




Review Article

Extraction, Chemical Analysis, and Therapeutic Potential of D-Limonene from Citrus Peels: A Comprehensive Review

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Abstract

Essential oils are complex mixtures of volatile compounds obtained from plants where they serve aromatic purposes, and defensive roles. They have been used for centuries in medicine, industry, and agriculture due to their broad spectrum of biological activity. Exhibiting antiviral, anti-inflammatory, antioxidant antimicrobial, and smooth muscle relaxant properties. Essential oils have been important substances the most common component is D-Limonene or 4-isopropenyl-1-methylcyclohexene (C₁₀H₁₆) is a monocyclic monoterpene abundant in citrus plants like orange, and grape. It used for a flavor and fragrance additive in perfumes, soaps, foods, and beverages is consistently increased due to its high-quality fragrance property, other uses and important were treated in this study indicates that the compound is neither mutagenic nor carcinogenic in humans, maintaining a low toxicity limit even with protracted administration over several years. the effects of D-limonene such as antioxidant, anticancer, anti-inflammatory, gastroprotective and acid reflux due to its gastric acid-neutralizing properties, Botanical Pesticide and Vermin Control, Oil Spill Correction and The ability to dissolve expanded polystyrene (EPS). This paper provides an overview of the properties of essential oils. D-Limonene is a bioactive compound of high economic and medicinal value. its Environmental Benefit D-Limonene has high biodegradability and lower Volatile Organic Compound (VOC) emissions compared to traditional solvents The study opening opportunities for its use in food by proved the efficiency of its extraction from fruit waste, pharmaceutical, and environmentally friendly pesticide industries D-limonene does not endure in the soil or contaminate groundwater.

Keywords

Essential Oils, Anti-inflammatory, Antiviral, Activity, Toxicity, Antimicrobial

1. Introduction

The essential oils and their components D-Limonene which is a major component in them it have many uses, both in pharmacology and in food. In addition, they are provided with interesting biological activities and have a therapeutic potential.

For example, essential oils exhibit antiviral activities, antimicrobial activities, and may be useful as natural remedies and it seems that essential oils can be used as a proper therapy for many pathologies. In the cosmetic and in the food industry,

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essential oils uses are an integral part, as they may play different roles. Therefore, economic importance of essential oils is indisputable.

Limonene or 4-isopropenyl-1-methylcyclohexene ($C_{10}H_{16}$) is a monocyclic monoterpene hydrocarbon naturally synthesized in many plants through the cyclisation of geranyl pyrophosphate by a monoterpene synthase [1].

It constitutes one of the most abundant monocyclic monoterpenes in the plant kingdom [2]. In fact, it has been found in more than 300 essential oils and principally in Citrus spp. (30–98%) [3]. It occurs as two optical isomers [4], named d- and l-limonene, as well as a racemic mixture [5-7]. The most common, d-limonene ((+)-limonene) is a colorless liquid with characteristic and pleasant lemon-like odor, normally obtained from the cold pressing of Citrus peels and pulps where it can be found at concentrations over 90% [8]. Whereas, l-limonene ((-)-limonene) is more present in other species such as Mentha spp. essential oils [9]. Both are common flavoring additives in cosmetics, food, industrial solvents and pharmaceuticals because of their fragrant and demonstrated harmlessness for humans [1, 6, 10].

Mechanical process or steam distillation techniques are typically the chosen methods to obtain limonene because they are green and non-organic solvents are involved [11]. However, other less conventional methods have also been tried in order to optimize d-limonene extraction. A high pressure-high temperature extraction (150°C, 30 min) saved more energy, reduced extraction time and gave a higher yield of d-limonene from Citrus dried peels [12]. Additionally, limonene's extraction by traditional hydro-distillation could be replaced by other eco-friendlier and time-saving alternative methods such as supercritical fluid extraction (15 MPa, 40°C).

D-limonene (4-isopropenyl-1-methylcyclohexene) is an important compound in several citrus essential oils such as orange, lemon, tangerine, lime, and grapefruit. It has been used as a flavoring agent and as a food preservative agent, with generally recognized as safe (GRAS) status.

It belongs to the family of terpenes and is readily volatile at room temperature. It is widely present in various citrus peels and essential oils, especially lemon oil, caramel oil, orange oil, bergamot oil.

Limonene molecule contains a chiral center and can be seen in three different structural forms: -limonene, D-limonene, and a racemic form. D-limonene has a pleasant lemony taste, making it widely used as a flavoring agent and food additive in common foods such as fruit juice, candy, chewing gum, beverages, and ice cream. D-limonene is one of the most frequently used and cheapest fragrances in cosmetic formulations and can be found in many beauty products such as soaps, fragrances, shampoos, conditioners and body washes, cleaning products, and eco-friendly pesticides [13]. In addition, D-limonene is considered to be safe for food preservation [14] and can be used to extract natural green solvents [15]. After oral administration, D-limonene is rapidly absorbed, distrib-

uted, and metabolized by the gastrointestinal tract. D-limonene is considered safe, with low toxicity to humans, while not causing human carcinogenic or nephrotoxic risk [16]. Figure 1 shows the chemical structure of D-Limonene component. The physical properties of D-Limonene are shown in Table 1.

2. D-Limonene Production

D-Limonene was first recovered as a commercial product from the steam evaporator condensate in the production of citrus molasses. It is the main volatile constituent of citrus peel oil, and the collected volatile portion of oil is usually referred to as d-limonene in the trade.

D-Limonene may be obtained by steam distillation of citrus peels and pulp resulting from the production of juice and cold-pressed oils or from d-terpenation of citrus oils. It is sometimes redistilled Citrus peel oil can contain up to 95% d-limonene and stripper oil over that amount. Stripper oil is the oil recovered during concentration of the liquor which separates from the peel during pressing. The press liquor is concentrated to give citrus molasses, and the vapor which separates during concentration is condensed to yield stripper oil [17]. Figure 2 shows the Clevenger apparatus that use in D-Limonene production.

