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REVIEW ARTICLE

A review on phytochemistry, ethnobotany and pharmacology of *Lantana camara* L.

B Harika[1]*, P Kumar[2]*, I Sekar[3], P Rajendran[3], R Ravi[1], K Baranidharan[1], Ashwin Niranjan M[4], K Prathyusha[1], Thejaswini L[5] & D Ashok Kumar[6]

[1]Department of Forest Products and Wildlife, Forest College and Research Institute, Mettupalayam, Tamil Nadu Agricultural University, Coimbatore 641 301, Tamil Nadu, India

[2]Horticultural College and Research Institute, Paiyur, Tamil Nadu Agricultural University, Coimbatore 635 112, Tamil Nadu, India

[3]Department of Forest Biology and Tree Improvement, Forest College and Research Institute, Mettupalayam, Tamil Nadu Agricultural University, Coimbatore 641 301, Tamil Nadu, India

[4]Department of Silviculture and NRM, Forest College and Research Institute, Mettupalayam, Tamil Nadu Agricultural University,Coimbatore 641 301, Tamil Nadu, India

[5]Department of Silviculture and Agroforestry, Forest College and Research Institute, Mettupalayam, Tamil Nadu Agricultural University, Coimbatore 641 301, Tamil Nadu, India

[6]Department of Fruit Science, College of Horticulture and Forestry, Central Agricultural University (Imphal), Pasighat 791102, East Siang District, Arunachal Pradesh, India

*Email: kumarforestry@gmail.com, bandarapu.harika@gmail.com

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Abstract

Lantana camara L., is a versatile plant belongs to the family Verbenaceae. It is indigenous to the Americas and is extensively distributed in tropical and subtropical areas. Despite its ecological challenges as an invasive species, it provides various benefits. This review explores its origin, distribution and adaptability to diverse ecosystems. The plant contains bioactive compounds like terpenoids, flavonoids, phenolics and alkaloids, which are extracted through solvent extraction and steam distillation. These substances have strong biological properties, such as antibacterial, antifungal and anticancer properties. *L. camara* has ethnomedicinal value and is being studied for its potential in treating conditions like inflammation, diabetes, ulcers and wounds. Its rapid growth and resilient seeds make it difficult to control, requiring targeted management strategies. Nevertheless, the plant offers ecological benefits, enriching soil nitrogen and supporting carbon sequestration. Industrially, *L. camara* provides resources like oleanolic acid, carboxymethylcellulose and biomass for bioethanol and biogas production. Its fibres reinforce biomaterials and its extract is used to treat bovine dermatophilosis. The plant's biomass has the potential for bio-energy, furniture making, basket weaving and insect repellents, offering sustainable solutions for cottage industries. This review highlights how *L. camara*, despite its invasiveness, can be harnessed for ecological and industrial applications.

Keywords

antimicrobial activity; antioxidant activity; bioactive compounds; *Lantana camara*

Introduction

Lantana camara L., commonly known as *Lantana*, is an invasive weed and belongs to the Verbenaceae family (1). Common names for *Lantana* include Lantana, red-flowered sage, wild sage and white sage (2). In 1753, Linnaeus published the first description of the species *Lantana camara.* A wide variety of adaptability to soil and climate conditions has also been essential in enabling *Lantana* to become naturalized and invasive in the areas where it has been

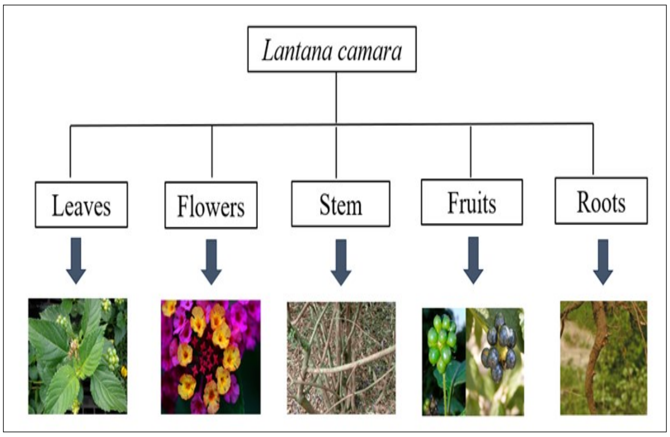


Fig. 1. Uses of different parts of *L. camara* (87).

introduced (3). It thrives in fertile organic soils but can also adapt to sandy and sandstone-derived soils with adequate year-round moisture. *L. camara* thrives in diverse environments, including wastelands, rainforest edges, beaches and disturbed forests. In the Western Himalayan mountains, soils where *L. camara* grows are richer in nutrients, aiding its spread and invasion (4). The various components of *L. camara* such as its leaves, flowers, stem, fruits and roots serve multiple functions (Fig. 1). *L. camara* is primarily recognized as a poisonous weed, though it also has medicinal properties, treating conditions like bronchitis and stomach pain. Phytochemicals such as steroids, flavonoids, saponins, alkaloids, triterpenoids and tannins are found in the plant and its oil is marketed as Lantana oil. A study demonstrated the potential of using invasive weeds as non-wood raw materials for sustainable paper production, providing an eco-friendly alternative to traditional methods (5). *L. camara* is a scrambling aromatic shrub that grows erect in open areas but tends to scramble in scrubland. *L. camara* is a perennial plant, typically reaching up to 2 meters in height but capable of growing as tall as 5 meters (2). The stem is woody, initially squarish in cross-section and hairy, later becoming cylindrical and thickening with age. Its leaves are ovate with serrated margins and arranged in opposite pairs along the stem. The plant produces axillary flower heads in various colours, including cream, yellow, orange, pink, purple and red, with flowering occurring from September to May or year-round if water is available (6). It has numerous variable strains and varieties. Although they are ubiquitous along roadsides and in open fields, *Lantana* species in Tropical America are not regarded as weeds since they often grow in small clumps that are 1 m in diameter (7). It is regarded as one of the toughest weeds in the world due to its invasiveness and capacity for spread (8). *L. camara* spreads through birds, animals, vegetative growth and human planting. It produces thousands of long-lasting seeds each year, which germinate rapidly, with a peak following summer rain (5). The oleanolic acid found in abundance in *L. camara* roots possesses anti-inflammatory, hepatoprotective, anticancer, antioxidant and anti-hyperlipidaemic properties (9). *L. camara* shrub and its extracts have antipyretic, diuretic and antimalarial properties (2). Handmade paper producers effectively use *L. camara* fibres, providing a sustainable option for the industry (5). Because of its exceptional tensile qualities, *L. camara* fiber is a good raw material for papermaking (10). All major plant groupings, including ferns, herbs, shrubs, trees and vines, are

