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REVIEW ARTICLE

Lantana camara L.: Biology, ecology and control

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Abstract

Lantana camara L., a highly invasive species, has rapidly spread and established itself in many countries, including India, thriving in unattended forests, wastelands and now invading cultivated areas. Aside from forests and fallow places, it has infected most grazing pastures (13.2 million ha) and its control is expected to cost US$70 per hectare in India. *Lantana* exhibits vigorous growth, high adaptability and allelopathic properties, enabling it to outcompete native flora. It thrives in disturbed habitats and alters ecological succession by becoming the dominant understory species, which leads to loss of biodiversity and degradation of ecosystem services. The weed proliferation threatens native vegetation. The pastures and rangelands which were earlier utilized for cattle grazing have now turned into bushy forests of *Lantana* that have no utility for cattle's, leading to scarcity of fodder. *Lantana* has a natural tendency to grow more vigorously and invade at faster rates. Therefore, it has become quite a challenge to control this weed. Mechanical, chemical and biological control strategies have been employed, but none has proven fully effective when used in isolation. Mechanical control is labour intensive, chemical methods are costly and harmful, while biological control is hindered by cultivar variation and ecological complexity. Following an integrated approach becomes our last resort by engaging the local public inhabiting the area along with community participation, offering benefits like increased awareness, shared responsibility and sustainable outcomes. The literature indicates that *Lantana* has more benefits than drawbacks. Therefore, further cost-benefit analysis is needed to make decisions on its management and elimination.

Keywords: biodiversity; ecology; invasiveness; weed control

Introduction

Lantana camara L., from the Verbenaceae family, is recognized as one of the ten most problematic invasive weeds worldwide (1). India is widely renowned as the hotspot for biodiversity of different plants. In the country, there are many exotics weed species that have been introduced from the Americas, Eurasia, Europe, Asia, Africa and Australia. Many of these introduced species have become naturalized in the Indian continent, although few have changed the functioning of the ecological balance and biodiversity loss. *Lantana* is one of the leading invaders among these pantropical weeds. With a geographical range between 35°N and 35°S, the species is native to the Americas and the Caribbean (2). This invasive species has extensively spread throughout India's dry deciduous forests (1, 3). Initially imported as a landscape plant in the early nineteenth century, *Lantana's* aggressive traits now endanger the region's biological diversity by competing local species for resources and establishing rapidly (1, 4).

These invasive species come in various forms and sizes. They might be trees, bushes, small herbaceous plants or aquatic flora, but they all share the ability to disperse and propagate quickly, surpassing biological, physical and environmental constraints. While some invasive species arrive unintentionally, a large proportion is deliberately introduced through various means. In Queensland, Australia, *Lantana* has been classified among the top invasive species (5). Additionally, it is included in the invasive species specialist group's list of the 100 most severe invasive alien species across the globe (6).

L. camara, known in Latin as *lento*, which signifies *bent*, is a member of the Verbenaceae family, comprising 600 varieties across the globe (7). There have been reports of three types, including *aculeate*, *mista* and *nivea*, coming from India (8). Throughout the Northwestern Himalaya, *L. camara* was introduced at Kathgodam in 1905 (9). The *L. camara* var. *aculeate*, which is the most abundant variety, features pubescent leaves that are thick, and its flowers are either yellow or pink, although they can turn orange or scarlet. This variety stands at an average height of 1.0-1.2 m and boasts strong seed-producing capabilities, in addition to propagating through seeds, stems and roots. Birds distribute it through their droppings, as do roaming sheep and goats that eat the seeds and excrete them. Furthermore, different varieties of *L. camara* are assumed to have originated from Africa and one from India (2). Seven to eight species of horticultural significance, including *L. camara*, *L. indica*, *L. veronicifolia* and *L. trifolia*, have been observed in India (10). *L. camara* var. *aculeata* is the foremost prevalent species of *Lantana* (11).

Lantana was initially introduced to India in 1807 and was later utilized as an aesthetic plant in the National Botanical Garden (12). Thereafter frequent spread and ecological impact of *L. camara* raised serious concerns regarding its threat to biodiversity, pasture availability and forest regeneration in India. While the mechanical, chemical and biological control methods have shown limited success, an integrated approach supported by community participation offers a more promising solution. To strengthen effective management strategies, it becomes essential to understand the spread pattern of *L. camara*, assess the ecological and socio-economic impacts. The main objectives of this review are to evaluate the invasion dynamics of *L. camara*, explore integrated management approaches and assess the potential benefits and costs associated with its control and utilization.