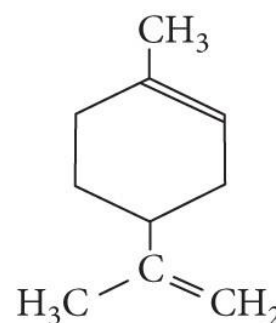


Figure 1. D-Limonene chemical molecular structure [18].

Table 1. Physical Properties of D-Limonene [19, 20].

Property	Value
Description	Colourless liquid with a pleasant, lemon-like odor
Melting-point	-74.3°C
Boiling-point	175.5-176°C
Density	0.8411 g/cm ³ at 20°C/4°C
Solubility	insoluble in water; soluble in benzene, carbon tetrachloride, diethyl ether, ethanol and petroleum ether; slightly soluble in glycerine

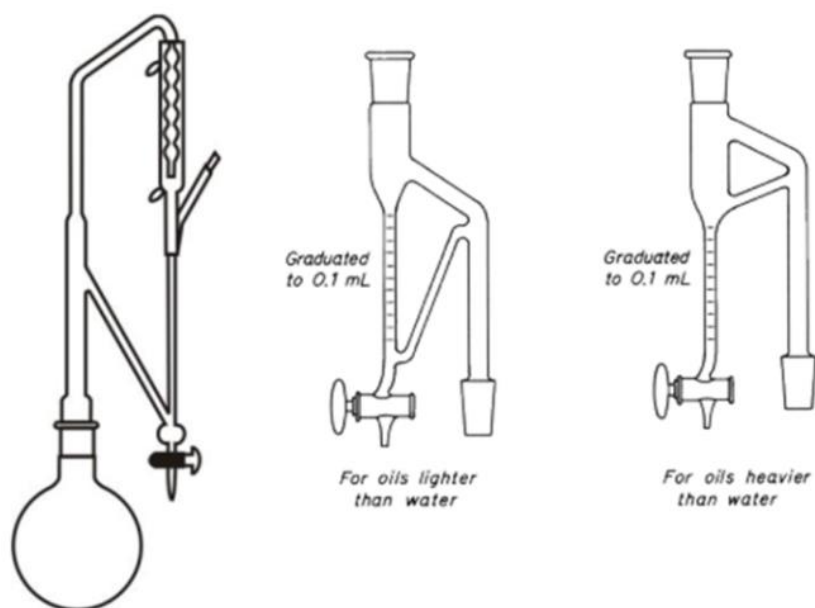


Figure 2. Apparatus for the quantitation of essential oils in peels (Clevenger apparatus).

In commercial practice, the essential peel oil is extracted by mechanical rupturing of oil sacs in the sub epidermal layer (flavedo) of the peel and expression of the oil as an aqueous emulsion, from which it is separated by D-Limonene is also present in various oils and essences obtained during citrus juice processing, including juice oil; deoiler oil, separated from juice by centrifugation or decantation; essence oil, obtained from the recovery unit during juice concentration; and aroma oil, obtained by distillation of the aqueous discharge from the centrifuge used to separate pressed oil [21-23].

D-limonene, a cyclic monoterpene, is a globally significant compound primarily recognized for its orange-like aroma and extensive industrial applications as shown in Figure 3 and Table 2 [24]. It is one of the most prevalent monocyclic monoterpenes found in the plant kingdom, identified in over 300 essential oils, with its primary source being citrus peels where

it can constitute more than 90% of the oil content [25]. Annually, over 100 million tonnes of citrus fruits are produced globally, with a significant portion utilized in the food processing industry, particularly for juice production, leaving approximately 50–60% of the fruit mass as waste [26]. This substantial citrus waste stream, amounting to approximately 22 million tons from oranges alone, represents a significant and sustainable reservoir for D-limonene extraction [27]. The global market for D-limonene was valued at approximately USD 473.72 million in 2021 and is projected to reach USD 694.59 million by 2029, demonstrating a compound annual growth rate of 4.90% [28].

This robust growth underscores its increasing importance across various sectors, including flavor and fragrance, cosmetics, pharmaceuticals, and as a green solvent [29].

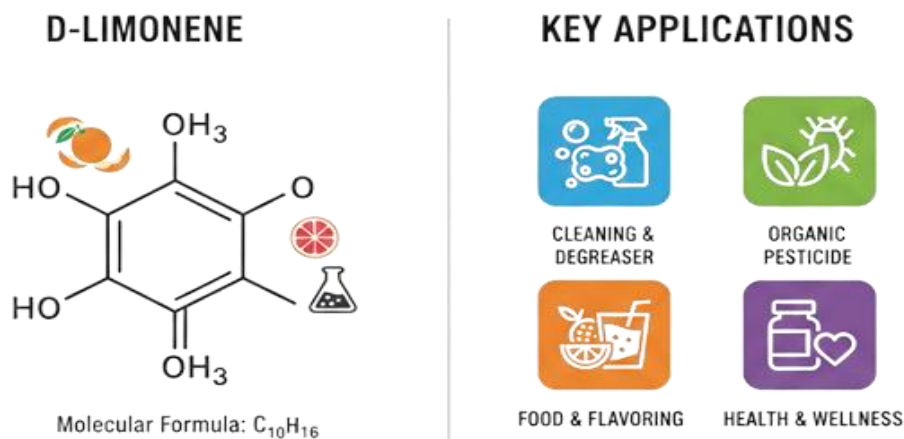


Figure 3. D-Limonene Structure and importance.

Table 2. Key Effect of D-Limonene.

Biological/ Industrial Effect	Description
Anti-Inflammatory	Reduces inflammatory cytokines and protects tissues from oxidative stress [30].
Anticancer potential	Inhibits tumor growth and induces apoptosis (cell death) in cancer cell [31].
Anti-ulcer	Effectively treats gastroesophageal reflux (GERD) and protect the stomach lining [32].
Antimicrobial	Disrupts the cell membranes of bacteria and fungi, acting as a natural preservative [33].
Anxiolytic (calming)	Acts on the central nervous system to reduce anxiety through Inhalation (aromatherapy).

