33]. BGB showed the highest retention, followed by TGB, AB, and PB, indicating an additional protective effect of light exclusion by brown glass. Twelve-month retention: BGB (74.38%) = TGB (74.38%) > AB (73.66%) > PB (73.28%).

Major reaction at low temperature

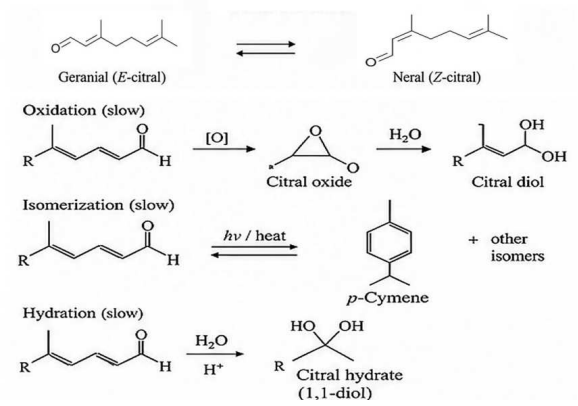


Fig. 7 (a). Proposed molecular mechanisms of citral degradation in lemongrass essential oil during dark ambient storage in different bottle types.

Under dark ambient conditions, citral declined to 68.56% (AB), 66.61% (PB), 70.02% (BGB), and 69.69% (TGB) after 12 months. Although light-induced reactions are minimized, oxidation and thermally accelerated degradation can continue in the presence of oxygen. Citral oxidation may generate hydroperoxide intermediates and subsequent aldehydes, ketones, alcohols, and other secondary products [34], as represented in Fig. 7(b). BGB retained the highest citral concentration, demonstrating the benefit of light-protective packaging.

Auto-oxidation

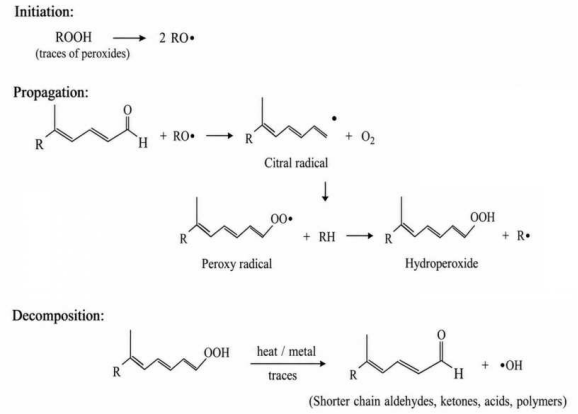


Fig. 7 (b). Proposed molecular mechanisms of citral degradation in lemongrass essential oil during dark ambient storage in different bottle types.

The greatest citral loss occurred under open ambient storage, with 12-month values of 66.69% (AB), 65.80% (PB), 69.98% (BGB), and 68.80% (TGB). Exposure to oxygen, light, and ambient temperature promotes simultaneous oxidative and photooxidative degradation, while temperature accelerates reaction kinetics [35]. These processes, including oxidation and subsequent molecular rearrangements, are summarized in Fig. 7(c). The retention order was BGB (69.98%) > TGB (68.80%) > AB (66.69%) > PB (65.80%).

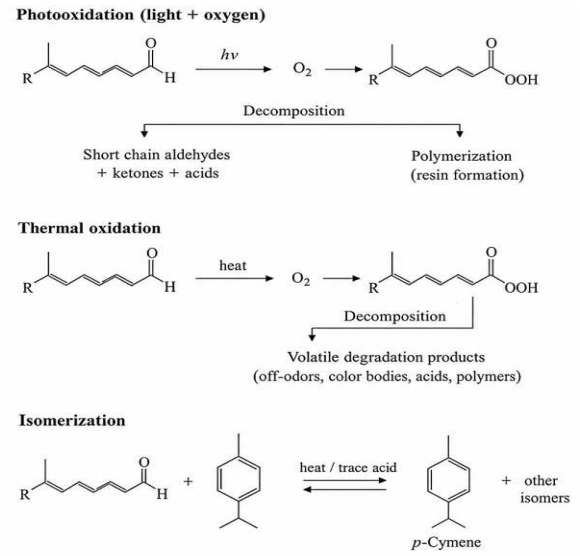


Fig. 7 (c). Proposed molecular mechanisms of citral degradation in lemongrass essential oil during open ambient storage conditions in different bottle types.