Biology of *L. camara*

L. camara is a spiny, deciduous shrub with several stems, typically reaching an average height of 2.0 m. It is classified under the family Verbenaceae, order Lamiales, class Magnoliopsida and genus *Lantana*. The stems have a square shape, bristly hairs while they are green and are frequently armed or have sporadic little prickles. It has a strong root system. Even after numerous cuts, the roots continue to produce new shoots. The opposite, simple leaves have long petioles and round, rough, hairy blades with bluntly serrated margins and a strong aroma. Its flowers consist of small, colorful, stalked clusters with flat-topped shapes, featuring a narrow tube and four short spreading lobes. After anthesis, the color of their blossom's changes. The flowers are clustered and show a variety of colors including red, orange, yellow, pink, lavender and white. The yellow color of the flowers attracts pollinators visually and undergoes color transformation immediately after pollination. Round, fleshy, two-seeded drupes, berries eventually transform from green to purple to blue-black in color. Insects and birds are drawn to the berries. In *L. camara*, seed germination is simple and quick.

It has a phyto-toxic effect on animals as it contains toxins such as lantadene A, lantadene B and lancamarone (13). When these toxins are released into the environment, it prevents the growth and development of other weed species (14, 15). Pollination in *L. camara* results in an 85 % fruit set, with each inflorescence bearing 8 fruits in Australia and 25-28 fruits in India, demonstrating intra-specific variation (16, 17). These fruits transform, starting green, then turning rich purple and finally maturing into a striking blue-black color. The fruit of *Lantana* is a round, fleshy drupe containing 1-2 seeds (18). *Lantana* seeds can germinate around the year given adequate soil water content, light and temperature conditions (19). The low germination rate (4-45 %) of *Lantana* might be due to factors such as dormancy of seed, low viability of seed and meiotic instability (20, 21). However, in the field conditions, the low germination rates are countered by the meager rates of seedling mortality (21). The genetic ploidy of *Lantana* in India closely resembles those in Australia, except that no diploid weedy variant has been identified in India (22).

Ecology and distribution of *L. camara*

Distribution of *L. camara* is widespread across diverse habitats, including wastelands, roadsides, and borders of rainforests, beachfronts and woods that have been damaged by fire and disturbed places and near to the canals, railway tracks and other similar sides. The plant can withstand rainfall from 750 to 5000 mm/year and can thrive in regions ranging from sea level to 1800 m above mean sea level (11). Anthropogenic activity makes the *Lantana* invasion worse and facilitates its spread (2). Its ability to flourish in diverse climatic conditions with absence of temperature or rainfall restrictions are the two main requirements for successful planting. This weed thrives in nutrient-poor, arid soils with more light conditions (11, 23, 24). However, locations inhabited by *Lantana* have increased soil nutrient levels compared to non-invaded regions, thereby enhancing its ability to spread further (25).

Life cycle of *L. camara*

Seed dispersal - *L. camara's* life cycle starts with seed dispersal by fruit-eating birds and mammals with each plant can produce up to 12000 fruits annually (Fig. 1).

Germination - The seed germination commences after it passes through a bird or mammal's digestive tract.

Pollination - Pollination is typically carried out by insects like butterflies, moths, bees and thrips.

Vegetative propagation - It propagates vegetatively through layering or reshooting. The plant's tendency to regrow at its base confirms its hardiness.

Seed viability - The seed viability varies between two to five years, depending on type of plant, soil and water content in soil.

Anthropogenic activities such as burning, cutting, removal and construction activities promote the growth and proliferation of this plant species. The plant grows year-round, with peak growth after summer rains and rapid germination within a few weeks under dry and open canopy conditions (Table 1). The plant starts producing seeds at the end of its first season and forms persistent dense thickets that suppress native vegetation through allelopathy. The species will die only under harsh conditions.

Fitness homeostasis and phenotypic plasticity

Fitness homeostasis - In biology, the ability of an organism to maintain a stable level of fitness across various environments is referred to as homeostatic fitness.

Table 1. Basic requirement for growth and development of *L. camara*

Parameters	Requirements	References
Soil	Sandy loam to clayey loam	(26)
Light	Sunny days preferably un-shaded conditions, but can tolerate shade up to some extent	(26)
pH	4.5-8.5	(26)
Rainfall	1000-4000 mm	(26)
Temperature	Intolerant to freezing up to some extent	(26)
Environment	Semi-arid to normal	(26)
Altitude	Up to 2000 m above mean sea level	(27)
Propagation	Vegetative propagation by layering	(26, 28)