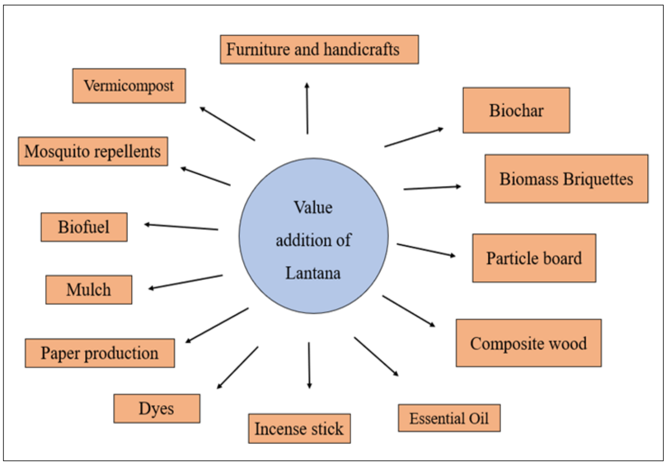


Fig. 2. Value addition of *L. camara* (88).

impacted by *L. camara* (11) (Fig. 2).

Adaptive ecology of L. camara

L. camara is an invasive plant species that demonstrates significant adaptability, allowing it to flourish in a wide range of environmental conditions. Originating from tropical and subtropical areas, it has effectively taken over various ecosystems because of its ability to withstand drought, endure high temperatures and resist oxidative stress (12). Due to its strong physiological and biochemical processes, *L. camara* can thrive in dry conditions where many other plants do not survive. Research indicates that its ability to tolerate stress is partially linked to its capacity to regulate heat shock proteins (HSPs), antioxidant enzymes and osmolytes, which safeguard cellular structures against damage caused by stress (13). A study found that *L. camara* plants showed a genotype-dependent rise (pink genotype) in ROS detoxifying enzymes, which effectively shielded them from ROS build-up and cellular harm during challenging abiotic conditions (14). The pink variety, known to be the most invasive, exhibited the greatest antioxidant capacity, especially in boiling-stable enzymes like Bacillus *subtilis* Glutathione S-Transferase (BsGST), *Bacillus subtilis* Protein Disulfide Isomerase (BsPDI), *Bacillus subtilis* Monodehydroascorbate Reductase (BsMDAR) when subjected to both cold and high-temperature stress. This indicates that there is a biochemical foundation for its invasive characteristics and ability to endure oxidative stress resulting from temperature and light extremes (14).

A study has examined how wild and ornamental *L. camara* species react to drought (limited water) and shade (limited light) environments (15). The findings indicate that ornamental *Lantana* varieties, especially those with white and purple flowers, demonstrate reduced resilience to these stressors in comparison to their wild counterparts. Previous research explains the capability to withstand stress with the help of heat shock proteins (HSPs), which enhance the activity of antioxidant enzymes and offer protection against heat and oxidative stress (16).

L. camara is a species characterized by polyploidy, with a foundational chromosome count of 11 (10). This species exhibits a range of ploidy levels from diploid (17) to hexaploid (18), especially among commercial varieties and breeding lines (19). It is thought that *L. camara* is an autopolyploid species, which can elevate its ploidy levels due to the occurrence of unreduced female gametes (20). The polyploid nature of this plant may enhance its adaptability and invasiveness, in addition to making it attractive as an ornamental species. The ornamental plants react to abiotic stress is a key factor that can affect their growth in unfamiliar environments, especially as water stress is a significant factor (21). Abiotic stressors greatly impact the invasiveness of plant species by modifying their growth, reproductive success and competitive strengths (22).

Biochemical composition and pharmacological activities

L. camara, recognized for its medicinal properties, is known for its diverse array of chemical components, comprising primary and secondary metabolites such as alkaloids, tannins, glycosides, saponins, carbohydrates, resins, steroids, cardiac glycosides, coumarins, phenols, flavonoids, terpenoids and anthraquinones, which contribute to its therapeutic efficacy. Numerous aspects of *L. camara* have been examined to evaluate its phytochemical composition. Various researchers have indicated that the leaf extracts are particularly rich in Phyto-constituents, including alkaloids, flavonoids, tannins, triterpenoids, saponins and glycosides (3). Various parts of *L. camara* contain bioactive compounds with significant medicinal properties (Fig. 3).

