

Review

Catalytic Conversion of Invasive *Lantana* Biomass to Renewable Fuels and Functional Biochar: Advances in Integrated Thermochemical Biorefinery System for Circular Bioeconomy

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Abstract

The *Lantana* genus, especially *L. camara*, has emerged as a potential yet underutilized lignocellulosic feedstock for various catalytic thermochemical conversion products and advanced carbon materials. This study reviews recent developments in the valorization of *Lantana* biomass to generate biofuels, bio-oil, syngas, and engineered biochar materials through pyrolysis, gasification, hydrothermal processing, and integrated biorefinery processes, in a critical manner. Particular focus will be on nanocomposite-modified, metal-doped biochar with catalytic elements such as ZSM-5, Fe₃O₄, TiO₂, and Ni-, Co-, and Zn-based oxides to enhance deoxygenation, catalytic cracking, tar reforming, pollutant remediation, and energy storage. Recent developments in catalyst synthesis techniques, such as impregnation, hydrothermal deposition, and in situ functionalization, are reviewed, along with characterization methods including BET, XRD, SEM/TEM, Raman spectroscopy, and XPS. The review further examines the impact of pore structure, surface chemistry, the presence of redox-active centers, and catalyst stability on product selectivity, syngas quality, and upgrading bio-oil performance. The effects of biochar on microbial immobilization, anaerobic digestion, and integrated biochemical conversion are discussed in detail, excluding thermochemical effects. The challenges of catalyst deactivation, biomass heterogeneities, scalability, techno-economic viability, and decentralized biomass logistics are also discussed. In summary, the development and implementation of catalytic reaction engineering, the design of nanocomposite biochar, and circular bioeconomy strategies have great potential to facilitate the conversion of invasive *Lantana* biomass into renewable fuels, multifunctional carbon materials, and environmentally friendly bioeconomy products.



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1. Introduction

As the world's demand for food, electricity, transportation, medical supplies, and industrial production continues to grow, there is increasing pressure on already overburdened natural and energy systems worldwide [1]. Although significant progress has been

made in renewable energy, fossil fuels remain the main energy sources worldwide, especially coal, natural gas, and petroleum, which together accounted for 61–62% of total energy consumption [2,3]. This dependency has heightened global greenhouse gas emissions, environmental degradation, and energy insecurity, especially in developing countries such as India and China, where fossil fuels are predominantly imported [4,5]. To facilitate the transition to a sustainable, low-carbon energy system, several countries have set long-term decarbonization targets ranging from 2050 to 2070 [6].

At the same time, issues related to unsustainable agriculture and/or the overuse of fertilizers, as well as the production of large volumes of plastic, continue to lead to soil degradation, biodiversity loss, and long-term ecological pollution [7–10]. The interrelated crises have revealed the critical urgency to adopt integrated, multi-sector solutions for renewable energy production and waste valorization, environmental rehabilitation, and the advancement of circular bioeconomy solutions in general [10]. With this in mind, the renewable, non-food, and abundant nature of Lignocellulosic biomass (LCB) positions it as a potential second-generation renewable carbon material [11]. Biomass from agricultural residues, forestry waste, and biomass grown on marginal areas can be used for sustainable bioenergy production without competing with food supply systems [12,13].

In recent years, invasive plant species have attracted significant attention as an alternative lignocellulosic feedstock due to their fast growth, adaptability, and biomass productivity [14]. The genus *Lantana* (Verbenaceae), comprising almost 150 species and found throughout tropical and subtropical regions, is considered one of the most vigorous groups of global invaders [15]. *Lantana* species typically grow are *L. camara*, *L. montevidensis*, *L. urticoides*, *L. trifolia*, *L. involucrata*, and *L. radula* [16]. The *Lantana* species were initially introduced as ornamental plants for their brightly colored flowers. Later, they were widely distributed across tropical and Asian ecosystems as well as other tropical ecosystems [17–20]. They are most commonly described as invasive species because they produce large numbers of seeds, exhibit allelopathy, are environmentally tolerant, and escape grazing pressure, factors that can all contribute to biodiversity loss, ecosystem disruption, and changes in fire regimes [21–26].