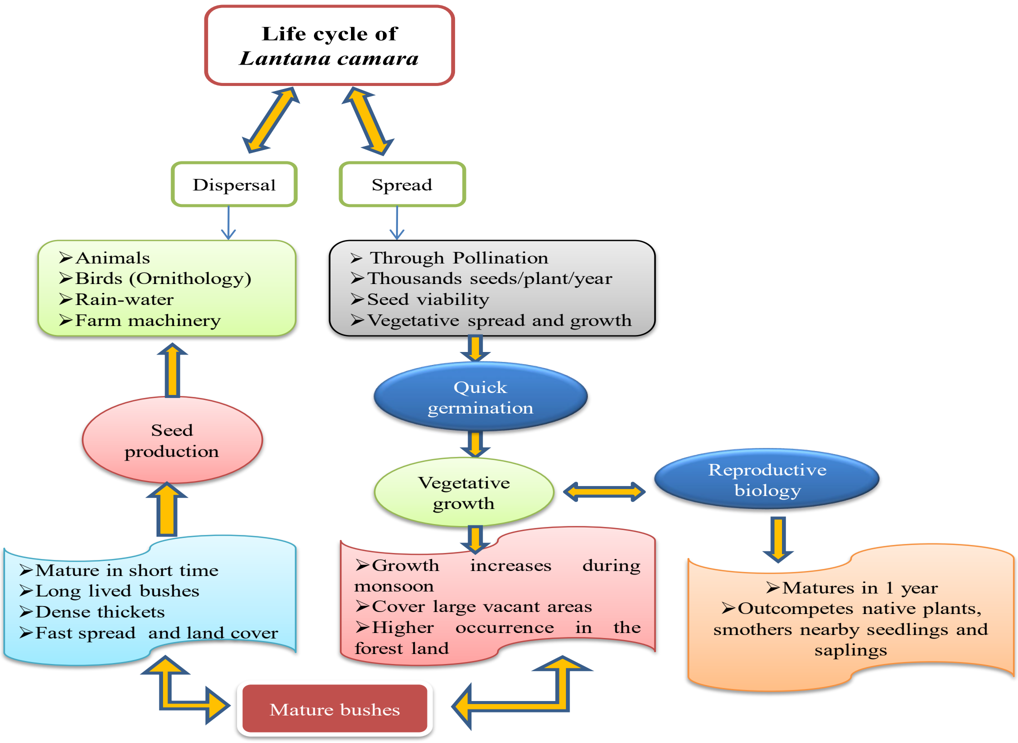

Fig. 1. Life cycle of *L. camara*.

Phenotypic plasticity - The potential of a genotype to alter its growth and development in reaction to environmental variations is known as phenotypic plasticity (29). Plastic responses in vegetative structure help exotic species survive and propagate in heterogeneous environments (30).

Instead of using population fitness homeostasis alternatives, such as average "relative physiological performance" or average "relative ecological performance" across environmental gradients, can also be applied (31). Artificial defoliation in spring leads to increased stem growth and more biomass allocated to reproductive structures compared to fall defoliation.

Nutrients content and litterfall of *Lantana* spp.

For *L. camara*, the total annual litterfall (leaf + wood + flower + fruit components) is reported to be 3.82 tons/ha/yr, out of which around 80 % occurred during winter (November and February) months of the year in north India (32). *Lantana* leaves contain N (nitrogen) (1.71 %) and P (phosphorus) (0.09 %), which decompose in around one year (33). Nevertheless, *L. camara* vegetative biomass contains 289.7 kg N/ha and 16 kg P/ha, out of which 57.3 kg N/ha and 3.1 g P/ha returned through the litterfall (34). High nutrient extraction efficiency and re-translocation of nutrients from the leaves may be the underlying reason for the productivity of *L. camara* under poor fertile and degraded land.

Biological threats by *L. camara*

Ecological threat

L. camara can have a significant impact on biodiversity through competition for essential resources such as water, nutrients, and sunlight (35). Roots of *Lantana* produce allelo-chemicals (phenolic acids and alkaloids) that inhibit seedling germination, growth and productivity of nearby plants, thereby affecting plant diversity (14, 36-39). Due to its fast growth and unpalatable nature, the weed also competes with native species, affecting biodiversity (40). *L. camara* threatens forest biodiversity in a serious way. *Lantana's* ability to cope with environmental stress in new environments is due to its rapid spread through growth in vegetative and reproductive forms, broad range of adaptability and ecological adjustments. It spreads easily from stumps, cuttings and seeds, which are carried by birds in their droppings. It quickly regrows after being cut, trampled and burned, forming a dense, impassable undergrowth and becoming practically impossible to remove. As a result of deforestation and fire, it grows in clumps, allowing it to be the dominant and ultimately contributing to biodiversity declines. This perception is also reflected in field observations, where 19 % of surveyed people reported impenetrable thickets and dense growth of *L. camara* in Ethiopia, while another 19 % noted its aggressive spread and dominance over native species. Similarly, 19 % believed it to be detrimental to biodiversity, with equal proportion reporting its negative impacts on livestock and livelihood (39). To adapt to the modified environment, the plant might experience genetic shifts as a response to selection pressure and quickly react to human-induced disturbances, like other introduced species (41). The growth and spread of *L. camara* are facilitated by moist deciduous forests in the tropical hotspot regions of India (42).

Agricultural threat

The *Lantana* weed can change soil nutrient pools and dynamics in the ecosystems it invades by modifying the type and amount of litter it produces. Several studies have examined the effects of *Lantana* on soil nutrient availability and nitrogen mineralization under the forest and *Lantana* canopies in the dry deciduous Vindhyan forest of India (4). Their findings indicate that the *Lantana* canopy can successively alter soil nitrogen dynamics as its cover. Increased turnover rates, indicative of nutrient cycling, demonstrate that *Lantana* litter inputs rise with greater weed cover. In a study conducted in the moist deciduous forests of Nagarahole Tiger Reserve, moderately infested area with *L. camara* recorded 2.62 % organic carbon, while highly infested area recorded 2.59 % of organic carbon at 15-30 cm soil depth (43).