Overall, citral degradation followed the order refrigerated < dark ambient < open ambient storage. BGB consistently provided the greatest protection, whereas PB showed the highest loss. These findings confirm that temperature, oxygen, light exposure and packaging material are important determinants of citral stability. The proposed molecular mechanisms responsible for citral degradation under these storage conditions are presented in Fig. 7 (a, b, c). Refrigerated storage in brown glass is therefore the most suitable condition for preserving citral-rich lemongrass essential oil.

CONCLUSION

This study demonstrated that storage conditions and packaging materials significantly influence the physicochemical quality and citral stability of *Cymbopogon citratus* essential oil during twelve months of storage. Refrigerated storage in brown glass bottles provided the highest citral retention, lowest oxidative degradation, and best preservation of oil quality, whereas ambient storage in plastic bottles caused the greatest deterioration. The proposed molecular degradation pathway explains the progressive oxidation of geranial and neral into secondary oxygenated compounds, supporting the observed decline in citral. The work lies in integrating physicochemical evaluation, GC-based citral monitoring, comparative assessment of packaging materials, and a molecular degradation mechanism to establish practical storage recommendations. Since citral is the principal aroma and bioactive constituent of lemongrass oil, its concentration directly determines fragrance quality, therapeutic efficacy, industrial grade, and market value. Therefore, preserving citral is essential for the aroma, flavour, pharmaceutical, cosmetic, food, and aromatherapy industries. These findings provide a scientific basis for improving storage practices, extending shelf life, minimizing quality losses, and enhancing the commercial value of citral-rich lemongrass essential oil.

CONFLICT OF INTEREST

The authors report there are no competing interests to declare.

References

1. Al-Breiki, A. M.; Al-Brashdi, H. M.; Al-Sabahi, J. N.; Khan, S. A. Comparative GC–MS Analysis, *In Vitro* Antioxidant and Antimicrobial Activities of the Essential Oils Isolated from the Peel of Omani Lime. *Chiang Mai J. Sci.* **2018**, *45*, 1782–1795.
2. Aziz, Z. A. A.; Ahmad, A.; Setapar, S. H. M.; Karakucuk, A.; Azim, M. M.; Lokhat, D.; Rafatullah, M.; Ganash, M.; Kamal, M. A.; Ashraf, G. M. Essential Oils: Extraction Techniques, Pharmaceutical and Therapeutic Potential—A Review. *Curr. Drug Metab.* **2018**, *19*, 1100–1110.
3. Yadav, A.; Ranjan, A. K.; Yadav, S. K. Review on Chemical Composition of Essential Oil Extracted from Aromatic Plants by Hydro-Distillation and Steam Distillation. *Eur. Chem. Bull.* **2023**, *12*, 1581–1600.
4. Sun, S.; Yu, Y.; Jo, Y.; Han, J. H.; Xue, Y.; Cho, M.; Bae, S.-J.; Ryu, D.; Park, W.; Ha, K.-T.; Zhuang, S. Impact of Extraction Techniques on Phytochemical Composition and Bioactivity of Natural Product Mixtures. *Front. Pharmacol.* **2025**, *16*, 1615338.
5. Lobiuc, A.; Pavăl, N.-E.; Mangalagiu, I. I.; Gheorghiță, R.; Teliban, G.-C.; Amăriucăi-Mantu, D.; Stoleru, V. Future Antimicrobials: Natural and Functionalized Phenolics. *Molecules* **2023**, *28*, 1114.
6. Pascall, M.; Lin, S. J. The Application of Edible Polymeric Films and Coatings in the Food Industry. *J. Food Process Technol.* **2013**, *4*, 1–2.
7. Raghuvanshi, N.; Gupta, B.; Joshi, V.; Bisht, S. S.; Manikpuri, M.; Shukla, K.; Khokhar, D.; Singh, N.; Ghosh, K. K. Influence of Essential Oil Composition on Antioxidant and Antibacterial Activities of Three Cultivars of *Cymbopogon flexuosus*: *In Vitro* and *In Silico* Study. *Chem. Biodiversity* **2025**, *22*, e202400966.
8. Kabotso, D. E. K.; Neglo, D.; Kwashie, P.; Agbo, I. A.; Abaye, D. A. GC/MS Composition and Resistance Modulatory Inhibitory Activities of Three Extracts of Lemongrass: Citral Modulates the Activities of Five Antibiotics at Sub-Inhibitory Concentrations on Methicillin-Resistant *Staphylococcus aureus*. *Chem.*