The leaves of *L. camara* were examined for their chemical constituents using Gas Chromatography-Mass Spectrometry (GC-MS) to pinpoint possible pharmacologically active substances. Phytochemicals were identified, such as steroids, terpenoids, flavonoids, quinones, carbohydrates and alkaloids. The results indicate that these bioactive compounds might play a role in the plant's antimicrobial, antioxidant and anti-inflammatory effects (23). The leaves and stem contain oleanonic acid, which exhibits anti-inflammatory activity. The leaves also have lactones comprising euphanes, known for their anti-thrombin effects. Aerial parts of the plant contain lantanoside and camarinic acid, both of which possess nematicidal properties (24). The roots, stem and leaves also contain oleanonic acid, contributing to antitumor, antimicrobial and anti-inflammatory activities. Additionally, the leaves contain apigenin, which has anti-proliferative effects and camaraside, which has anti-tumour properties. The branches and leaves hold martynoside, known for its cardioactive effects (25).

Other pharmacological properties

Insecticidal property : *L. camara* demonstrates effective insecticidal properties against various types of insects. The use of *L. camara* as a potential insecticidal agent is examined, emphasizing its bioactive compounds such as terpenoids, flavonoids and alkaloids. Research has shown that these compounds can repel, kill, or hinder the growth of a variety of insect pests. The proposal for utilizing *L. camara* as a natural insecticide presents an environmentally friendly alternative to synthetic pesticides. According to a study, *L. camara* extract killed 100 % of Aedes mosquito larvae in 24 hr at a concentration of 100 ppm (parts per million). Significant larvicidal action was still observed at lower dosages (50 ppm) (12). *L. camara* is recognized for its potential medicinal properties, yet its insecticidal capabilities have been relatively under-researched. Both methanol and ethanol extracts from *L. camara* have shown toxicity towards pests infesting stored grains and have caused developmental issues in agricultural pests (17).

Molecular docking analyses have highlighted the insecticidal properties of phytochemicals from *L. camara,* including β-caryophyllene, linalool and kaempferol. These compounds inhibit acetylcholinesterase (AChE) and interfere with digestive enzymes, affecting neural functions and nutrient absorption processes in insects (26, 27). Structure-activity relationship (SAR) assessments indicate that their molecular frameworks, such as the bicyclic structure of β-caryophyllene and the hydroxyl groups in kaempferol, improve their binding strengths to target proteins. ADMET (Absorption, Distribution, Metabolism, Excretion and Toxicity properties) evaluations point to advantageous pharmacokinetic profiles; however, additional research is necessary to assess their environmental safety and potential impacts on non-target organisms. These results positioned *L. camara* as a strong candidate for the development of eco-friendly bioinsecticides (28, 29).

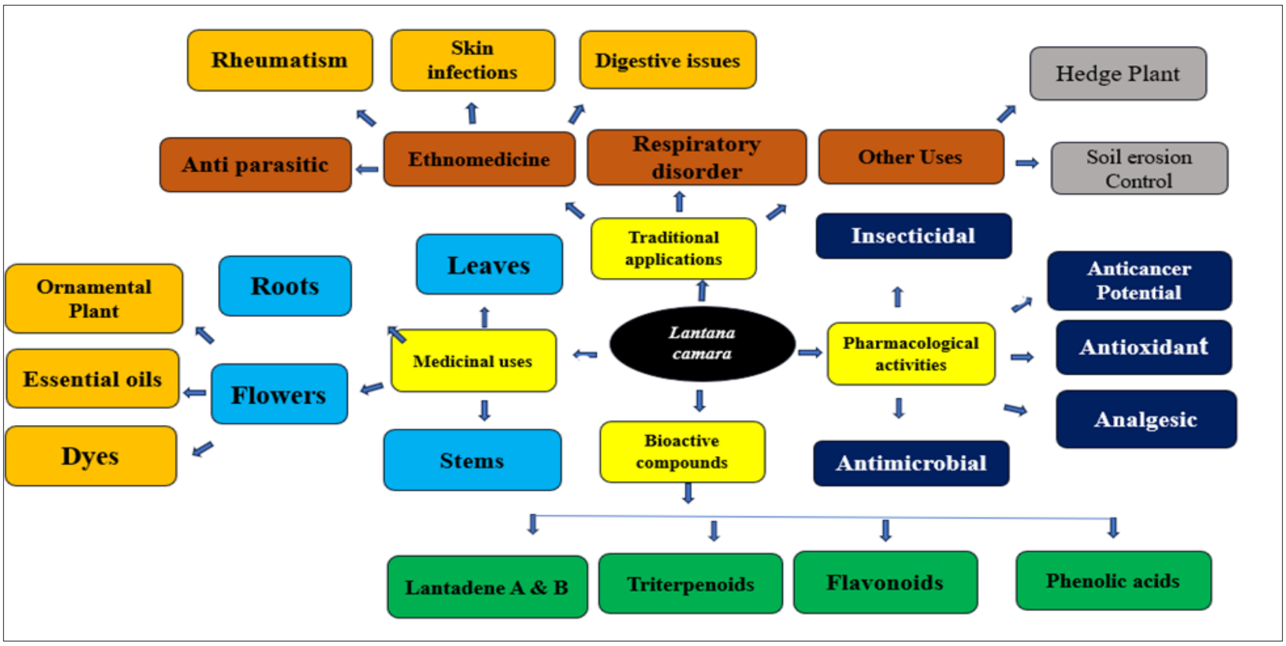


Fig. 3. Therapeutic and economic uses of *L. camara* (89).