Additionally, the chemical makeup of *Lantana* biomass differs significantly from native forest species biomass. The elevated nitrogen and reduced lignin proportion of the *Lantana* litter, coupled with the ideal microclimate under its canopy, accelerate decomposition and nitrogen release. These findings suggest that a positive nutrient cycle may be present under the *Lantana* canopy, enhancing its growth by enriching the soil nutrients under its canopy. This observation indicates that the *Lantana* canopy likely began to alter the nutrients under it at the time of its initial invasion, implying that *Lantana* biomass inputs drive ongoing shifts in nutrient dynamics over time beneath its canopy. These findings indicate that the *Lantana* canopy progressively affects soil nitrogen dynamics as its coverage expands. Given the enhanced soil fertility conditions, this promotes its revival, highlighting the need for mechanical or chemical control of fully grown plants to manage their spread effectively (20).

Several researchers have reported about the loss of agricultural ecosystems under the presence of *L. camara* (26, 37). In reference to this, field surveys revealed that *L. camara* was found to invade all ecosystems and 20 % of surveyed respondents noted that agricultural lands were more infected and negatively impacted in terms of biodiversity in Ethiopia (39). Owing to the prevalence of insects-pests, *L. camara* may have a subsequent effect on crop production (26). In addition to providing shelter for wild animals, *Lantana* can also harm agriculture by attracting threats like wild cats, hyenas (which consume cattle, goats and sheep), and warthogs (which can damage crops). *L. camara* can negatively affect cattle mustering by outcompeting native pastures that provide the cattle with preferential feed (14).

Human and animals' health threats

Globally, invasive alien species pose serious health risks including *L. camara* (44, 45). It has been shown that eating *Lantana* green fruit can be lethal. However, this may not always be the case, as people frequently eat ripe *L. camara* fruits without experiencing any negative consequences in India (26). *L. camara* can indirectly harm people's health by keeping malaria vectors in its thickets (26). The rapid growth and spread of this weed hinder the growth of native flora including trees, shrubs and grasses, posing a substantial threat to plant diversity. This also raises the risk of wild animals for residents and their livestock. Due to the scarcity of fodder caused by these invasive weeds, farmers are forced to let their livestock graze freely, leading to damage to cultivated crops. In these regions, other problematic weeds include *Oxalis latifolia*, *Chromolaena adenophorum*, *Imperata cylindrica*, *Sorghum halepense*, *Cyperus rotundus*, *Cuscuta* sp., and *Utrica dioca* (46). These weeds have negatively impacted the productivity of grass in pastures and grasslands. There are several villages in the Himalayan regions with steep slopes and arable lands that have been heavily invaded by weeds. As a result, to meet their fodder demands, people are forced to depend on other forest trees, which ultimately leads to deforestation and loss of vegetation (47, 48).

Despite it's widespread ecological, agricultural and health threats, *L. camara* also possesses certain utilitarian values. These include its use in herbal medicine (antimicrobial and anti-inflammatory properties), erosion control, handicrafts, fuelwood supply and even as potential source for biopesticides and industrial chemicals. In some resource scarce regions, it provides essential ecosystem services where alternative resources are limited. However, ecological and economic costs such as biodiversity loss, soil nutrient imbalances, crop damage, altered forest dynamics and increased human-wildlife conflict often outweigh its benefits, particularly in biodiversity rich and agriculturally sensitive zones. Eradication should be prioritized in protected areas and biodiversity hotspots, agricultural zones where it severely impacts productivity or animal movement and regions where it contributes to deforestation and fodder scarcity. Sustainable utilization of this weed may be considered in degraded or non-arable lands where eradication is impractical, when local communities depend on *Lantana* for fuel, fencing or traditional medicine and in managed systems where periodic harvesting can prevent uncontrolled spread.

Management of *L. camara*

Prevention

The best management method is to prevent invasive alien species since it lowers management costs while minimizing environmental threats. To curb the proliferation of introduced weeds in non-infested areas within the country, it is necessary to identify high-risk species and enforce strict measures and quarantine laws. Furthermore, local authorities are key in controlling the spread of *Lantana* by creating biosecurity plans for their jurisdiction and the use as an ornamental plant should also be avoided (49).

Mechanical control

Mechanical methods have some limitations, including the issue of re-growth if the rootstock is not thoroughly removed during the weeding process. However, this approach is restricted to smaller regions, and it is not advised in locations prone to erosion (50). Manual and mechanical control methods are appropriate for small regions, whereas fire can cover vast areas (26). *L. camara* can be managed by uprooting, cutting stems, burning and manual grubbing with root removal. However, research evidence shows that these methods may not completely eradicate *L. camara* infestation. Despite this, cutting and burning are more effective than uprooting methods and the recovery of grasses is similar with both methods (51).