The same invasive traits render *Lantana* species feedstocks for renewable bioenergy production [27], obtained from their lignocellulosic tissues. Species regenerate very quickly, have high annual biomass productivity, and do not depend on agricultural inputs or irrigation [28–30]. Cellulose, hemicellulose, and lignin are abundant in biomass and are suitable for both thermochemical and biochemical conversion technologies [31]. Pyrolysis, gasification, hydrothermal liquefaction, fermentation, and anaerobic digestion have been studied for producing bio-oil, syngas, bioethanol, biogas, biohydrogen, and biochar from *Lantana* biomass [32,33]. Other conventional and biofuels from *Lantana* plants have also been harnessed for multiple applications, such as activated carbon production, catalytic biochar production, and nanocomposites (in addition to their use as biofuels) [34–37]. Synergistic biorefinery strategies that can facilitate the production of renewable energy, reduce waste and carbon emissions, and support the sustainable development of materials can act as enablers of the circular bioeconomy [38–40].

Recently, engineered biochar- and nanocomposite-based catalytic systems derived from *Lantana* biomass are attracting particular attention [41]. Metal-doped or nanocomposite prepared biochars possess tunable surface chemistry, hierarchical pore structure, and high porosity, and consequently have been found to have tremendous applications for deoxygenation, catalytic cracking and tar reforming, hydrogenation, pollutant remediation, microbial immobilization, and electrochemical energy storage [41–44]. These multipurpose catalytic systems can significantly enhance the efficiency and selectivity of thermochemical conversions, paving the way for the development of sustainable carbon-based processes.

Although there is increasing interest in the research community, several technical and industrial challenges remain to be addressed to enable the widespread implementation of biorefinery systems based on *Lantana* [45]. Existing knowledge is still mostly descriptive and focuses on relatively minor studies of catalytic mechanisms, the development of nanocomposites, catalyst stability, and process intensification [46]. In thermochemical upgrading systems, catalyst deactivation due to coke deposition, pore plugging, and metal agglomeration remains a significant problem [47]. Furthermore, inadequate TEAs, LCA, logistics optimization of biomass, and pilot-scale optimization tests still prevent the commercialization of biomass at a larger scale [45–47]. In addition, most experimental research has focused on *L. camara*, and comparative research with other *Lantana* species is sparse. Thus, cross-species extrapolations should be treated with some care going forward without experimental tests.

In this connection, the present review critically examines the valorization potential of the *Lantana* species in an integrated biorefinery system; special focus is given to catalytic thermochemical conversion and the engineering of nanocomposite-modified biochar. The review systematically explores biomass composition, biomass pretreatment methodologies, thermochemical and biochemical conversion technologies, synthesis and characterization of engineered biochar, catalytic upgrading mechanisms, multifunctional applications, sustainability assessment, techno-economic feasibility, and future research directions, in line with the circular bioeconomy and low-carbon energy systems [48–60].

2. *Lantana* Species: The Unutilized Potential

Lantana is a woody shrub belonging to the family Verbenaceae, but it has become extremely popular due to its botanical and ecological features, which are highly invasive [61]. It was introduced worldwide as both a deliberately planted ornamental and a naturalized plant, initially under control in the Neotropical region, but escaped domestication and began to proliferate elsewhere [20]. The species is highly phenotypically plastic and can therefore tolerate a wide range of environmental conditions, including diverse soils, high altitudes of 1800 m, and different light and moisture conditions [34]. The initial cause of its invasiveness is its intensive reproductive nature, which has a botanical explanation. It produces many small fruits (berries) annually, which are effectively dispersed by fruit-eating mammals and birds [62].

It also spreads vegetatively through root suckers and stem fragments, thereby further augmenting its dispersal ability [63]. A combination of these factors, along with the plant's rapid growth, provides an opportunity to build thickets of a single plant within a relatively short time (Figure 1).



Figure 1. Representative photographs of *Lantana camara* collected from Math village, Chamoli district, Uttarakhand, India.