Essential oils

A study examined the effectiveness of essential oils as environmentally friendly alternatives to chemical larvicides for mosquitoes. Oils extracted from plants such as *L. camara* have demonstrated the ability to eliminate mosquito larvae while remaining safe for the ecosystem. The bioactive components, including terpenoids and phenols, have been proven to interfere with the growth and development of larvae. These natural oils are seen as valuable options for sustainable mosquito management, decreasing the dependence on harmful synthetic chemicals (30). The leaves of *L. camara* were subjected to hydro distillation to extract their essential oils, which were then analysed for chemical composition using GC-MS. Notable compounds identified include β-caryophyllene, germacrene-D and α-humulene. The essential oils exhibited significant insecticidal effects, showing both fumigant and contact toxicity against *Tribolium castaneum*, *Lasioderma serricorne* and *Callosobruchus chinensis*. The study underscored the potential of *L. camara* essential oils as environmentally friendly alternatives for managing pests in stored grains (17).

Essential oils derived from *L. camara* and *Artemisia absinthium* were encapsulated within chitosan nanoparticles and evaluated for their fumigant toxicity and acetylcholinesterase (AChE) inhibition against *Callosobruchus maculatus* and *Sitophilus granarius*. An increase in fumigant toxicity was noted, resulting in considerable pest mortality (31). The lyophilized residues from the distillation of essential oil from *L. camara* were evaluated for their activity against *Phytomonas*. Notable anti-parasitic properties were detected, suggesting that bioactive compounds remain present in the residues. The study emphasized the potential of these distillation by-products as sustainable methods for managing plant pathogens. It was recommended to investigate their further applications in agriculture (32). The essential oils of *L. camara* from Vietnam were examined through GC-MS, identifying compounds like caryophyllene, germacrene-D and α-humulene. Notable molluscicidal effects were observed against snails, as well as larvicidal effects on mosquito larvae (33). The essential oils extracted from *L. camara* were examined for their effectiveness in killing molluscs and controlling mosquito larvae that affect agriculture and spread diseases. Notable differences in the compositions rich in sesquiterpenes were found across various geographical samples. The oils demonstrated significant toxicity towards freshwater snails and mosquito larvae while showing lower toxicity towards non-target organisms. These findings indicate that essential oils from *L. camara* could be utilized as a sustainable botanical pesticide (34).

L. camara leaf essential oil contains mosquito-killing qualities and can be used as an oil-based substitute for synthetic insecticides (18, 35). The extract from the *L. camara* plant shows encouraging cytotoxicity against the Jurkat Leukaemia cell line and A375 cells, which are malignant skin melanoma (36). As a result, this plant holds great promise for creating new therapeutic agents and anti-cancer chemicals. Flavonoids, crude alkaloids, leaf extract and essential oil are among the plant's antibacterial qualities that have been well-documented against a variety of microbes (37). Additionally, the plant extract has been proposed as a possible biocide against nematodes and water hyacinth (38). A study demonstrated that the essential oils derived from *L. camara* leaves, collected from two different sites in North East India, exhibit distinct chemical profiles and biological activities (6). These findings underscore the significant role of geographical location in influencing the therapeutic potential of plant-derived essential oils, suggesting that environmental factors play a crucial role in shaping the bioactive properties of such natural products.

Phytochemistry

L. camara is a medicinal herb that has received attention for its variety of phytochemicals, including both primary and secondary metabolites, such as alkaloids, flavonoids, tannins, saponins and terpenoids (Table 1). These compounds play a significant role in its medicinal properties, which makes *L. camara* an intriguing topic for research in pharmacology (12). Although the leaves of *L. camara* have been widely researched in phytochemical investigations, there have also been analyses of the stem and fruit extracts, which have shown these extracts to be abundant in saponins, flavonoids, tannins

Table 1. Phytochemicals identified in the solvent extracts of *L. camara*

S. No.	Plant parts assessed	Fractions screened	Categories of phytoconstituents reported	References
1.	Leaf	Methanol	Alkaloids, phenols, flavonoids, tannins, coumarins, steroids, cardiac glycosides	(80)
	Flower	Methanol	Phenols, flavonoids, anthocyanin, tannins, alkaloids	
2.	Leaf	Methanol	Steroids, flavonoids, glycosides, tannins, saponins	(81)
		Ethanol	Steroids, alkaloids, flavonoids, saponins	
		Ethyl acetate	Fixed oils, glycosides, flavonoids	
		Petroleum ether	-	
3.	Leaf	Methanol	Triterpenoids, proteins	(42)
		Water	Resins, carbohydrates, proteins	
		Methanol/water (100:10)	Triterpenoids, steroids, resins	
		Hexane	Flavonoids, tannins, fixed oils	
		Chloroform	Triterpenoids, steroids, lactones	
		n-Butanol	Flavonoids	
4.	Leaf	Methanol	Tannins, saponins, terpenoids, glycosides, alkaloids	(42,82)
	Stem	Methanol	Saponins, flavonoids, terpenoids, alkaloids	
	Fruit	Methanol	Tannins, saponins, flavonoids, terpenoids	
5.	Whole plant	Methanol	Tannins and saponins	(83)

and terpenoids. Additionally, oleanolic acid has been confirmed to be present in its roots (39). *L. camara* is inherently abundant in essential oils that are primarily composed of monoterpenes and sesquiterpenes and it is well-known commercially for its *Lantana* oils. Globally, *L. camara* has been utilized as a medicinal plant to treat various ailments (11).