Long-term eradication of *L. camara* requires uprooting followed by weeding after the rainy season (52). Despite this, mechanical control measures (such as bulldozers and tractors), grubbing, cutting of branches and protracted root system digging are costly and time-consuming to keep *L. camara* under control, especially for large area invasion (2, 50). In contrast, this is disadvantageous since soil disturbance leads to the exposure of *L. camara* seeds to a light and favorable environment, which stimulates germination and seedling establishment (50). Mechanical weed management is often effective at killing weeds while causing lesser disruption to surrounding crops. However, areas under mechanical measures may cause soil erosion and disturbance unless proper vegetation or control measures are followed. In India, methods like as grubbing, branch-cutting and deep root-digging are employed to manage the *L. camara* in forest lands (50).

Uprooting is the most effective way to eliminate *Lantana*. Its roots are easily removed during the rainy period when the soil is wet and loose. *Lantana* can be effectively managed, by depleting its food reserves, cutting off its food supply and fostering competition through the cultivation of beneficial vegetation. During the rainy season, this method involves cutting and removing stumps, introducing robust plants or grasses and regularly uprooting new growth. Nevertheless, it requires a lot of labor and is not suitable for rocky areas and steep slopes.

By treating the site, not only *Lantana* but also other perennial weeds such as *Ageratum houstonianum*, *Eupatorium adenophorum* and *Imperata cylindrica* can be effectively managed. Planting appropriate grasses or trees based on the land's capacity can check the invasion of *Lantana* and other weeds. The total cost amounts to Indian net rupees (INR) 25000 per hectare, including the cost of plantation. Due to low temperatures from November to March, *L. camara* bushes cut during these months regenerate in April. When glycel 41 SL (1 % solution) is applied solely or together with other herbicides in April, it does not distribute into the plant's system, possibly due to low relative humidity. As a result, the leaves may experience temporary burning and stumps may regrow. The herbicide may not be very effective due to the washing effect of intense rains from May to September. In such cases, complete control can be achieved with a higher dose (1.50 %) of glyphosate (46).

Chemical control

Amongst all methods, chemical control of *L. camara* is the most effective although it's also the costliest one (Table 2). When it comes to mechanical and chemical management, factors such as land use, the distribution and density of invasive species, access to infested areas, the economic value of the land and costs all influence the choice of other management options. Effectiveness varies depending on the size of the plant, method, mode and time of application along with the surfactants used (40). Different herbicide treatments work best when sprayed directly on leaves or the bases of stems and cut stumps (57). Benzoic acid, phenoxy acid and pyridine groups appear to work more effectively on *L. camara* (2, 58).

The herbicide application of glyphosate + 2,4-D (Na) at 1.0 L + 0.5 kg/ha in tea recorded *Lantana* count of 2.49 number/m^2 at both at 30 and 60 days after start of experiment (DASE), glyphosate ammonium 79.2 % at 4.356 kg active ingredient /ha recorded 2.75 and 2.49 plants/m^2 at 30 and 60 DASE, respectively, glyphosate ammonium 79.2 % at 2.178 kg active ingredient/ha have resulted in 2.95 and 2.75 plants/m^2 and with glyphosate 1.5 L/ha, it was 3.20 and 2.75 plants/m^2 at 30 and 60 DASE, respectively. These treatments were equally effective in reducing the plants/m^2 of *L. camara* (59). However, the native ecosystem is adversely affected as a result of the use of such chemicals which negatively affect the soil health, soil biota and causes water pollution.

Biological control

An invasive alien plant can be controlled biologically by using natural enemies to reduce its vigour or reproduction potential. *L. camara* can be removed and controlled by using defoliating herbivores which reduce seed production and cause some branches and leaves to die back. Currently, there are no effective biological control agents for *L. camara* available on a commercial scale. Due to the lack of constraints, biocontrol is considered optimal and favorable method for managing *L. camara* (2). There are several biological organisms that have been used to control *L. camara* as shown in Table 3. The presence of various cultivars or forms of the weed complicates the establishment and efficacy of invasive insects, further impeding successful biological control (65). In region like Hawaii and Fiji, species such as *Teleonemia scrupulosa*, *Ophiomyia lantanae* and *Orthezia insignis* have only managed to suppress *Lantana* growth by upto 40 % (59). Similarly, in Australia nearly 30 biocontrol agents have been introduced, however, species like *Aconophora compressa, Epinotia lantana* and *Strymon bazochii* have shown limited success in reducing *Lantana* populations (11).

Ecological barriers such as allelopathic compounds in *Lantana*, polyploidy and high genetic variability among cultivars hinder insect establishment and effectiveness. Hyper-parasitism and predation by native insects also reduce control efficacy (60, 63). Despite these setbacks, some agents jointly slow *L. camara* growth and reproduction by about 40 %, which significantly cuts the expense of manual and chemical control strategies (60). The weed diversity and the high prevalence of

Table 2. Chemical treatments for the control of *Lantana* spp.

