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Eco-friendly management of *Lantana camara* and its Potential utilization

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ABSTRACT
Lantana camara L. is a widespread invasive species in tropical and subtropical regions, including India. It poses a serious threat to native plant biodiversity due to its rapid growth, high reproductive capacity, and adaptability to diverse environmental conditions. It also releases allelopathic compounds that inhibit the germination and growth of surrounding native plants. Beyond its ecological impacts, *L. camara* adversely affects agricultural productivity and creates challenges for effective land management, thereby significantly influencing the livelihoods of local communities. Consequently, integrated management strategies are essential for controlling this invasive species.
Keywords: *Lantana camara*, invasive species, allelopathy, biodiversity, integrated management

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INTRODUCTION
The introduction of invasive species has catastrophic effects on environmental health, economic stability, and societal welfare. Over centuries, non-native species have been introduced into existing ecosystems in response to cultural, social, and ecological changes, often resulting in substantial financial and ecological costs [1]. Invasive species frequently outcompete native flora due to their strong competitive ability and high adaptive capacity. Among these, *Lantana camara* is regarded as one of the most aggressive invasive plant species [2]. Native to Central and South America, it has become widely established across tropical and subtropical regions. It commonly invades forests, forest edges, shrublands, grasslands, agricultural fields, orchards, wastelands, and abandoned lands [3,4]. In disturbed forest ecosystems, *L. camara* often dominates the understorey vegetation, disrupting natural succession processes and contributing to a decline in biodiversity [5]. Its presence along forest margins is also associated with increased fire risk, as dense thickets can facilitate the spread of fire into forested areas. Although various herbicides are effective against weeds in agricultural systems, they often show limited efficacy in controlling *Lantana* infestations [6]. Furthermore, in tropical regions, the plant can provide habitat for disease vectors such as tsetse flies (*Glossina* sp.), which are responsible for transmitting African sleeping sickness [7].
Despite its negative impacts, *L. camara* has gained attention for its potential applications in bioprospecting and environmental management [8]. Recent studies have highlighted its utility in phytoremediation, including the removal of particulate pollutants and the phytoextraction of heavy metals. Therefore, the scientific utilization of this species may provide a sustainable approach for managing this invasive weed while harnessing its potential benefits [9].

LANTANA CAMARA AS AN INVASIVE SPECIES
The impact of invasive species on native plant communities varies with environmental conditions; however, their overall influence on biodiversity remains a major ecological concern. Comprehensive investigations are therefore essential for effective restoration planning and management strategies. *L.*

camara is widely recognized as a major agricultural weed affecting various field crops [10,11]. Owing to its profuse flowering and efficient dispersal mechanisms, it alters terrestrial ecosystem dynamics through its dense and gregarious growth habit [4]. This weed suppresses the growth of neighbouring plants through the release of allelopathic compounds, particularly via root leachates [12]. It propagates through both seeds and vegetative means and exhibits remarkable ecological adaptability, including tolerance to nutrient-poor soils, moderate drought conditions, and a wide range of environmental stresses. Such adaptability contributes significantly to its competitive dominance over native vegetation. Reduced growth and productivity have been reported in crops such as *Triticum aestivum*, *Zea mays*, and *Glycine max* in the presence of *L. camara* [5]. Additionally, volatile oils and aqueous leachates of this species have been shown to inhibit seed germination and seedling development in several vegetable crops, including cucumber, radish, and tomato [13]. Its seeds can withstand adverse environmental conditions and germinate when favourable conditions return, further enhancing its invasive potential [12].
To date, no single management strategy has proven entirely effective in eradicating *L. camara*, primarily due to its extensive distribution and resilience. Control measures are typically implemented only after establishment, when prevention is no longer feasible. Most available approaches focus on suppressing population density, limiting spread, or mitigating ecological impacts rather than achieving complete eradication [4]. The cost of eradication using methods such as the cut rootstock approach and the rebuilding of weed-free landscapes, has been estimated at approximately Rs 9000 per hectare [13]. A structured weed management approach, often referred to as the "3-W" framework, has been proposed, which considers the weed (target species), the context of infestation (location), and the appropriate management tools (methods) for effective control.