The chemical makeup of *L. camara* has been well investigated; leaf extracts have shown a wide variety of chemicals, such as triterpenoids, alkaloids, flavonoids, tannins, saponins and glycosides (40-42). The stem and fruit of *L. camara* have also been the subject of phytochemical investigations in addition to the leaves (43). It was discovered that *L. camara's* stem and fruit contained terpenoids, flavonoids, tannins and saponins. 'Oleanolic acid,' a substantial bioactive chemical found in the plant's root, with a patented isolation method (8, 15). It is acknowledged that *L. camara* is a valuable source of essential oils sold commercially as *Lantana* oils (44). There have been reports of *L. camara* essential oils from several nations worldwide, highlighting the diversity of compounds present. For example, Saudi Arabia's essential oil contains spathulenol, caryophyllene oxide and β-caryophyllene (44) while in Congo, β-caryophyllene, α-humulene and bicyclogermacrene are prominent (45). Other countries, such as Iran and Cameroon, report compounds like 1,8-cineole, ar-curcumene and caryophyllene epoxide (46). Essential oil profiles from regions like Madagascar, Nigeria and Egypt also feature β-caryophyllene, sabinene and germacrene derivatives (47-50). These findings illustrate the wide range of bioactive compounds in *L. camara,* with variations in composition across different geographical regions (9, 51-53).

Medicinal and ethnobotanical applications

Worldwide, *L. camara* is used as a medicine. Its leaf decoction treats cough, tetanus and malaria, while a lotion from its leaf's aids wound healing. In Ghana, a whole-plant infusion treats bronchitis and powdered roots with milk relieve stomach pain (44). Traditionally, the leaves are used as a tonic to relieve abdominal pain and as an insecticide (45). The plant's leaves are used to heal rheumatism, wounds and ulcers in some Asian countries (54). Aesulin, quercetin, isorhamnetine, fisetine, gossypetine, tricine, aesculetine and triterpenoids are among the phenolic chemicals and essential oils abundant in the leaves (55). Itches, cuts, ulcers, swellings, bilious fever, catarrh, eczema, dysentery, children's chest complaints, fistula, pustules, tumours, tetanus, malaria, rheumatism, toothache, cold, headache, uterine hemorrhage, chicken pox, eye injuries, tonic for abdominal pains, whooping cough and arterial hypertension are all treated with different parts of the plant (56). *L. camara* leaf extract is considered a potent source of chemotherapeutic agents for triple-negative breast cancer (57). The reduction and stabilization of metal nanoparticles are facilitated by the bioactive compounds present in *L. camara*, making them suitable for diverse biomedical and environmental applications (58).

Antioxidant property

The antioxidant activity of *L. camara* leaves was evaluated using the DPPH radical scavenging assay and measurements of reducing power. The leaf extracts exhibited significant antioxidant effects, with younger leaves showing greater activity compared to older leaves. *In vivo* experiments demonstrated that the ethanolic extract effectively reduced lipid peroxidation in the kidneys of urolithic rats, indicating strong antioxidant activity. Additionally, the robust antioxidant properties of the extract were confirmed *in vitro* through the DPPH and nitric oxide radical scavenging assays (59).

Wound healing property

The ethanol extract derived from *L. camara* leaves exhibited wound-healing properties in adult male Wistar rats. Histological analysis of the healed lesions indicated that the extract significantly accelerated the healing process when applied topically. Additionally, an aqueous extract of *L. camara* leaves demonstrated wound-healing effects in another study. With topical administration (100 mg/kg/day), the rate of wound contraction improved by 98 %, collagen production was enhanced and the healing process was expedited (60).

Anticancer and antiproliferative properties

L. camara has shown notable antiproliferative and anticancer abilities. Research indicated that methanol extracts derived from its leaves effectively inhibited cell lines associated with lung and laryngeal cancer, such as NCI-H292, in MTT assays. Furthermore, the extract exhibited cytotoxic effects on Vero cells, decreasing cell growth by 2.5 times at a concentration of 500 µg/mL. Oleanonic acid obtained from *L. camara* displayed significant cytotoxicity against lymphoma (U937), laryngeal cancer (Hep2) and malignant skin melanoma (A375) cell lines, particularly demonstrating strong activity against A375 cells (61).

Haemolytic properties

A modified spectroscopy method was employed to evaluate the haemolytic effect of *L. camara's* aqueous extract and solvent fractions at concentrations of 125, 250, 500 and 1000 µg/mL. Both the solvent fractions and the aqueous extract exhibited minimal haemolytic activity in human erythrocytes (62).

Anti-microbial activities

The antimicrobial potential of different plant extracts has been evaluated against various microbial strains. The methanol extract of leaves exhibited strong antibacterial and antifungal activity, particularly against *Staphylococcus aureus* and *Candida albicans*, due to the presence of flavonoids, tannins and alkaloids (55). The ethanol extract of flowers showed moderate antibacterial effects against *Bacillus subtilis* and *Klebsiella pneumonia*, containing phenolic compounds and flavonoids. The aqueous extract of the stem was effective against *Salmonella typhi* and *Candida tropicalis*, attributed to alkaloids and tannins (63). The chloroform extract of roots inhibited *Staphylococcus epidermidis* and *Aspergillus flavus*, rich in terpenoids and phenolic acids (64). Essential oil from the leaves exhibited high activity against *Pseudomonas aeruginosa*, dominated by monoterpenes and linalool (65). The methanol extract of the whole plant showed strong action against *Streptococcus mutans*, with flavonoids and saponins as active components. The acetone extract of leaves displayed moderate antimycobacterial and antifungal properties, particularly against *Mycobacterium smegmatis* (66). The ethyl