Its widespread utility stems from its classification as a generally recognized as safe additive, coupled with its antioxidant and antimicrobial properties, which make it valuable in food preservation and various other industrial applications [34]. The escalating demand necessitates an exploration of efficient and sustainable extraction methods, as well as alternative production pathways beyond traditional citrus-derived sources, to ensure a consistent and high-quality supply for its diverse applications [29]. Current global production of D-limonene is estimated at approximately 70,000 tonnes per year, predominantly as a byproduct of the citrus juice industry, though this supply is subject to fluctuations in availability and quality [29, 35]. For instance, bacterial diseases affecting citrus crops have led to decreased yields and increased prices, highlighting the vulnerability of this supply chain [36].

3. D-Limonene Percentages in Citrus Essential Oils

D-Limonene is the most common compound in many citrus essential oils, often comprising the majority of their composition according to recent studies. D-Limonene percentages in citrus essential oils vary by source, typically highest in orange peel (90-96%), followed by mandarin (>70%), sweet lemon (>72%), lime (46.03%), and lemon peel (45-62%). These figures derive from recent GC-MS studies up to 2025. Variations stem from extraction methods and origins. Table 3 shows previous studies for D-Limonene Percentages in several essential oils.

Table 3. D-Limonene content by oil type.

Essential Oil Source	D-Limonene (%)	Year	Ref.
Orange peel	90-95%	2025	[34]
Sweet orange peel	9.75-96%	2023	[37]
Lime	46.03%	2024	[38]
Lemon peel	44.74-61.8%	2025	[39]
Grapefruit peel	93.1% - 95.8%	2013	[40]
Mandarin	>70%	2024	[38]
Sweet lemon	>72%	2024	[38]

4. Medical Applications of D-Limonene

4.1. Elevating Pharmacological Capability Through Nanotechnology

Extensive experimental data prove that D-limonene possesses significant clinical pharmacological and antimicrobial

properties. However, its integrative therapy is often limited by limited solubility and chemical instability. To bypass these barriers, current research focuses on nanoencapsulation to optimize its delivery. For instance, a complementary nanodelivery system (including nanoemulsions and niosomes) combining D-limonene with the chemotherapeutic drug Doxycycline attained a loading efficiency of 75.8%. This system not only improved constancy and antioxidant capacity but also enhanced anticancer activity against hepatic tumor cells

while simultaneously reducing cytotoxicity in healthy liver cells [41]. Figure 4 shows various applications of D-limonene.

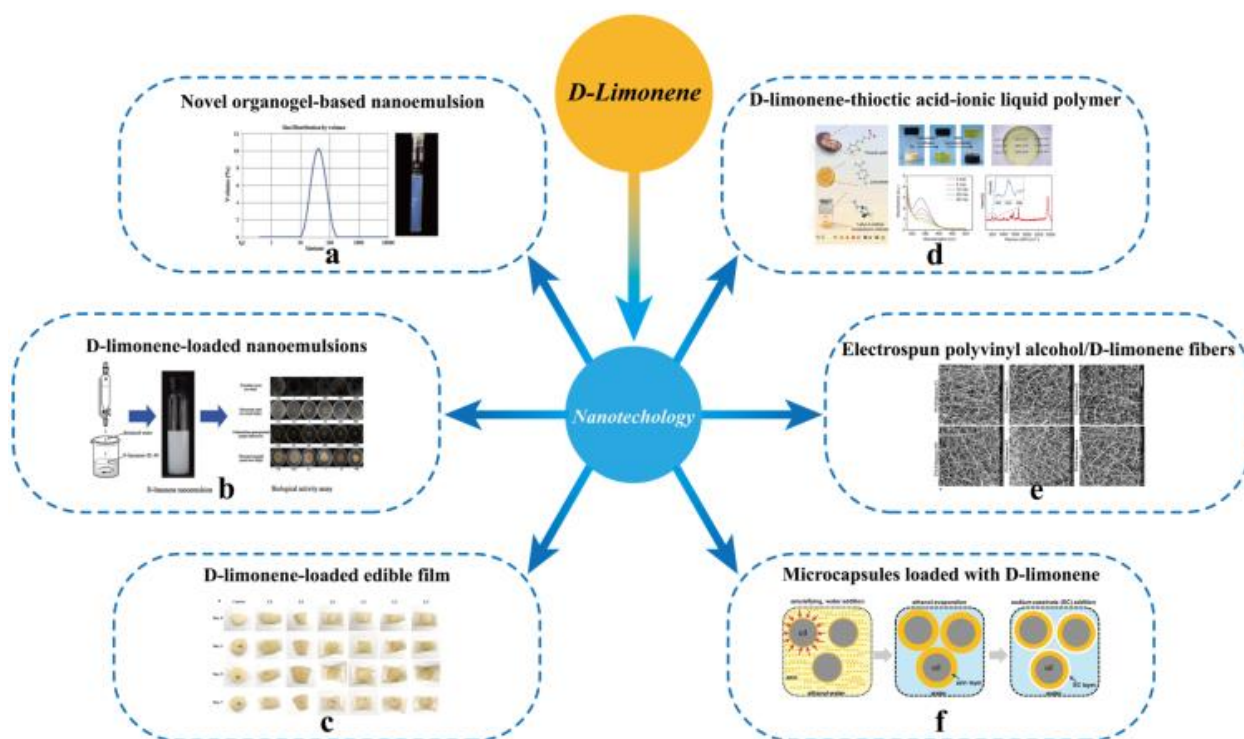


Figure 4. Various delivery and application systems incorporating D-limonene: (a) D-limonene formulated in a novel organogel-based nanoemulsion; (b) nanoemulsions encapsulating D-limonene; (c) edible films containing D-limonene; (d) D-limonene–thioctic acid–ionic liquid polymer systems; (e) electrospun poly (vinyl alcohol)/ D-limonene fibrous mats; and (f) microcapsules encapsulating D-limonene [42].