INTEGRATED MANAGEMENT STRATEGIES OF *LANTANA CAMARA*

The wide geographic distribution of *Lantana camara* reflects its broad ecological tolerance. It occurs across a variety of climates, habitats, and soil types, thriving particularly in open, unshaded environments such as wastelands, forest margins, coastal areas, and regions recovering from fire or logging [8]. The species also proliferates in disturbed anthropogenic habitats, including roadsides, railway tracks, canal banks and building cavities [15,16]. The efficacy of invasive species eradication relies on numerous factors, including the drivers that facilitated the initial invasion, as well as the effectiveness of removal and post-removal management strategies [17]. Instead of relying solely on chemical herbicides, management strategies emphasize integrated approaches, including physical, mechanical, biological, and community-based interventions. Thus, eco-friendly integrated management approaches aim to regulate weed populations while minimizing environmental impacts. In parallel, researchers and local communities have explored the potential beneficial uses of *Lantana* biomass. When utilized effectively, the species can be converted from a problematic weed into a valuable resource. Therefore, the study of *Lantana camara* is important not only for its control and management but also for its sustainable utilization.

Planting Native Species

The cultivation of native plant species is considered an effective ecological strategy for suppressing the proliferation of invasive weeds. Plant communities dominated by indigenous, non-invasive species are generally less susceptible to invasion. In the context of *Lantana camara*, the introduction of fast-growing native species capable of rapid establishment and competitive exclusion can serve as a practical management approach. Such species can outcompete *Lantana* for resources, thereby limiting its spread and facilitating ecosystem recovery [18]. Successful restoration requires a thorough understanding of the interactions between native and invasive species, as well as the dynamics of invasion within affected ecosystems. Ecological restoration approaches that prioritize native species establishment are often preferred over purely mechanical or chemical methods, as they provide longer-term and sustainable control. In some cases, biological strategies, including the use of plant-based extracts or natural competitors, may complement these approaches. Evidence from field studies supports the effectiveness of such strategies. For example, S. Babu *et al.* (2009) demonstrated the successful restoration of *Lantana*-infested areas in Corbett Tiger Reserve, India, through the application of ecological restoration principles [19]. Their work led to the conversion of degraded landscapes into productive grasslands and mixed forests dominated by native species. The restoration of these habitats not only reduced reinvasion by *Lantana* and other weeds but also improved habitat quality for herbivores, thereby supporting higher trophic levels, including apex predators.

Management through Cultural Control

Cultural control involves the systematic and ecological handling of invasive plant species through habitat manipulation and agronomic practices. Developing and executing cultural strategies to mitigate infestation by *L. camara*, including crop rotation; re-vegetation of treated areas through the planting of trees or the promotion of naturally occurring native seedlings that harmonize with local flora, sowing pastures that outcompete and suppress *L. camara*. Additional measures such as controlled grazing, use of physical barriers (e.g., fencing), can further limit its spread [4]. The use of controlled, low- to moderate-intensity fire has also been explored as a management tool. Prescribed burning can reduce above-ground biomass of *L. camara* and may contribute to invasion control when integrated into a broader management strategy. However, fire alone is often insufficient, as the plant readily resprouts from rootstocks. Moreover, uncontrolled burning can negatively affect native vegetation and soil microbial communities. Therefore, the application of fire should be carefully regulated, site-specific, and combined with subsequent removal, restoration, and monitoring. In ecologically sensitive areas, manual and biological methods are generally preferred over burning [20].