Table 2. Summarizes the antimicrobial activity, tested microbial strains, key findings and identified phytochemicals from various studies on *L. camara*

Plant part/ extract	Microbial strains tested	Main findings	Phytochemicals identified	References
Leaf (Methanol extract)	*Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Candida albicans*	Strong antibacterial and antifungal activity, especially against *S. aureus* and *C. albicans*.	Flavonoids, tannins, saponins, alkaloids and terpenoids.	(57)
Flowers (Ethanol extract)	*Bacillus subtilis*, *Klebsiella pneumoniae*, *Aspergillus niger*	Moderate antibacterial activity against *B. subtilis* and *K. pneumoniae*; weak antifungal	Phenolic compounds, flavonoids and glycosides.	(63)
Stem (Aqueous extract)	*Salmonella typhi*, *Proteus vulgaris*, *Candida tropicalis*	Significant activity against *S. typhi* and *C. tropicalis*.	Alkaloids, tannins and steroids.	(64)
Roots (Chloroform extract)	*Staphylococcus epidermidis*, *Enterococcus faecalis*, *Aspergillus flavus*	Effective against *S. epidermidis* and *A. flavus*.	Terpenoids, flavonoids and phenolic acids.	(65)
Leaves (Essential oil)	*Escherichia coli*, *Pseudomonas aeruginosa*, *Candida albicans*	High antimicrobial activity, particularly against *P. aeruginosa*	Monoterpenes, sesquiterpenes and linalool.	(66)
Whole plant (Methanol extract)	*Streptococcus mutans*, *Lactobacillus acidophilus*, *Candida glabrata*	Strong activity against oral pathogens, especially *S. mutans*.	Flavonoids, tannins and saponins.	(67)
Leaves (Acetone extract)	*Mycobacterium smegmatis*, *Aspergillus fumigatus*	Moderate antimycobacterial and antifungal activity.	Alkaloids, flavonoids and tannins.	(68)

acetate extract of leaves was highly effective against *Vibrio cholerae* and *Candida krusei*, due to flavonoids and terpenoids (67). The hexane extract of leaves showed strong antibacterial effects against *Staphylococcus aureus*, attributed to fatty acids and sterols. These findings confirm the plant's broad-spectrum antimicrobial potential, driven by its diverse phytochemical composition (68) (Table 2).

Bioactivities

Various extracts of *L. camara* exhibit significant bioactivities. The ethanolic extract demonstrates antileishmanial properties by inducing multi-targeted cell death in *Leishmania amazonensis*, with sesquiterpenes and flavonoids identified as key compounds (48). The methanolic leaf extract shows cytotoxic effects against cancer cells, promoting apoptosis through alkaloids, flavonoids and triterpenoids. The essential oil extract exhibits anti-inflammatory effects by reducing arthritis-induced inflammation through COX-2 inhibition by terpenoids and polyphenols (26). Antioxidant potential is evident in ethanol and acetone extracts, which show strong radical scavenging activity attributed to flavonoids and phenolic acids (40). Additionally, the hydroalcoholic extract enhances wound healing by stimulating fibroblast proliferation and collagen formation through glycosides and saponins (69) (Table 3).

Industrial applications

Ornamental plants : Despite its classification as an invasive species, *L. camara* is still a favoured ornamental plant, playing a significant role in the flowering plant market in the United States. The colour of flowers is vital for the attractiveness and choice of ornamental plants, significantly impacting breeding methods and the overall horticulture sector (3, 19). *L. camara*, a popular flowering shrub, offers a diverse array of flower colors. Its simultaneous appeal as an attractive decorative plant and its status as a troublesome invasive species draw attention for both ecological and economic reasons.

Biochar: as a potent remover of dye : Biochar produced from the leaves and stems of *L. camara* was investigated for its ability to remove methylene blue dye from water solutions. The biochar underwent characterization for its surface characteristics and its adsorption capacity was assessed under different conditions. A high level of adsorption efficiency was noted, which was linked to the biochar's porous structure and its functional groups. The findings indicate that biochar from *L. camara* can serve as a viable and eco-friendly adsorbent for the removal of dyes in wastewater treatment (70). Biochar derived from the leaf and stem of *L. camara* has been shown to effectively adsorb methylene blue dye from contaminated water. The high adsorption capacity, along with the sustainable and cost-effective nature of biochar, makes it a promising solution for water pollution (71).

Pulp and particle board : Sekhar et al. (72) demonstrated the potential of *L. camara* can be used as a substitute raw material for the manufacturing of particleboard and briquettes. Particleboards produced from *L. camara* showed a density comparable to that of traditional hardwood, while its briquettes showed a high energy density of 23 GJ/m^3.