Ecologically, the enormous destruction of native ecosystems in the name of propagating *Lantana* species has far-reaching, negative effects [64], such as direct competition and the deposition of native plants due to the heavy, thickening monopolization of essential resources such as light, water, and nutrients [65]. The loss of native plant biodiversity

has a trickle-down effect on the numbers of local animals, particularly ground-dwelling birds and insects, which depend on native species for survival and habitat [66]. *Lantana* species also exhibits allelopathic behavior, releasing chemicals that prevent the germination and growth of other plants, thereby disrupting natural succession and the regeneration of natural vegetation [67]. This species also produces pentacyclic triterpenoids, which are toxic to grazing animals and can cause massive animal deaths [68]. It is also associated with flammable biomass, which, despite being in its green form, could alter fire regimes, further aggravating fire severity and frequency and damaging forest ecosystems even more [69].

A *Lantana* species native to the Neotropics has, in its pan-tropical style, spread to over 60 countries in tropical, subtropical (as shown in Figure 1), and warm-temperate areas [28]. It underwent an immense expansion at the time of its introduction into Europe in the 17th century and was later exported as an ornamental species during the colonial period [70]. Now the plant is flourishing in various conditions and soils across 35–35° N and 35–35° S, enabled by human introduction through horticultural trade and accidental spread [71]. It can colonize disturbed areas, enabling it to spread along the edges of forests, farms, and grasslands, as well as along roads and railways [45]. It has been very severe in regions such as Australia, India, and large parts of Africa, where it is highly naturalized [71].

A combination of particularly effective invasive traits leads to the designation of *Lantana* species as one of the 100 worst examples of invasive alien species worldwide [71]. Its remarkable adaptive phenotypic plasticity enables it to thrive in a wide range of environmental conditions. As a result, successfully inhabit and exploit alternative ecological niches [45]. This flexibility is also afforded by a robust reproductive plan, which encompasses high seed production and effective dispersal by frugivorous animals [72]. Also, *Lantana* species employs allelopathic mechanisms, releasing chemical compounds that inhibit seed germination and plant development of indigenous vegetation species, thereby enhancing its competitiveness [73]. The species' resilience is also enhanced by its ability to regenerate effectively from vegetative fragments and rootstocks following disturbances such as fire and vegetation cutting [74].

The invasive ecological impact of *Lantana* is extensive and significant. Its ability to form dense, impermeable thicket leads to competitive exclusion and the displacement of native plant species, ultimately reducing species richness and homogenizing plant communities [45]. This disturbance disrupts the native food webs and reduces habitat for local wildlife, including herbivores and pollinators [75]. The leaves of *Lantana* species contain hepatotoxic pentacyclic triterpenoids, which are toxic to grazing livestock and have a detrimental impact on pastoral economies [76]. Additionally, *Lantana* species greatly alter the ecosystem processes. Its biomass, with the capacity to burn, even when green, has been used as fuel and may cause more frequent and more intense forest fires, a process that tends to lead to the natural replacement of native species [21]. Nutrient cycling may also be impaired by invasion and changes in soil properties, further weakening the ecosystem's functionality [77]. The net impact of these threats indicates that *Lantana* poses a significant challenge to biodiversity conservation and management of the ecosystem on a global scale.

The *Lantana* species are exceptionally prolific, ensuring a continuous, high level of biomass. India, in particular, has seen a rapid and extensive proliferation of it, leaving millions of hectares of forested and pasture land covered by it [28]. Productivity rates vary, yet one study conducted in India reported above-ground biomass production of 10.7 T ha⁻¹ yr⁻¹ [78]. The long life and rapid restoration of the species following disruption, through cutting or fire, only add to its persistent supply; it would provide a continuously available feedstock for biorefineries.