Herbicide/Herbicide combination	Dose and duration	Reference
Picloram	240 g/kg on stumps and foliage	(55)
Imazapyr	100 g/L on stumps and foliage	(53)
Aminopyralid	0.12 kg/ha (2 months prior to frost)	(54)
Fluroxypyr + aminopyralid	Twice within 6 months	(54)
Fluroxypyr	0.56 kg/ha as basal application	(54)
Fluroxypyr	Two applications	(26)
Fluroxypyr	0.55 kg/ha (2 application in 2 months prior to frost or in the fall followed by a spring application)	(54)
Aminocyclopyrachlor	0.2 kg/ha (two times prior to frost or in the fall followed by a spring application)	(54)
Tebuthiuron (soil application), glyphosate (foliage) and picloram + triclopyr (stumps)	Multiple applications	(53)
Glyphosate + 2,4-D (Na)	1.0 L + 0.5 kg/ha	(55)
Glyphosate ammonium	79.2 % at 4.356 and 2.178 kg active ingredient/ha	(55)
Glyphosate ammonium	71.0 % at 2.13 kg active ingredient/ha	(55)
Glyphosate	1.5 L/ha	(55)
Triclopyr	1 L/ 60 L of water	(54)
Grazon	300 g/l triclopyr + 100 g/l picloram)	(54)
Glyphosate + carfentrazone-ethyl	620 or 720 + 4 or 8 g/ha	(56)

Table 3. Biological organisms used for the control of *L. camara*

Biological organisms	Common name/Feeding behavior	Reference
Calcomyza lantanae	Leaf miner	(60)
Hypena strigata	Chews leaves	(60)
Salbia haemorrhoidalis	Chews leaves	(60)
Teleonemia scrupulosa	*Lantana* bug	(61)
Uroplata girardi	*Lantana* hispid	(2, 61)
Calycomyza lantanae	Agromyzid seed fly	(2)
Ophiomyia lantanae	Fruit-mining fly	(2)
Teleonemia scrupulosa	Leaf-sucking bug	(2)
Octotoma scabripennis	Leaf beetle	(61, 62)
Teleonemia elata	Leaf-sucking bug	(62)
Aceria lantanae	*Lantana* flower gall mite	(63)
Ophiomyia camarae	*Lantana* leaf eater	(63)
Euproctis subnotana	Flower buds and fruits feeder	(64)
Spilosoma oblique	Leaf, shoot and fruits feeder	(64)
	Host-specific insects	
Diastema tigris	Flower-mining moth	(2)
Salbia haemorrhoidalis	Leaf-folding caterpillar	(2)
Epinotia lantanae	Flower-mining moth	(64)
	Defoliating herbivores	
Teleonemia scrupulosa	*Lantana* lace bug	(2)
Uroplata girardi	*Lantana* hispid	(2)

hyper-parasitism of bio-control organisms prevent biological control agents from reducing *L. camara's* spread. Based on a cost-benefit analysis, a return on investment of 8-34 times can be achieved for *Lantana* biocontrol (66).

Integrated weed management

At Palampur (Himachal Pradesh), India, an integrated weed management strategy has been developed, and it includes, in August-September, cut the *Lantana* bushes to 5-7 cm above the ground. Use the cut biomass for making fragrance sticks, briquettes, charcoal, fuelwood, furniture, mulch and vermicompost etc. In September-October, apply 0.41 % or 0.31 % glyphosate + 0.1 % surfactant on 30-40 cm regenerated foliage and make use of land based on its capability to prevent the growth of other weeds by cultivating fast-growing grasses (such as *Guinea* spp., Napier bajra hybrid and *Setaria* spp.), forage trees and beneficial vegetation. Additionally, pull out or give localized treatment to plants (1-2 %) that have emerged from already fallen seeds (67). Similarly, in Jammu and Kashmir's Shivalik foothills application of glyphosate (1 %) on 30 cm regenerated growth of *Lantana* followed by plating of improved grasses such as hybrid napier or *Setaria* reduced *Lantana* biomass up to 99 % and also provided effective soil cover with high forage yields (68). The integrated approach is more sustainable and cost effective (long term) compared to other methods (Table 4).

Alternative strategies to reduce *L. camara* invasion

In many regions, the extensive infestations and low land values render traditional control methods unfeasible. However, mechanical removal and manual pulling are effective for small areas, while fire can be utilized for larger regions. Additionally, various chemical herbicides work best when applied to new growth after other treatments. Due to the limited success of biocontrol in most regions, planners and managers must devise strategies for the optimal utilization of the species. Some potential commercial uses of *L. camara* include:

Handicrafts

Parts of *L. camara* are being effectively used to make furniture less expensive than cane and just as durable. The furniture is durable and resistant to termites. The Soligas, tribal artisans from south India, creatively use the introduced weed *L. camara* as a sustainable alternative for *Calamus* spp. and *Wrightia tinctoria*. Through their craftsmanship they turn this weed into high-quality products like furniture, playthings and domestic items (69). At present, these artisans create approximately 50 replicas of cane furniture and 25 toy designs using *L. camara*. ATREE assists the tribals with the marketing and certification of these products, branded as *L. camara* crafts (LCC). This innovative initiative won the global development marketplace award in 2003. Furniture, toys and household items can be made from *L. camara* (69, 70). Furniture can be made from the stems of *Lantana* bushes which are cheaper than cane (71).