4.2. Specific Anticancer Effect

The efficacy of D-limonene against specific malignancies, such as melanoma (A-375) and breast cancer (MDA-MB-468), has been extensively reported. While its raw form shows moderate IC₅₀ values, chitosan nanoencapsulation significantly boosts its potency, reducing IC₅₀ from 246.05 to 30.24 µg/mL for melanoma and from 2118.94 to 650.7 µg/mL for breast cancer [43, 44]. This advancement is probable due to enhanced lipophilicity and cell membrane penetration enhanced by facilitated by the nanocarrier.

4.3. D-Limonene as a Skin-penetrating Diffusion Intensifier

The permeation enhancer of D-limonene acts as a powerful by liquefying or disrupting the stratum skin parrier, which promotes more efficient transdermal drug delivery. Bioavailability of this method will increase and minimizes systemic side effects. Studies show that: Adding D-limonene to benzocaine-loaded nanoparticles increased the permeation rate and prolonged anesthetic effects [45].

D-limonene nanovesicles outperformed other agents like cineole in delivering asenapine maleate, significantly boosting bioavailability from 3% (oral) to 54.5% (transdermal) [46]. This preeminence is ascribed to the structural advantages of hydrocarbon terpenes over ketone terpenes in carrying lipophilic molecules.

4.4. Synergistic Antimicrobial Effects and Discharge Pump Suppression

To flight microbial resistance, investigated of D-limonene has been as an Efflux Pump (EP) inhibitor [47]. Research indicates it works synergistically with ciprofloxacin to fight drug-resistant *Staphylococcus aureus*, reducing the Minimum Inhibitory Concentration (MIC) from µg/mL to 3.17 µg/mL; a result superior to standard inhibitors [48]. Molecular attachment suggests this occurs through competitive or non-competitive inhibition. Furthermore, D-limonene exhibits varying degrees of synergy with other antimicrobials against Gram-positive and Gram-negative bacteria, likely due to differences in their respective cell wall architectures [49]. Figure 5 shows the antimicrobial mechanisms associated with D-limonene.

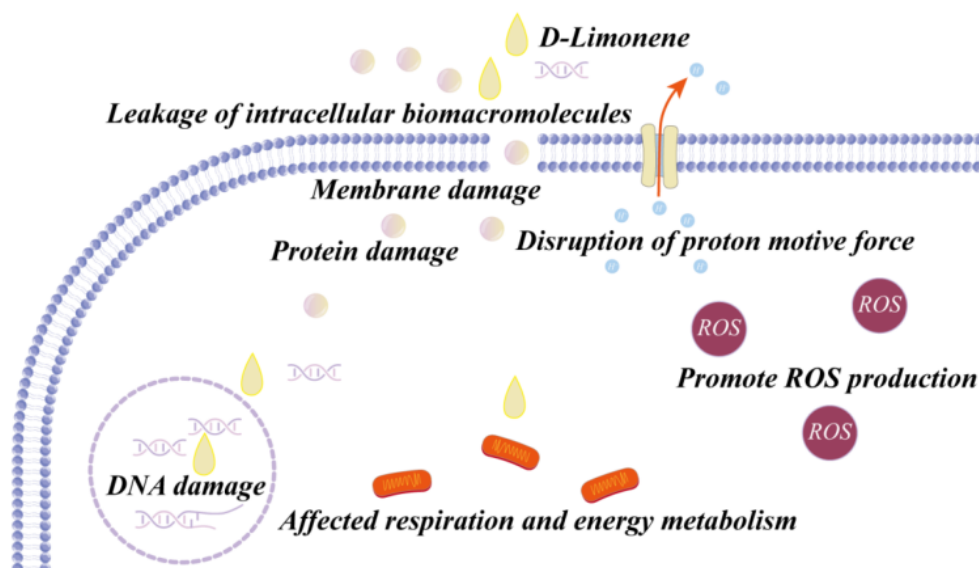


Figure 5. Schematic illustration of the antimicrobial mechanisms associated with D-limonene [42].

4.5. Future Directions and Obstacles

While nanoencapsulation successfully refines the physico-chemical attributes of D-limonene and broadens its potential use, in animal models, current indication remains largely confined to in vitro. Extensive clinical reviews and clinical trials are essential before these applications can be standardized in medical practice.

5. Toxicity of D-limonene

Regarding its safety profile, low toxicity of D-limonene exhibits relatively and has exhibited no evidence of significant risk in animal models [50]. Research indicates that the compound is neither mutagenic nor carcinogenic in humans, maintaining a low toxicity limit even with protracted administration over several years. According to Tao et al. [51], the oral LD50 values for male and female rats are 4.4 and 5.1 g/kg, respectively.

However, the toxic effect may conduct by chronic exposure or high-dosage intake, particularly through cosmetic applications [52]. Furthermore, certain preclinical investigations have identified potential nephrotoxicity and hepatotoxicity associated with its use [53].

As a safety profile and unique chemical properties D-limonene is a versatile monoterpene found abundantly in citrus peels, it is widely used across several major industries.

6. Uses of D-Limonene

D-Limonene has been clinically utilized to dissolve cholesterol gallstones and alleviate heartburn due to its solvent properties and gastric acid neutralization.

Table 4. Application and uses of D-Limonene.

Category	Primary uses
Industrial cleaning	Degreasing and solvent
Food & beverage	Flavouring agent, antioxidant
Cosmetic & care	Fragrance, penetration Enhancer
Agriculture/ pests	Natural Insecticide, Repellent
Medicine/ health	Therapeutic, pharmaceuticals
Scientific Lab	Histology clearing, green extraction
Household products	General cleaners, Hand Soaps

Furthermore, it exhibits well-established chemo preventive and antitumor activities across various cancer types, demonstrated in both animal models and human trials, where it has shown efficacy in inducing tumor regression and stabilizing disease progression. Table 4 summaries the uses of D-Limonene.

6.1. The Primary Uses of D-limonene

6.1.1. Food and Liquid Refreshment Industry

D-limonene is classified as GRAS (Generally Recognized as Safe) by the US FDA.

Flavoring Agent: It is used as a flavor in fruit juices to provide a citrus (orange or lemon), soft drinks, candies, baked goods, and chewing gum.