Studies have demonstrated that the effectiveness of removal techniques such as cutting, burning, and uprooting is limited without adequate follow-up management. For instance, J. Hiremath *et al.* (2018) reported that *Lantana* removal in tropical deciduous forests was unsuccessful without continuous monitoring and secondary weeding [21]. The species exhibits rapid regeneration from crown buds following cutting or burning, often forming dense thickets [22]. Mechanical innovations, such as the "Monkey Jack" device developed by the Himachal Pradesh Forest Department, have been used to uproot *Lantana* by leveraging root systems after cutting the plant at ground level [23,24]. Post-removal management is critical for long-term control. Practices such as manual weeding of regenerating plants, particularly after the rainy season, can significantly reduce reinvasion [17]. Additionally, mulching cleared areas with organic residues can suppress *Lantana* seed germination by limiting light availability and conserving soil moisture. This approach is particularly effective in orchards, gardens, and small-scale restoration sites. Furthermore, mulching enhances soil quality and supports the establishment of desirable vegetation, making it a sustainable and eco-friendly management practice.

Management through Chemical Control

Chemical control of *Lantana camara* using herbicides is feasible, particularly in non-cropped areas. However, its application remains limited due to environmental concerns. The species is susceptible to systemic (translocated) herbicides, among which glyphosate has been reported as the most effective. Other herbicides, including 2,4-D, fosamine, dichlorprop, and triclopyr, have also been used with varying degrees of success. In addition, certain residual herbicides, such as hexazinone and bromacil, have shown effectiveness in controlling *Lantana* populations [25]. Despite their rapid action, the repeated use of herbicides can lead to several adverse effects, including soil degradation, water contamination, loss of beneficial organisms, and potential risks to human and animal health. Consequently, reliance on chemical control alone is not considered sustainable. Recent approaches emphasize eco-friendly alternatives within chemical control, particularly the use of phytotoxic compounds derived from plants. Some indigenous weed species have been reported to exhibit allelopathic effects against *L. camara*. However, further research is required to identify the active compounds and to understand their mechanisms of action for potential application in sustainable weed management.

Management through Biological Control

Biological control, or biocontrol is an eco-friendly approach for managing invasive species through the use of natural enemies such as herbivores, pathogens, or predators. This method reduces dependence on chemical herbicides and offers a sustainable alternative for long-term weed management. The lantana lace bug, *Teleonemia scrupulosa*, was among the earliest and most widely investigated biological control agents for lantana [23]. This insect feeds on young leaves, leading to defoliation and a temporary reduction in plant vigor, particularly in arid and semi-arid regions [26]. In addition to foliar feeders, certain insect species target reproductive structures of *Lantana*. For instance, larvae of *Spilosoma obliqua* feed on leaves, shoots, and fruits, while *Euproctis subnotata* primarily consumes flower buds and fruits, thereby potentially reducing seed production and limiting the spread of the species [27]. Other biocontrol agents, including *Teleonemia scrupulosa*, *Octotoma scabripennis*, *Uroplata girardi*, and *Ophiomyia lantanae*, have shown partial success in controlling *Lantana* populations [20]. Notably, *T. scrupulosa* and *O. scabripennis* have been introduced in countries such as India and Australia for biological management purposes [28]. Biological control relies on the introduction of organisms that have co-evolved with the target species, making them more specialized and potentially effective. However, the success of biocontrol programs can vary depending on environmental conditions, species interactions, and ecological compatibility [25]. However, all biological control agents must undergo rigorous evaluation to ensure host specificity and to prevent unintended impacts on non-target species, including native flora and economically important crops. Many agents that perform well under controlled experimental conditions may show limited effectiveness in natural field settings. Despite these challenges, biological control is particularly suitable for extensive natural landscapes where repeated mechanical or chemical interventions are impractical and costly.