Biodiversity **2022**, *19*, e202200296.
9. Ekpenyong, C. E.; Akpan, E.; Nyoh, A. Ethnopharmacology, Phytochemistry, and Biological Activities of *Cymbopogon citratus* (DC.) Stapf Extracts. *Chin. J. Nat. Med.* **2015**, *13*, 321–337.
10. Akinkunmi, E. O.; Oladele, A.; Esho, O.; Odusegun, I. Effects of Storage Time on the Antimicrobial Activities and Composition of Lemon Grass Oil. *J. Appl. Res. Med. Aromat. Plants* **2016**, *3*, 105–111.
11. Bråred Christensson, J.; Forsström, P.; Wennberg, A.-M.; Karlberg, A.-T.; Matura, M. Air Oxidation Increases Skin Irritation from Fragrance Terpenes. *Contact Dermatitis* **2009**, *60*, 32–40.
12. Plata-Rueda, A.; Martínez, L. C.; da Silva Rolim, G.; Coelho, R. P.; Santos, M. H.; de Souza Tavares, W.; Zanuncio, J. C.; Serrão, J. E. Insecticidal and Repellent Activities of *Cymbopogon citratus* (Poaceae) Essential Oil and Its Terpenoids (Citral and Geranyl Acetate) against *Ulomoides dermestoides*. *Crop Prot.* **2020**, *137*, 105299.
13. Turek, C.; Stintzing, F. C. Stability of Essential Oils: A Review. *Compr. Rev. Food Sci. Food Saf.* **2013**, *12*, 40–53.
14. Li, Y.; Li, Y.; Fang, T.; Feng, X.; Gao, D. Impact of Processing Methods and Storage on the Chemical Composition of *Artemisia argyi* Essential Oil. *Ind. Crops Prod.* **2025**, *229*, 121024.
15. Ricci, M.; Padín, S.; Ringuelet, J.; Kahan, A. Use of Lemongrass (*Cymbopogon citratus* Stapf) Essential Oil as a Repellent of *Diuraphis noxia* Kurdj. (Hemiptera: Aphididae) in Wheat. *Agric. Téc.* **2006**, *66*, 256–263.
16. Hernández-Lambraño, R. E.; Pajaro-Castro, N.; Caballero-Gallardo, K.; Stashenko, E.; Olivero-Verbel, J. Essential Oils from Plants of the Genus *Cymbopogon* as Natural Insecticides to Control Stored Product Pests. *J. Stored Prod. Res.* **2015**, *62*, 81–83.
17. Moreira da Silva, T. L.; Beltrame, F. L.; Ferrari, P. C. Lemongrass Essential Oil Micro- and Nanoencapsulation for Industrial Application: Production Techniques and Potential Applications. *Arch. Pharm.* **2024**, *357*, e2300726.
18. Martins, W. S.; Fernandes de Araújo, J. S.; Feitosa, B. F.; Oliveira, J. R.; Viana Kotzebue, L. R.; Agostini, D. L. S.; Vasconcelos de Oliveira, D. L.; Mazzetto, S. E.; Cavalcanti, M. T.; da Silva, A. L. Lemongrass (*Cymbopogon citratus* DC. Stapf) Essential Oil Microparticles: Development, Characterization, and Antioxidant Potential. *Food Chem.* **2021**, *355*, 129644.
19. Jovanović, J.; Ćirković, J.; Radojković, A.; Tasić, N.; Mutavdžić, D.; Branković, G.; Branković, Z. Enhanced Stability of Encapsulated Lemongrass Essential Oil in Chitosan-Gelatin and Pectin-Gelatin Biopolymer Matrices Containing ZnO Nanoparticles. *Int. J. Biol. Macromol.* **2024**, *275*, 133335.
20. Korenblum, E.; Goulart, F. R. V.; Rodrigues, I. A.; Abreu, F.; Lins, U.; Alves, P. B.; Blank, A. F.; Valoni, E.; Sebastián, G. V.; Alviano, D. S.; Alviano, C. S.; Seldin, L. Antimicrobial Action and Anti-Corrosion Effect against Sulfate Reducing Bacteria by Lemongrass (*Cymbopogon citratus*) Essential Oil and Its Major Component, Citral. *AMB Express* **2013**, *3*, 44.
21. Tran, T. K. N.; Dao, T. P.; Ngo, T. C. Q.; Tran, T. H.; Dat, U. T.; Cang, M. H. Impact of Different Storage Conditions on Composition of Lemongrass (*Cymbopogon citratus* L.) Essential Oil of Tien Giang Province, Vietnam. *Asian J. Chem.* **2020**, *32*, 2743–2747.
22. Kumar, V.; Yadav, S. K.; Rai, A.; Ranjan, A. K. Impact of Storage Containers on Chemical Degradation and Antibacterial Activity of Lemongrass (*Cymbopogon citratus* L.) Essential Oil. *Int. J. Biochem. Res. Rev.* **2026**, *35*, 177–188.
23. Bureau of Indian Standards. *Methods of Sampling and Test for Natural and Synthetic Perfumery Materials: Part 4: Determination of Optical Rotation*, IS 326 (Part 4):2005/ISO 592:1998; Bureau of Indian Standards: New Delhi, 2005.
24. Bureau of Indian Standards. *Methods of Sampling and Test for Natural and Synthetic Perfumery Materials: Part 5: Determination of Refractive Index*, IS 326 (Part 5):2006/ISO 280:1998; Bureau of Indian Standards: New Delhi, 2006.
25. Bureau of Indian Standards. *Methods of Sampling and Test for Natural and Synthetic Perfumery Materials: Part 3: Determination of Relative Density*, IS 326 (Part 3):2006/ISO 279:1998; Bureau of Indian Standards: New Delhi, 2006.
26. Bureau of Indian Standards. *Determination of Solubility*, IS 326 (Part 6):2005 (RA 2015); Bureau of Indian Standards: New Delhi, 2005.
27. Bureau of Indian Standards. *Methods of Sampling and Test for Natural and Synthetic Perfumery Materials: Part 7: Determination of Acid Value*, IS 326 (Part 7):2006/ISO 1242:1999; Bureau of Indian Standards: New Delhi, 2006.
28. Bureau of Indian Standards. *Methods of Sampling and Test for Natural and Synthetic Perfumery Materials: Part 8: Determination of Ester Value*, IS 326 (Part 8):2005/ISO 709:2001; Bureau of Indian Standards: New Delhi, 2005.
29. Bureau of Indian Standards. *Methods of Sampling and Test for Natural and Synthetic Perfumery Materials: Part 9, Section 1: Determination of*