Table 3. Provides a clear overview of the various bioactivities of *L. camara*, highlighting the extracts used, key findings and mechanisms or compounds associated with each activity

Activity	Extract used	Main findings	Mechanism/key compounds	Study/ reference
Antileishmanial Activity	Ethanolic extract	Induces multi-targeted cell death in *Leishmania amazonensis*	UFLC-QTOF-MS analysis identified sesquiterpenes and flavonoids as active compounds	(49)
Cytotoxic Activity (Cancer Therapy)	Methanolic leaf extract	Demonstrated apoptosis in cancer cells	Alkaloids, flavonoids and triterpenoids disrupt cell membranes and induce apoptosis	(84)
Antimicrobial Activity	Aqueous and methanolic extracts	Strong inhibition against *E. coli*, *S. aureus*, *Candida albicans*	Lantadenes, phenolics and tannins disrupt microbial cell walls	(86)
Anti-inflammatory Activity	Essential oil extract	Reduced inflammation in induced arthritis models	Terpenoids and polyphenols inhibit COX-2 enzyme activity	(66)
Antioxidant Activity	Ethanol and acetone extracts	High radical scavenging activity in DPPH assays	Flavonoids and phenolic acids act as free radical scavengers	(41)
Wound Healing Activity	Hydroalcoholic extract	Enhanced collagen formation and wound contraction	Glycosides and saponins stimulate fibroblast proliferation	(69)

Table 4. Commercialized products of *L. camara* biomass

Product	Process	Applications	References
Biomass Briquettes	Compression of dried *L. camara* biomass into solid fuel briquettes	Alternative fuel for domestic and industrial use	(72)
Particle Board	Chipping, binding with adhesives, and pressing into boards	Used in furniture, interior panelling and construction	(72)
Composite Wood	Mixing *L. camara* fibres with resin and other wood materials	Used for flooring, cabinets and decorative woodwork	(74)
Furniture	Processed *L. camara* wood crafted into tables, chairs, and cabinets	Lightweight and sustainable furniture products	(87)
Biochar	Pyrolysis of *L. camara* biomass at high temperatures	Soil amendment, carbon sequestration and water filtration	(71)

According to the results, *L. camara* may be a good alternative to the traditional wood in industrial applications with additional benefits (72) (Table 4). A study shown that Cd (II) and Cu (II) are effectively removed from contaminated water using biochars derived from *Clerodendrum viscosum*, *L. camara* and sewage (73). Cellulose (65 %), hemicellulose and lignin (25 %), which are essential building blocks for reinforcing polymers, make up *L. camara* fibres. As a sustainable reinforcement material in polymer composites, LC lignocellulose fibers exhibit a lot of potentials. In addition to offering a sustainable substitute for synthetic fibers, the use of LC fibers reduces the ecological damage caused by this invasive species (74). *L. camara* wood's use is further expanded by pre-treating it *viz.,* (i) to create pulp fit for writing and printing and (ii) as an inexpensive feedstock for the production of bioethanol (75). Its biomass has been recycled to produce biofuels, natural dyes and nanomaterials and its bioactive chemicals have been used for antibacterial, antioxidant and insecticidal applications (75).

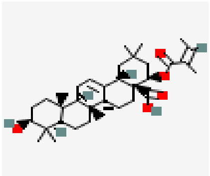
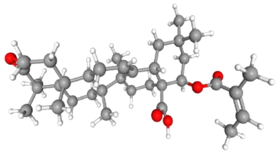
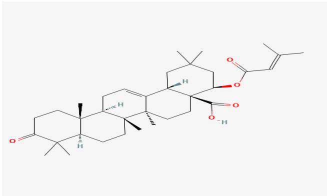
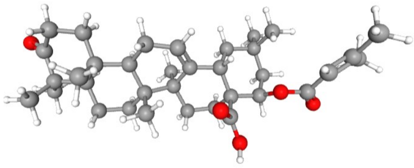
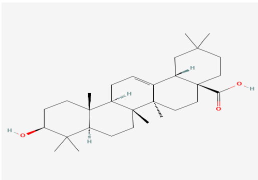
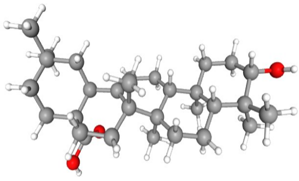
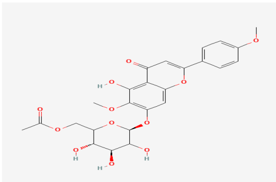
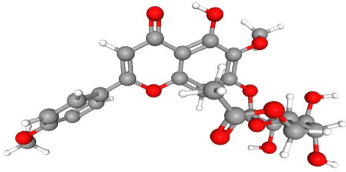
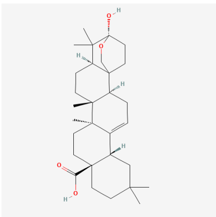
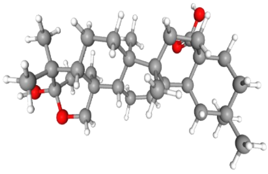
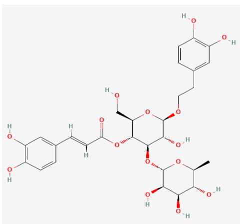
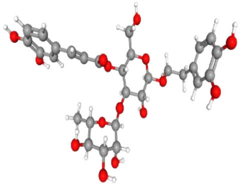
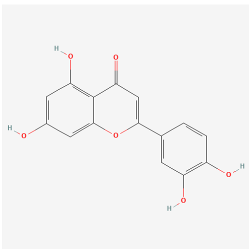
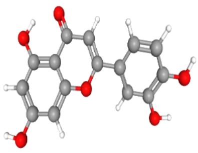
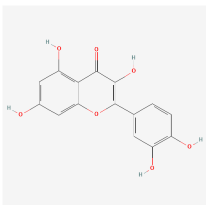
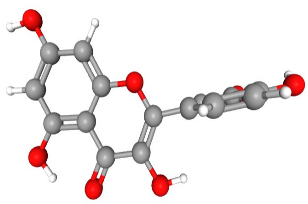
Nano particles : It has been shown to have sustainable uses in pharmaceuticals, textiles and environmental remediation, making it a useful but invasive species that needs careful control (76). In the manufacturing of nanoparticles, bioactive substances found in *L. camara*, such as terpenoids, alkaloids and flavonoids, are used as natural stabilizing and reducing agents. They stimulate the formation of metal and metal oxide nanoparticles, such as titanium dioxide (TiO_2), zinc oxide (ZnO), gold (Au) and silver (Ag).