3. Biorefinery Suitability and Biomass Chemistry

Lantana biomass has been tested as a solid fuel by direct combustion at the genus level. A number of the species possess calorific and combustion properties that may also resemble those of commonly used woody biomass feedstocks, thereby making them a possibility for use as decentralized energy sources, particularly in rural areas. Research indicates that biochar and charcoal-based briquettes made from various *Lantana* species have been successful in previous operational trials using harvested stems and pruning residues [79]. The programs have already shown promise regarding energy supply, in addition to providing livelihoods to communities affected by the *Lantana* species invasion and minimizing uncontrollable burning or in situ degradation of the invasive stands [45].

3.1. Lignocellulosic Composition

The lignocellulosic composition of the key *Lantana* species varies, with immediate consequences for the pretreatment method, conversion efficiency, and biorefinery design. *Lantana camara* has 31–56% cellulose, 15–25% hemicellulose, and 17–27% lignin, making it one of the best-described species, suggesting a close-knit woody construction and a mixed tissue composition owing to an established stem and the ecological setting [80]. A characteristic cellulose, hemicellulose, and lignin fraction of *L. montevidensis* is 30–48%, 18–28%, and 18–30%, respectively, which contributes to the greater susceptibility of this species to hydrolytic pretreatments and fermentation-based mechanisms to convert the raw material to high-energy derivatives because of the comparatively softer stems and a relatively small value of high hemicellulose [81].

The cellulose, hemicellulose, and lignin content of *L. involucrata* are 28–45%, 16–26%, and 20–32%, respectively, with old shrubs having high lignin content being of special value for thermochemical valorization and biochar production [82]. *L. urticoides* contains 32–52% cellulose, 14–22% hemicellulose, and 18–29% lignin and is of significance because of the relatively high degree of crystallinity of cellulose and, consequently, is conventionally employed in the production of pulp, paper, and bioethanol [83]. *L. trifolia* has a cellulose, hemicellulose, and lignin content of 27–42%, 20–30%, and 16–25%, respectively, and the hemicellulose content is higher and, therefore, contributes to the release of fermentable sugars during the pretreatment [84]. Meanwhile, *L. radula* contains 29–50% cellulose, 17–25% hemicellulose, and 19–33% lignin, with more fibrous tissues and more lignin, which are positively conducive to pyrolysis, gasification, and other thermochemical routes [85].

The species within the genus *Lantana* share a widely resembling lignocellulosic structure that promotes their use as decentralized biorefinery feedstock. Woody stem, coniferous bridges, and phenolic leaves of *L. camara*, *L. montevidensis*, *L. trifolia*, *L. involucrata*, *L. urticoides*, and *L. radula* possess compositional ranges where cellulose (34–66%), hemicellulose (10–25%), lignin (12–25%), and intermediate extractives are in a position of low ash content [80–85]. Although the proportions of the exact ratios vary depending on species, age, nutrient status, and habitat, the high proportion of holocellulose in stems is constant throughout the genus, rendering these biomass sources compatible with biochemical conversion pathways.

Most *Lantana* species have leaf tissues that contain high levels of terpenoids, flavonoids, phenolics, and resinous metabolites, which increase recalcitrance and add value, as realized through co-extractive recovery pathways [86,87]. These large lignin and aromatic extractive pools, including high levels of *L. camara* and *L. trifolia*, are suitable for thermochemical processes like pyrolysis, gasification, and catalytic reforming to produce biochar, bio-oil, and syngas [88]. In the meantime, fibrous stem fractions that contain high levels of crystalline cellulose serve as high-quality feedstock for saccharification, fermentation, hydrogen-rich hydrolysates, and biopolymer formulations [89]. Therefore, in *Lantana* species, biomass

offers a two-fold biorefinery strategy: biochemical valorization using cellulose-rich tissues and thermochemical valorization using lignin-rich and extractive-rich fractions (Table 1).

Table 1. Comparative Lignocellulosic Composition of Major *Lantana* species.