Herbal medicine

L. camara has various medicinal uses, primarily in herbal medicine. Leaf extracts demonstrate antimicrobial, biocidal, fungicidal, insecticidal and nematicidal properties (72). Additionally, *Lantana* oil is applied externally to treat diseases like scabies and leprosy (7). Plant extracts are used medicinally to treat malignancies, chicken pox, measles, bronchial asthma, sores, lumps, dermatitis, tumors, high blood pressure, liver

Table 4. Comparison of control methods for *L. camara*

Control method	Effectiveness	Cost	Limitations	Scalability	Reference
Mechanical	Moderate for short term	Medium to high	Labour intensive, soil erosion and not suitable on slopes	Small to medium	(2, 50)
Chemical	High for short term	High	Environmentally unsafe, water pollution and soil fertility degraded	Medium to large	(40, 57-59)
Biological	Moderate	Low to medium	Act slowly, variable success, hyper-parasitism and climatic limitations	Suitable for large areas	(65)
Integrated	Very high for long term	Initial cost is high but cost effective in long run	Requires planning, coordination and frequent monitoring	Highly scalable	(67, 68)

related fever, mucosal infections, lockjaw, joint inflammation, malaria and abdominal hypotonia (73). Also, plant's extract has potential cytotoxicity against jurkat leukemia cell line and A375 cells, which are malignant skin melanoma cells (11).

Biofuel

Biofuels derived from branches and stalks of *L. camara* serve as valuable sources for cooking and heating across various parts of India. Research findings recommend its application for fuel ethanol production (74, 75).

Kraft pulping

With composition of hollo-cellulose (75.0 %), extractives (8.5 %), lignin (18.2 %) and silica (2.3 %), *L. camara* presents a promising base material for paper making, offering an alternative to forest-based resources such as timber and bamboo (76). Research indicates *L. camara's* potential as a viable source for paper production (76, 77).

Antioxidant

Several active components in *Lantana* leaves show insecticidal, nematicidal, fungicidal and antimicrobial properties, for which it can be used for the preparation of ethno-medicine (7, 72, 73).

Legislation

India has implemented several laws to combat the problem of invasive alien species, including: the Destructive Insects and Pests Act (1914) and its amendments, the Indian Forest Act (1927), the Wildlife (Protection) Act (1972), the Forest (Conservation) Act (1980), the Environment Protection Act (1986). The plants, fruits and seeds (regulation of import into India) order 1989 (PFS Order 1989), the Livestock Importation Act (1898) and its 2001 amendment, the National Policy and Macrolevel Action Strategy on Biodiversity (1999). The Biological Diversity Act (2002), the plant quarantine (regulation of import into India) order (2003), the National Environment Policy (2004) and the Prevention and Control of Infectious and Contagious Disease in Animals Act (2009). It has been found that none of the existing laws efficiently address the issue of introduced species, including their management and regulation, such as in the case of *L. camara*.

In India, the invasive alien species are not adequately identified due to lack of comprehensive reporting system. Eradication and control measures are only implemented when a particular species becomes problematic and starts having socio-economic impacts. Various research studies have shown that efforts are made to evaluate the risks of invasive alien species on ecosystem, habitat and particular species. Furthermore, the control strategies are only implemented at local levels. Therefore, it becomes imperative to develop control and management strategies that are cost-effective, eco-friendly and capable of covering vast tracts of infestation for the sustainable management of *L. camara*.

Allelochemicals and target plant species

Lantadene A and lantadene B, two allelochemicals, were first extracted from the leaves of *L. camara* (78, 79). The *Lolium multiflorum* Lam. germination and seedling growth has also suppressed by aqueous extracts of *L. camara* (*p*-hydroxybenzoic acid, *p*-coumaric acid, α-resorcylic acid, β-resorcylic acid, caffeic acid, ferulic acid, methyl coumarin, vanillic acid, salicylic acid and quercetin) (80). *L. camara* leaves, stems, blossoms, fruits and roots contained secondary metabolites such as monoterpenes, diterpenes, triterpenes, sesquiterpenes, flavonoids, glycosides and phenylethanoid glycosides (81). *L. camara* secreted harmful chemicals into the surrounding soil which retard the germination and growth of surrounding plants and weed species (82). The impact of *L. camara* plant parts on different weed species and crop plant have been given in Table 5 and 6.