Ester Values before and after Acetylation, and Evaluation of the Contents of Free and Total Alcohols, IS 326 (Part 9), Sec. 1:2017/ISO 1241:1996; Bureau of Indian Standards: New Delhi, 2017.

30. Li, Y.; Mei, J.; Xie, J. Citral: Bioactivity, Metabolism, Delivery Systems, and Food Preservation Applications. *Compr. Rev. Food Sci. Food Saf.* **2025**, *24*, e70168.
31. Corradi, M. P.; Juncos, N. S.; Cravero Ponso, C. F.; Olmedo, R. H. Effect of Thermo-Degradation on the Thermal Stability, Antioxidant and Sensory Properties of Lemongrass Essential Oil during Storage. *J. Stored Prod. Res.* **2026**, *116*, 102987.
32. Ay, E.; Gérard, V.; Graff, B.; Morlet-Savary, F.; Mutilangi, W.; Galopin, C.; Lalevée, J. Citral Photodegradation in Solution: Highlighting of a Radical Pathway in Parallel to Cyclization Pathway. *J. Agric. Food Chem.* **2019**, *67*, 3752–3760.
33. Weerawatanakorn, M.; Wu, J. C.; Pan, M. H.; Ho, C. T. Reactivity and Stability of Selected Flavor Compounds. *J. Food Drug Anal.* **2015**, *23*, 176–190.
34. Elgendy, E. M.; Khayyat, S. A. Oxidation Studies on Some Natural Monoterpenes: Citral, Pulegone, and Camphene. *Russ. J. Org. Chem.* **2008**, *44*, 814–822.
35. Zhou, L.; et al. Characterization of the Aldehydes and Their Transformations Induced by UV Irradiation and Air Exposure of White Guanxi Honey Pummelo (*Citrus grandis* (L.) Osbeck) Essential Oil. *J. Agric. Food Chem.* **2016**, *64*, 5000–5010.