Management through Sustainable Utilization

Although *Lantana camara* has long been regarded as a noxious weed, recent studies highlight its potential for sustainable utilization. The species exhibits a wide range of applications in medicinal, environmental, and industrial sectors. Traditionally, dried leaves and flowers of *L. camara* have been used in the treatment of ailments such as fever, asthma, and tuberculosis [29]. Furthermore, the plant has been reported to possess diverse bioactivities, including antidiabetic, anticancer, anti-inflammatory, antihypertensive, antibacterial, cytotoxic, larvicidal, herbicidal, antioxidant, and anticoagulant properties [30,31]. It is also a rich source of secondary metabolites, and advanced research approaches may facilitate the identification of novel bioactive compounds with therapeutic potential [32].

In recent years, *Lantana* has been extensively explored for green nanotechnology applications. Plant extracts have been used for the synthesis of metallic nanoparticles with promising biomedical properties [33,34]. For instance, silver nanoparticles synthesized using *Lantana* leaf extracts have demonstrated significant antioxidant and antibacterial activities against pathogens such as *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa* [35,36]. Moreover, such nanoparticles have shown anticancer potential against human cancer cell lines, including A549 (lung cancer) and MCF-7 (breast cancer) [37]. Recent studies have also highlighted their potential application in the development of biodegradable biofilms [38].

Beyond biomedical applications, *L. camara* contributes to environmental management. It has been reported to improve certain soil properties, with invaded soils exhibiting elevated levels of nutrients such as calcium, magnesium, and potassium, which may contribute to its competitive success [39]. The species also demonstrates considerable potential in phytoremediation, including the phytoextraction of heavy metals such as Cu, Zn, Cr, and Mn from contaminated soils [40,41]. Additionally, it exhibits bioaccumulation capacity for metal pollutants and has been identified as a potential hyperaccumulator of cadmium, owing to its tolerance and efficient physiological adaptations [42,43]. The biosorption potential of *Lantana* leaves for the removal of Pb (II) ions from wastewater has also been documented [44].

From an industrial perspective, *Lantana camara* biomass can be utilized as a source of lignocellulosic material for the production of bio-composites and value-added products [45,46]. It has also been explored for the extraction of commercially important compounds such as oleanolic acid and carboxymethyl cellulose [6,12]. Recent studies have demonstrated its potential in the manufacture of particleboards and briquettes, highlighting its suitability as a renewable raw material [47]. The species is rich in cellulose and lignin, making it an attractive feedstock for bioenergy production. The biomass of *L. camara* can be effectively used for the production of bioethanol and biogas. Its relatively high holocellulose content supports its use as an economical substrate for bioethanol generation through hydrolysis and fermentation processes [48-50]. Additionally, biogas production from *Lantana* biomass has been reported [51], and recent investigations have demonstrated its potential for gasification into hydrogen-rich producer gas, although the process may be kinetically and thermodynamically challenging [52].

Moreover, *Lantana* offers additional ecosystem and economic benefits. It has been reported to enhance soil fertility through nitrogen enrichment, exhibit termiticidal and antifungal properties, and serve as a natural insecticide and fumigant for grain storage. It is also being explored as a substrate for mushroom cultivation and as a bioherbicide against aquatic weeds such as water hyacinth [12]. The stems can be utilized for fuelwood, while the aromatic leaves are used in the production of insect repellents and incense sticks [4]. Overall, the sustainable utilization of *Lantana camara* presents a promising strategy for transforming this invasive species from an ecological threat into a valuable bioresource, thereby contributing to both weed management and resource sustainability.