Dyes : The eco-friendly natural dye made from *L. camara* flowers is devoid of lead, cadmium, arsenic and antimony. This extract can be used commercially to dye cotton and natural fibres with a variety of chemical mordants to create a wide range of colour shades (34). GC and GC–MS were used to analyze volatile oils that were steam- and hydro-distilled from *L. camara* leaves and flowers. It was determined that there were forty-four components in the hydro-distilled oil and twenty-five in the steam-distilled oil. Sabinene was the primary component that was characterized (16.5 % and 7.3 %), The hydro- and steam-distilled oils contained β-caryophyllene (14.0 % and 22.5 %), 1,8-cineole (10.0 % and 6.0 %), bicyclo germacrene (8.1 % and 18.4 %) and α-humulene (6.0 % and 10.8 %), in that order (46). Caryophyllene oxide, β-caryophyllene and β-elemene are the most common in Algerian country (53). While Nigerian country exhibits α-humulene, β-caryophyllene, 1,8-cineole and sabinene, Madagascar's essential oils are abundant in β-caryophyllene, davanone, sabinene, linalool and α-humulene (43). Germacrene-D, β-caryophyllene, bicyclogermacrene, farnesol, spathulenol and α-humulene are among the noteworthy compounds found in Egyptian oils (50).

Mulch : The plant has 16.2 % lignin, 26 % cellulose, 21 % hemicellulose and 31 % hot water-soluble fiber (many bioactive compounds dissolve in Hot water). other extractives (soluble polysaccharides, pectins, tannins and phenolic compounds). Numerous studies have examined its antibacterial properties and it has been proven to be useful in the treatment of malaria, rheumatism and tetanus. It has been demonstrated that leaf extracts possess nematicidal, insecticidal, fungicidal and antibacterial qualities (70). *L. camara* offers several ecological benefits (35). A study found that the rainfed crop fields of *L. camara* leaves may be appropriately mixed with forest tree leaves to enhance nutrient release and decomposition, preserve soil moisture and soil fertility and increase the yield of wheat and rice (77). It was found that Vermicomposting can detoxify *L. camara*, converting it into a beneficial organic fertilizer that enhances seed germination and plant growth (78). *L. camara* can enhance soil fertility and alter the nutrient cycle. Previous study has highlighted the eco-friendly synthesis of ZnO using plant extracts and its application as a sustainable catalyst for biodiesel production and a systematic approach to process optimization rewrite excluding author name (79). The findings contribute to the field of green nanotechnology, renewable energy and waste valorization (79).

Other uses : Thermochemical conversion (pyrolysis) of *L. camara* biomass yields bio-oil with an energy content of 18.53 MJ/kg, making it a viable alternative for biofuel applications. The durable wood of *L. camara* has been employed in crafting furniture and wickerwork. Initiatives in regions like Karnataka and around the Mudumalai Tiger Reserve in India have trained local communities to utilize *L. camara* in their crafts, providing economic opportunities and aiding in the management of this invasive species. *L. camara* sticks are extensively used for making baskets for packing and transporting vegetables in some parts of the Himalayan mountains. Additionally, leafy twigs are placed in grain containers to deter termites, mice and other insects, showcasing its utility as a natural insect repellent (2).

Table 5. Ligands (chemical compounds) derived from *L. Camara* (80)

Compound Name (ID)	2D structure	3D structure
Lantadene A (73346049)		
Lantadene B (15560077)		
Oleanolic Acid (10494)		
Lantanoside (44258471)		
Lantanolic Acid (182076)		
Verbascoside (5281800)		
Luteolin (5280445)		
Quercetin (5280343)		

L. camara contains various ligands such as Lantadene A, Lantadene B, Oleanolic Acid, Lantanoside, Lantanolic Acid, Verbascoside, Luteolin and Quercetin. These substances are recognized for their wide range of biological properties, which include anti-inflammatory, antioxidant and cytotoxic effects (80) (Table 5).

Conclusion

This comprehensive review on *L. camara* as a potential pharmacological resource highlighting its adaptive ecology, significant biomass productivity and diverse industrial applications. Its ability to thrive in various ecological conditions has contributed to its invasive nature, yet this resilience also underscores its potential as a valuable bioresource. The plant's rich biochemical profile, including flavonoids, alkaloids and triterpenoids, is responsible for its broad spectrum of pharmacological activities, such as antimicrobial, antioxidant, anti-inflammatory and anticancer effects. Ethnobotanically, *L. camara* has been extensively used in traditional medicine across different cultures, offering remedies for respiratory ailments, skin disorders, infections and gastrointestinal issues. Beyond its medicinal uses, the plant's biomass has found applications in bioenergy production, furniture making, basket weaving and pest control, highlighting its economic and environmental significance. Despite its invasive nature, re-evaluating *L. camara* as a bioresource can aid in sustainable utilization while mitigating its ecological impact. Future research should focus on refining extraction techniques, enhancing its pharmacological potential and exploring sustainable management strategies. By leveraging its diverse applications, *L. camara* can be transformed from a problematic species into an asset for medicine, industry and environmental conservation.

Authors' contributions

All authors listed have made a substantial, direct and intellectual contribution to the work and approved it for publication.

Data Availability

All datasets generated or analysed during this study are included in the manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethics issues: None

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