Table 5. Allelopathic effects of *L. camara* leaves, extracts, residues and rhizosphere soil on target weed species

Plant part/source	Target	Stimulation	Inhibition	Reference
	Eichhornia crassipes	Superoxide dismutase (SOD) activity, hydrogen peroxide (H_2O_2) accumulation	Suppressed the emergence and chlorophyll content	(83)
	Lactuca sativa	Reactive oxygen form		(84)
	Mimosa pudica	Proportions of amino acid and soluble saccharides	Carbohydrates, protein molecules and DNA/RNA (deoxyribonucleic acid/ ribonucleic acid). Roles of catalase, dehydrogenase and peroxidase	(85, 86)
	Capsicum annuum L. and *Daucus carota* L.		Germination and seedling growth	(87)
	Asterella angusta		Germination	(88)
Stem aqueous extract	*Parthenium hysterophorus*		Inhibit growth at flowering stage	(81, 89)
	Cassia sophera, *Cassia tora* and *Crotalaria pallida* var pallida		Inhibition of germination, hypocotyls length, fresh weight and chlorophyll content	(90)
Stem	*Lolium multiflorum*, *Cicer arietinum*, *Phaseolus mungo*, *Lens esculenta*		Germination, growth and development	(91, 92)
Stem aqueous extract	*Lolium multiflorum* Lam.	Inhibitory activity of salicylic acid and methyl coumarin	Germination and growth of seedlings	(93)
Root	*Triticum aestivum*		Germination and growth and protein synthesis	
Shoot, flower	*Abutilon theophrasti*, *Eichhornia crassipes*, *Glycine max*, *Lepidium virginicum*, *Triticum aestivum*, *Zea mays*		Growth	(94)
Decomposed leaf litter	*Bidens bipinnata*, *B. pilosa*, *Urena lobata*		Growth	(95)

Table 6. Allelopathic effects of *Lantana camara* and surrounding rhizosphere soil on crop plants

Plant part/Source	Target	Inhibition	Reference
Root, shoot and leaf extract	Urd bean	Germination and growth of seedling	(96)
Rhizosphere soil	*Achyranthes aspera*, *Albizia lebbeck*, oats, chickpea, barley, wheat	Germination, growth and development	(97)
Leaf extracts	Brown mustard, radish, cucumber, chickpea, black gram, cowpea	Germination and seedling growth	(37)
Aqueous extracts of leaf	Maize and finger millet	Early growth	(98)
Shoot	Wheat, maize, soybean, *Lepidium virginicum*, *Abutilon theophrasti*	Germination and growth	(94)

Conclusion

L. camara is a highly invasive weed species, causing irreversible degradation of natural ecosystems. For effective management of *Lantana,* efforts in chemical, mechanical and biological control are essential, but it also requires clear identification of sites and setting priorities. Considering the ecological importance of the native community, it is of utmost importance to prevent the detrimental impacts of the invasive species. Early detection is crucial in minimizing the impact of invasive species. Now, there is only limited information about how far they might spread geographically. Integration of various techniques can significantly improve control and mitigation strategies. *L. camara* is regarded as a weed of global significance. Limited research has been undertaken to assess the magnitude of *Lantana* infestation and its impacts. It is crucial to investigate the impact of invasive alien species on ecosystems and raise public awareness which leads to environmental changes and deterioration, for developing sustainable land-use systems.

Predicting the invasion of *Lantana* at this stage is complex, but the socio-economic and environmental impacts, whether positive or negative, will soon become critical issues for all parts of society. Developing a country-specific strategy for identifying and cataloguing invasive species like *Lantana* is important, with consultation from government representatives at district and state levels, along with non-governmental organizations engaged in environmental conservation. Government should prioritize the establishment of national invasive species management frameworks that focus on early detection, rapid response and public awareness.

Utilizing a combination of remote sensing methods, geographic information system (GIS) and specialized expertise could reveal unidentified invasions by creating scientific models and risk maps. Remote sensing technologies, such as high-resolution satellite imagery could be used be monitor *Lantana's* spread. These data can be processed and visualized using GIS software to create risk maps and identify new invasion for effective management and action plans. Given its global significance, the collective efforts of various countries are critical in addressing the spread of *L. camara* effectively. Unexpectedly, there have been no documented efforts so far to create an invasion map for *L. camara*. Therefore, it is imperative to secure collaborations from other countries and organizations for the successful implementation of management and action plans, given its global importance. In particular, the participation of bordering countries is important to regulate the trans-boundary movement of invasive species and to develop a unified approach to control invasive alien species, like *Lantana.*

L. camara is a highly invasive species causing significant ecological damage and effective management requires early detection, prioritization and a combination of chemical, mechanical and biological control methods. To combat its spread, collaborative efforts involving remote sensing, GIS technology and international cooperation are crucial for creating risk maps and implementing national and regional management frameworks.

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Authors' contributions

SK contributed to conceptualization, research design, writing and drafting. SSR participated in the conceptualization, idea curation and visualization. M contributed to writing, editing and revision. MCR and MS participated in the visualization and supervision. PC contributed to editing and revising. All authors read and approved the final manuscript.

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