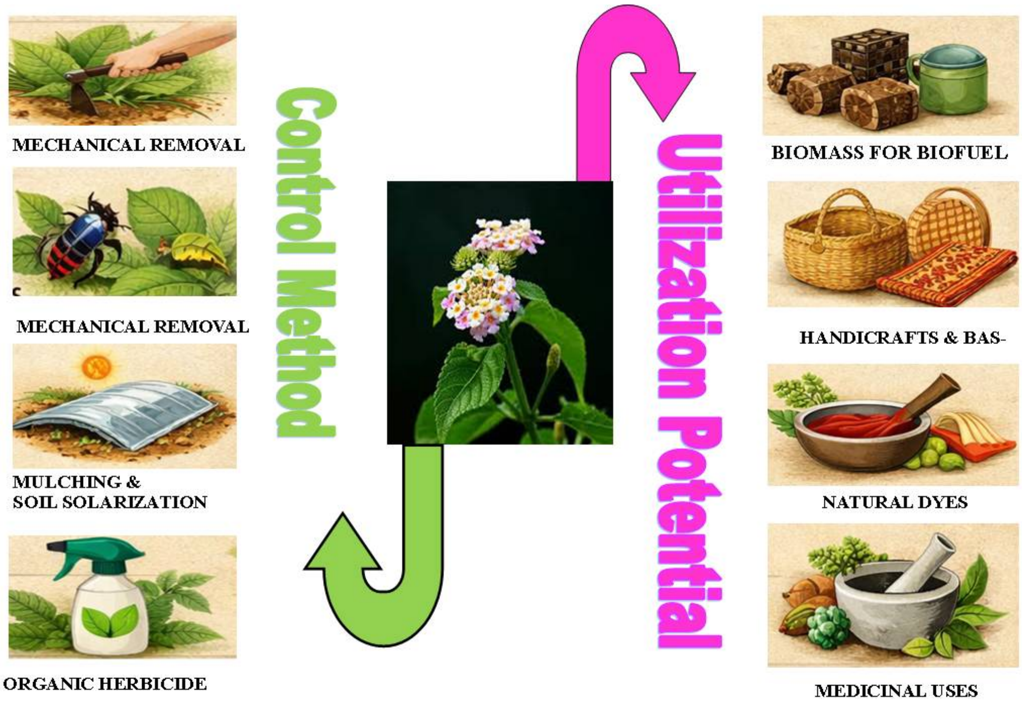

Figure 1: Sustainable ecofriendly approaches for control measure of *Lantana camara*.

CHALLENGES IN MANAGEMENT

The sustainable management of invasive species like *L. camara* is complex yet essential, as invasion-induced ecosystem changes are often difficult to reverse. Conventional approaches, including physical removal and herbicide application have not achieved satisfactory results. Consequently, *L. camara* has become a focus of classical biological control strategies. However, despite the availability of multiple management approaches, their implementation is frequently constrained by inadequate resources, limited funding, insufficient research, and socio-economic and policy-related challenges.

FUTURE DIRECTIONS IN RESEARCH

Despite extensive research over the past several decades, *Lantana camara* continues to resist effective control and remains a major invasive species of global concern. Its expansion across diverse agroclimatic zones, particularly in arid and semi-arid regions, highlights the need for more innovative and scalable management approaches. Although preliminary studies have explored the utilization of *L. camara* in medicinal, environmental, and industrial sectors, most applications have yet to achieve large-scale economic viability. Considering the limited efficacy of biological control, future research should prioritize the development of integrated strategies that combine effective management with sustainable utilization of biomass. Further efforts are required to strengthen invasive species management frameworks by improving early detection, risk assessment, and impact evaluation. Research should also focus on identifying gaps in current management practices, optimizing resource use, and enhancing decision-making for policymakers. Importantly, future strategies must adopt a holistic approach that integrates environmental, social, economic, and policy dimensions across spatial and temporal scales to ensure long-term sustainability.

CONCLUSION

Effective management of *Lantana camara* requires an integrated and multidisciplinary approach. Mechanical removal, combined with herbicide application, biological control, and sustainable utilization, remains central to long-term management strategies. However, the development of more efficient and region-specific biological control agents is urgently needed. Furthermore, advancing technologies for the economic utilization of *Lantana* biomass can contribute to its management by transforming it into a valuable resource. Therefore, a comprehensive, large-scale management strategy for *L. camara*, implemented on a coordinated basis with active participation from local communities, government agencies, researchers, and policymakers is essential for achieving sustainable and long-term control of this invasive species.

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