Masking Agent: in functional foods It helps mask the bitter taste of certain alkaloids [54].

6.1.2. Pharmaceutical and Medical Applications

Gallstone Solubilizer: D-limonene used clinically as a non-surgical treatment to dissolve cholesterol gallstones, it has the chemical ability to dissolve cholesterol [13].

Gastroprotective Effects: It is used to relieve symptoms of GERD (Gastro esophageal Reflux Disease) and acid reflux due to its gastric acid-neutralizing properties.

Anticancer Potential: Clinical trials have investigated its ability to slow lump growth in breast and colorectal cancers by inducing apoptosis (cell death) in cancer cells [10].

Anti-inflammatory & Antioxidant: Reduce inflammation in conditions like ulcerative colitis and liver scarring.

6.1.3. Industrial and Household Uses

Eco-friendly Solvent: bio-solvent for degreasing metals due to its ability to dissolve oils and fats, cleaning electronic components, and removing adhesives or oil from machine parts.

Fragrance Additive: Used in soaps lotions, detergents, shampoos, and perfumes to provide a fresh "clean" scent.

Botanical Insecticide: It acts as a natural pest control agent and is an active ingredient in many eco-friendly pesticides and organic defoliants.

due to its biodegradability and low toxicity compared to petroleum based solvents D-limonene is used as a "green" chemical has expanded significantly in recent years [13].

6.2. The Primary Environmental Uses of D-limonene

6.2.1. Sustainable Bio-Solvent and Degreaser

D-limonene is widely used as a renewable alternative for hazardous chlorinated hydrocarbons and petroleum-based solvents (like toluene or xylene).

Application: It is used for cleaning electronic components, degreasing industrial machinery, and removing sludge from oil tanks.

Environmental Benefit: It has high biodegradability and lower (VOC) emissions compared to customary solvents [55].

6.2.2. Polystyrene (Styrofoam) Up Cycling

The ability to dissolve expanded polystyrene (EPS) is the most creative environmental applications of D-limonene.

Application: D-limonene acts as a solvent that reduces the volume of large expanded polystyrene (EPS) by up to 95%, turning it into a liquid gel that can be easily transported to recycling amenities.

Environmental Benefit: for a plastic it provides a green solution that is otherwise notorious for occupying vast spaces in landfills and being difficult to recycle.

6.2.3. Botanical Pesticide and Vermin Control

D-limonene serves as a potent natural pesticide used in organic farming and home Vermin control.

Application: leading to dehydration it is used to control ants, termites, flies, and mites. It works by dissolving the waxy coating (cuticle) of the insect's respiratory system.

Environmental Benefit: Unlike artificial pesticides (like organophosphates), D-limonene does not endure in the soil or contaminate groundwater [55].

6.2.4. Oil Spill Correction

D-limonene is used in environmental cleanup operations to manage oil spills on shorelines.

Application: It acts as a dispersing agent that analyzes heavy crude oil, making it easier to remove from rocks and sand.

Environmental Benefit: Because it is a natural terpene, it is much less toxic to marine life and seaside birds than traditional chemical dispersants [56].

6.2.5. Eco-Friendly Herbicides

D-limonene is the active ingredient in non-selective organic herbicides, in the agricultural sector (e.g., "Avenger Weed Killer").

Application: It is sprayed on weeds to strip away their protective wax, causing them to dry out and die within hours [57].

Environmental Benefit: It allows for "fire context" wild grass control without leaving chemical waste that harm beneficial soil microbes or pollinators like bees.

7. Conclusions

D-limonene is considered to be a chemical with moderately low toxicity. Studies have determined d-limonene does not constitute a mutagenic, carcinogenic, or nephrotoxic risk to humans. D-limonene dissolve cholesterol-containing gallstones as a clinically used, improvement of peristalsis, and It has also been used for relief of heartburn/GERD, because of its gastric acid neutralizing effect. D-limonene has well-established chemopreventive activity against many types of cancers. Evidence from a phase I clinical trial shows a partial response in a patient with breast cancer and stable disease for more than six months in three patients with colorectal cancer.

Abbreviations

EP	Efflux Pump
EPS	Expanded Polystyrene
VOC	Volatile Organic Compound
GERD	Gastro Esophageal Reflux Disease
MIC	Minimum Inhibitory Concentration

Author Contributions

Salma Zaki Abdulrhman Humaida: Data curation, Formal Analysis, Investigation, Writing – original draft

Adil Ali Mohammed Alhussein: Conceptualization, Resources, Supervision, Validation

Mohamad Hassan Hamadelnil Deifalla: Conceptualization, Methodology, Writing – review & editing

Conflicts of Interest

Authors declare there are no conflicts of interest.

References

- [1] P. Yamuna, P. Abirami, P. Vijayashalini, and M. Sharmila, GC-MS analysis of bioactive compounds in the entire plant parts of ethanolic extract of *Gomphrena decumbens* Jacq, *Journal of Medicinal Plants Studies*, 2017, 5(3), pp. 31-37.
- [2] R. Kumar, S. Kumar, A. Patra, and S. Jayalakshmi, Hepatoprotective activity of aerial parts of *Plumbago zeylanica* linn against carbon tetrachloride-induced hepatotoxicity in rats, *International Journal of Pharmacy and Pharmaceutical Sciences*, 2009, 1(SUPPL. 1), pp. 171-5.
- [3] B. Pleasant. (2013, 2/8/2019). Spring Onions, Green Onions, Welsh Onions or Scallions? Available: <https://www.growveg.co.uk/guides/spring-onions-green-onions-welsh-onions-or-scallions/>
- [4] S. Dawang, D. Affiah, N. Lanka, and L. Fannap, Preliminary checklist of spices and culinary Herbs sold in Jos, Plateau State, Nigeria, *IOSR Journal of Pharmacy and Biological Sciences*, 2016, 11(4), pp. 24-29. <https://doi.org/10.9790/3008-1104032429>
- [5] B. Singh and Y. Ramakrishna, Welsh onion (*Allium fistulosum* L.): A promising spicing-culinary herb of Mizoram, *Indian Journal of Hill Farming*, 2017, 30(2), pp. 201-208.
- [6] L. Vlase, M. Parvu, E. Parvu, and A. Toiu, Phytochemical analysis of *Allium fistulosum* L. and *A. ursinum* L, *Digest Journal of Nanomaterials & Biostructures (DJNB)*, 2013, 8(1), p. 457.
- [7] T. Nohara, Y. Fujiwara, R. Kudo, K. Yamaguchi, T. Ikeda, K. Murakami, M. Ono, T. Kajimoto, and M. Takeya, Isolation and characterization of new onionins A2 and A3 from *Allium cepa*, and of onionins A1, A2, and A3 from *Allium fistulosum*, *Chemical and Pharmaceutical Bulletin*, 2014, 62(11), pp. 1141-1145. <https://doi.org/10.1248/cpb.c14-00461>
- [8] P. L. Crowell and M. N. Gould, Chemoprevention and therapy of cancer by d-limonene, *Critical Reviews™ in Oncogenesis*, 1994, 5(1), pp. 1-22. <https://doi.org/10.1615/CritRevOncog.v5.i1.10>
- [9] A. Sobel. (2023, 31/12/2025). What Is Limonene? Everything You Need to Know. Available: <https://www.healthline.com/nutrition/d-limonene>
- [10] L. Yu, J. Yan, and Z. Sun, D-limonene exhibits anti-inflammatory and antioxidant properties in an ulcerative colitis rat model via regulation of iNOS, COX-2, PGE2 and ERK signaling pathways, *Molecular medicine reports*, 2017, 15, pp. 2339-2346. <https://doi.org/10.3892/mmr.2017.6241>
- [11] M. Souza, A. Siani, M. Ramos, O. Menezes-de-Lima Jr, and M. Henriques, Evaluation of anti-inflammatory activity of essential oils from two Asteraceae species, the Pharmacy-An International Journal of Pharmaceutical Sciences, 2003, 58(8), pp. 582-586.
- [12] B. Sever Yilmaz and H. Özbek, Investigation of the anti-inflammatory, hypoglycemic activity and median lethal dose (LD50) level of limonene in mice and rats, *ACTA Pharmaceutica Scientia*, 2018, 56(1), pp. 85-94. <https://doi.org/10.23893/1307-2080.aps.05606>
- [13] J. Sun, D-Limonene: safety and clinical applications, *Alternative medicine review*, 2007, 12(3), p. 259.
- [14] W. W. Nazaroff and C. J. Weschler, Cleaning products and air fresheners: exposure to primary and secondary air pollutants, *Atmospheric environment*, 2004, 38(18), pp. 2841-2865. <https://doi.org/10.1016/j.atmosenv.2004.02.040>
- [15] S. Chemat, V. Tomao, and F. Chemat, Limonene as green solvent for extraction of natural products, in *Green solvents I: properties and applications in chemistry*, ed: Springer, 2012, pp. 175-186. https://doi.org/10.1007/978-94-007-1712-1_5
- [16] J. S. Sidhu and T. A. Zafar, Bioactive compounds in banana fruits and their health benefits, *Food quality and safety*, 2018, 2(4), pp. 183-188. <https://doi.org/10.1093/fqsafe/fyy019>
- [17] H. Zhang, S. Yang, D. C. Joyce, Y. Jiang, H. Qu, and X. Duan, Physiology and quality response of harvested banana fruit to cold shock, *Postharvest Biology and Technology*, 2010, 55(3), pp. 154-159. <https://doi.org/10.1016/j.postharvbio.2009.11.006>
- [18] E. Babaeenezhad, F. Hadipour Moradi, S. Rahimi Monfared, M. D. Fattahi, M. Nasri, A. Amini, O. Dezfoulilian, and H. Ahmadvand, D-limonene alleviates acute kidney injury following gentamicin administration in rats: Role of NF-κB pathway, mitochondrial apoptosis, oxidative stress, and PCNA, *Oxidative medicine and cellular longevity*, 2021, 2021, p. 6670007. <https://doi.org/10.1155/2021/6670007>
- [19] D. G. Barceloux, *Medical toxicology of natural substances: foods, fungi, medicinal herbs, plants, and venomous animals*: John Wiley & Sons, 2012. <https://doi.org/10.1002/9780470330319>
- [20] P. F. Onyekere, D. O. Nnamani, C. O. Peculiar-Onyekere, and P. F. Uzor, *Green Sustainable Process for Chemical and Environmental Engineering and Science: Limonene*: Elsevier, 2021. <https://doi.org/10.1016/C2018-0-01748-X>
- [21] M. K. Park, J. Y. Cha, M. C. Kang, H. W. Jang, and Y. S. Choi, The effects of different extraction methods on essential oils from orange and tangerine: From the peel to the essential oil, *Food Science & Nutrition*, 2024, 12, pp. 804-814. <https://doi.org/10.1002/fsn3.3785>
- [22] M. Golmohammadi, A. Borghei, A. Zenouzi, N. Ashrafi, and M. J. Taherzadeh, Optimization of essential oil extraction from orange peels using steam explosion, *Heliyon*, 2018, 4(11), pp. 1-18. <https://doi.org/10.1016/j.heliyon.2018.e00893>

- [23] J. Guo, M. Mäkinen, and J. Jänis, Comprehensive chemical profiling of citrus peel essential oils by direct-infusion ultra-high-resolution FT-ICR MS and high-resolution GC-QTOF MS, *Journal of Food Composition and Analysis*, 2025, 148(1), p. 108204. <https://doi.org/10.1016/j.jfca.2025.108204>
- [24] F. Rizzioli, V. Benedetti, F. Patuzzi, M. Baratieri, D. Bolzonella, and F. Battista, Valorization of orange peels in a bio-refinery loop: recovery of limonene and production of volatile fatty acids and activated carbon, *Biomass Conversion and Bio-refinery*, 2024, 14, pp. 9793-9803. <https://doi.org/10.1007/s13399-023-03738-4>
- [25] M. D. Ibáñez, N. M. Sanchez-Ballester, and M. A. Blázquez, Encapsulated limonene: A pleasant lemon-like aroma with promising application in the agri-food industry. A review, *Molecules*, 2020, 25(11), p. 2598. <https://doi.org/10.3390/molecules25112598>
- [26] D. A. Teigiserova, L. Tiruta-Barna, A. Ahmadi, L. Hamelin, and M. Thomsen, A step closer to circular bioeconomy for citrus peel waste: A review of yields and technologies for sustainable management of essential oils, *Journal of environmental management*, 2021, 280, p. 111832. <https://doi.org/10.1016/j.jenvman.2020.111832>
- [27] B. Sandei, V. Massardier, and R. Brunel, Alternative building blocks sources for poly (ethylene terephthalate): A short review with socio-economical points of view, *Frontiers in Materials*, 2022, 9, p. 1005770, 2022. <https://doi.org/10.3389/fmats.2022.1005770>
- [28] M. Usman, A. Rehman, F. Saleem, A. Abbas, V. C. Eze, and A. Harvey, Synthesis of cyclic carbonates from CO₂ cycloaddition to bio-based epoxides and glycerol: an overview of recent development, *RSC advances*, 2023, 13(33), pp. 22717-22743. <https://doi.org/10.1039/D3RA03028H>
- [29] A. T. Rufino, M. Ribeiro, C. Sousa, F. Judas, L. Salgueiro, C. Cavaleiro, and A. F. Mendes, Evaluation of the anti-inflammatory, anti-catabolic and pro-anabolic effects of E-caryophyllene, myrcene and limonene in a cell model of osteoarthritis, *European journal of pharmacology*, 2015, 750, pp. 141-150. <https://doi.org/10.1016/j.ejphar.2015.01.018>
- [30] X. Yu, H. Lin, Y. Wang, W. Lv, S. Zhang, Y. Qian, X. Deng, N. Feng, H. Yu, and B. Qian, D-limonene exhibits antitumor activity by inducing autophagy and apoptosis in lung cancer, *OncoTargets and therapy*, 2018, pp. 1833-1847. <https://doi.org/10.2147/OTT.S155716>
- [31] M. C. de Souza, A. J. Vieira, F. P. Beserra, C. H. Pellizzon, R. H. Nóbrega, and A. L. Rozza, Gastroprotective effect of limonene in rats: Influence on oxidative stress, inflammation and gene expression, *Phytomedicine*, 2019, 53, pp. 37-42. <https://doi.org/10.1016/j.phymed.2018.09.027>
- [32] H. Igimi, R. Tamura, K. Toraiishi, F. Yamamoto, A. Kataoka, Y. Ikejiri, T. Hisatsugu, and H. Shimura, Medical dissolution of gallstones: Clinical experience of d-limonene as a simple, safe, and effective solvent, *Digestive diseases and sciences*, 1991, 36, pp. 200-208. <https://doi.org/10.1007/BF01300757>
- [33] E. Jongedijk, K. Cankar, M. Buchhaupt, J. Schrader, H. Bouwmeester, and J. Beekwilder, Biotechnological production of limonene in microorganisms, *Applied microbiology and biotechnology*, 2016, 100, pp. 2927-2938. <https://doi.org/10.1007/s00253-016-7337-7>
- [34] H. Karne, V. Kelkar, A. Mundhe, M. Ikar, S. Betawar, and N. Chaudhari, Essential oil extraction from orange and lemon peel, in *E3S web of conferences*, 2023, p. 01005. <https://doi.org/10.1051/e3sconf/202345501005>
- [35] W. B. Cunningham, J. D. Tibbetts, M. Hutchby, K. A. Maltby, M. G. Davidson, U. Hintermair, P. Plucinski, and S. D. Bull, Sustainable catalytic protocols for the solvent free epoxidation and anti-dihydroxylation of the alkene bonds of biorenewable terpene feedstocks using H₂O₂ as oxidant, *Green Chemistry*, 2020, 22, pp. 513-524. <https://doi.org/10.1039/C9GC03208H>
- [36] A. Braga, C. Guerreiro, and I. Belo, Generation of flavors and fragrances through biotransformation and de novo synthesis, *Food and Bioprocess Technology*, 2018, 11, pp. 2217-2228. <https://doi.org/10.1007/s11947-018-2180-8>
- [37] A. N. R. Corrêa, P. Weimer, R. C. Rossi, J. F. Hoffmann, L. S. Koester, E. S. Suyenaga, and C. D. Ferreira, Lime and orange essential oils and d-limonene as a potential COVID-19 inhibitor: Computational, in chemico, and cytotoxicity analysis, *Food Bioscience*, 2023, 51, p. 102348. <https://doi.org/10.1016/j.fbio.2022.102348>
- [38] K. L. Vasquez-Gomez, D. Mori-Mestanza, A. C. Caetano, G. Idrogo-Vasquez, C. Culqui-Arce, E. A. Auquiñivín-Silva, E. M. Castro-Alayo, R. Cruz-Lacerna, H. A. Perez-Ramos, and C. R. Balcázar-Zumaeta, Exploring chemical properties of essential oils from citrus peels using green solvent, *Heliyon*, 2024, 10(21), pp. 1-14. <https://doi.org/10.1016/j.heliyon.2024.e40088>
- [39] T. P. Toker, M. Bouali, M. H. M. Al Bayati, and M. F. Cengiz, Extraction and Comparison of Limonene Contents of Wastes in Citrus Species for Reuse, *International Journal of Life Sciences and Biotechnology*, 2025, 8(2), pp. 85-94. <https://doi.org/10.38001/ijlsb.1596068>
- [40] W. O. Okunowo, O. Oyediji, L. O. Afolabi, and E. Matanmi, Essential oil of grape fruit (*Citrus paradisi*) peels and its antimicrobial activities, *American Journal of Plant Sciences*, 2013, 4(7B), pp. 1-9. <https://doi.org/10.4236/ajps.2013.47A2001>
- [41] Y. Chen, M. Shu, X. Yao, K. Wu, K. Zhang, Y. He, K. Nishinari, G. O. Phillips, X. Yao, and F. Jiang, Effect of zein-based microencapsules on the release and oxidation of loaded limonene, *Food hydrocolloids*, 2018, 84, pp. 330-336. <https://doi.org/10.1016/j.foodhyd.2018.05.049>
- [42] H. Lin, Z. Li, Y. Sun, Y. Zhang, S. Wang, Q. Zhang, T. Cai, W. Xiang, C. Zeng, and J. Tang, D-Limonene: Promising and sustainable natural bioactive compound, *Applied Sciences*, 2024, 14(11), p. 4605. <https://doi.org/10.3390/app14114605>
- [43] M. Assali, N. Jaradat, and L. Maqboul, The Formation of self-assembled nanoparticles loaded with doxorubicin and d-limonene for cancer therapy, *ACS omega*, 2022, 7(46), pp. 42096-42104. <https://doi.org/10.1021/acsomega.2c04238>

- [44] H. Alipanah, M. Farjam, E. Zarenezhad, G. Roozitalab, and M. Osanloo, Chitosan nanoparticles containing limonene and limonene-rich essential oils: potential phytotherapy agents for the treatment of melanoma and breast cancers, *BMC Complementary Medicine and Therapies*, 2021, 21(186), p. 1-10. <https://doi.org/10.1186/s12906-021-03362-7>
- [45] E. V. Campos, P. L. Proença, T. G. da Costa, R. de Lima, L. F. Fraceto, and D. R. de Araujo, Using chitosan-coated polymeric nanoparticles-thermosensitive hydrogels in association with limonene as skin drug delivery strategy, *BioMed Research International*, 2022, 2022(1), p. 9165443. <https://doi.org/10.1155/2022/9165443>
- [46] V. Rani, J. Venkatesan, and A. Prabhu, D-limonene-loaded liposomes target malignant glioma cells via the downregulation of angiogenic growth factors, *Journal of Drug Delivery Science and Technology*, 2023, 82, p. 104358. <https://doi.org/10.1016/j.jddst.2023.104358>
- [47] B. C. Monk and A. Goffeau, Outwitting multidrug resistance to antifungals, *Science*, 2008, 321(5887), pp. 367-369. <https://doi.org/10.1126/science.1159746>
- [48] F. S. e. El-Tokhy, M. M. Abdel-Mottaleb, E. A. El-Ghany, and A. S. Geneidi, Design of long acting invasomal nanovesicles for improved transdermal permeation and bioavailability of asenapine maleate for the chronic treatment of schizophrenia, *International journal of pharmaceuticals*, 2021, 608, p. 121080. <https://doi.org/10.1016/j.ijpharm.2021.121080>
- [49] P. R. Freitas, A. C. J. de Araújo, C. R. dos Santos Barbosa, D. F. Muniz, R. S. de Almeida, I. R. A. de Menezes, J. G. M. da Costa, F. F. G. Rodrigues, J. E. Rocha, and F. N. Pereira-Junior, Inhibition of the MepA efflux pump by limonene demonstrated by in vitro and in silico methods, *Folia Microbiologica*, 2022, 67(1), pp. 15-20. <https://doi.org/10.1007/s12223-021-00909-6>
- [50] N. Caballero Gómez, J. Manetsberger, N. Benomar, S. Castillo Gutiérrez, and H. Abriouel, Antibacterial and antibiofilm effects of essential oil components, EDTA and HLE disinfectant solution on *Enterococcus*, *Pseudomonas* and *Staphylococcus* sp. multiresistant strains isolated along the meat production chain, *Frontiers in Microbiology*, 2022, 13, p. 1014169. <https://doi.org/10.3389/fmicb.2022.1014169>
- [51] N. Tao, Y. Chen, Y. Wu, X. Wang, L. Li, and A. Zhu, The terpene limonene induced the green mold of citrus fruit through regulation of reactive oxygen species (ROS) homeostasis in *Penicillium digitatum* spores, *Food chemistry*, 2019, 277, pp. 414-422. <https://doi.org/10.1016/j.foodchem.2018.10.142>
- [52] V. Rolseth, R. Djurhuus, and A. M. Svardal, Additive toxicity of limonene and 50% oxygen and the role of glutathione in detoxification in human lung cells, *Toxicology*, 2002, 170(1-2), pp. 75-88. [https://doi.org/10.1016/S0300-483X\(01\)00537-6](https://doi.org/10.1016/S0300-483X(01)00537-6)
- [53] C. Ravichandran, P. C. Badgujar, P. Gundev, and A. Upadhyay, Review of toxicological assessment of d-limonene, a food and cosmetics additive, *Food and Chemical Toxicology*, 2018, 120, pp. 668-680. <https://doi.org/10.1016/j.fct.2018.07.052>
- [54] M. Sawamura, *Citrus essential oils: flavor and fragrance*: John Wiley & Sons, 2011. <https://doi.org/10.1002/9780470613160>
- [55] R. Ciriminna, M. Lomeli-Rodriguez, P. D. Cara, J. A. Lopez-Sanchez, and M. Pagliaro, Limonene: a versatile chemical of the bioeconomy, *Chemical Communications*, 2014, 50(97), pp. 15288-15296. <https://doi.org/10.1039/C4CC06147K>
- [56] T. Noguchi, M. Miyashita, Y. Inagaki, and H. Watanabe, A new recycling system for expanded polystyrene using a natural solvent. Part 1. A new recycling technique, *Packaging Technology and Science: An International Journal*, 1998, 11(1), pp. 19-27. [https://doi.org/10.1002/\(SICI\)1099-1522\(199802\)11:1<19::AID-PTS414>3.0.CO;2-5](https://doi.org/10.1002/(SICI)1099-1522(199802)11:1<19::AID-PTS414>3.0.CO;2-5)
- [57] R. G. Hollingsworth, Limonene, a citrus extract, for control of mealybugs and scale insects, *Journal of Economic Entomology*, 2005, 98(3), pp. 772-779. <https://doi.org/10.1603/0022-0493-98.3.772>

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