Species	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Features	Ref.
<i>L. camara</i>	31–56	15–25	17–27	Highly woody, Suitable thermochemical conversion.	[80]
<i>L. montevidensis</i>	30–48	18–28	18–30	Softer steams, Favorable for hydrolysis and fermentation.	[81]
<i>L. involucrata</i>	28–45	16–26	20–32	High lignin in older shrubs is suitable for biochar production.	[82]
<i>L. urticoides</i>	32–52	14–22	18–29	High cellulose crystallinity, Relevant for pulp and bioethanol	[83]
<i>L. trifolia</i>	27–42	20–30	16–25	High hemicellulose, enhanced fermentable sugar release.	[84]
<i>L. radula</i>	29–50	17–25	19–33	Fibrous and lignocellulosic structures are suitable for thermochemical conversion.	[85]

The combination of these profiles shows that *Lantana* species exhibit compositional properties similar to those of other 2G lignocellulosic feeds [80]. Their high cellulose content, medium hemicellulose content, and high lignin content make them versatile across temperature-, chemical-, biochemical-, and hybrid biorefinery routes. Figure 2 represents the relative distribution of the three main lignocellulosic polymers, cellulose, hemicellulose, and lignin, in different species of *Lantana*. Cellulose was the major fraction (≈ 34 – 44%), indicating that crystalline polysaccharides are abundant and responsible for mechanical strength and carbon yield during thermochemical conversion. The hemicellulose content varies between ≈ 18 – 25% , reflecting the differences in amorphous carbohydrate content and thermal degradability. Lignin content is maintained at about 20 – 28% , which enhances aromaticity, rigidity, and biochar formation. Both *L. camara* and *L. urticoides* exhibit higher cellulose levels, while *L. involucrata* has relatively higher lignin content. This indicates improved thermal stability and suitability for carbon-rich biochar and energy-related applications.

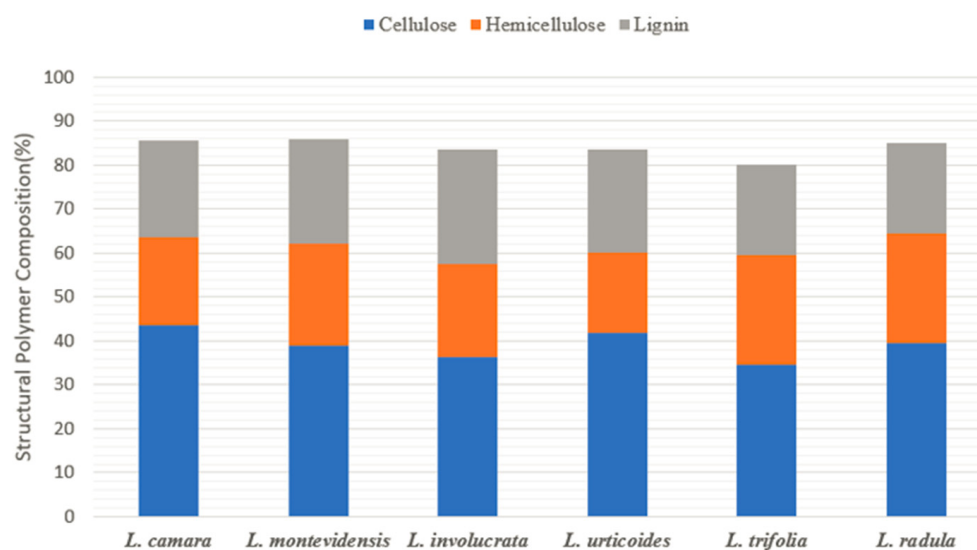


Figure 2. Comparative Lignocellulosic Composition of Major *Lantana* Species.

3.2. Secondary Metabolites and Extractive

In addition to their large lignocellulosic mass, other species in the *Lantana* genus are abundant sources of extractives and secondary metabolites, which have been shown to have industrial, ecological, and pharmacological significance [90]. Despite differences in profiles among taxa, the majority of *Lantana* species can accumulate intricate blends of terpenoids, phenolics, flavonoids, and other bioactive compounds, all of which have many biologically significant and functional applications [91].

3.2.1. Terpenoids

Terpenoids are among the most widespread secondary metabolites in *Lantana* plants [91]. Throughout the genus, pentacyclic triterpenoids are biosynthesized, although most (e.g., lantadenes in *L. camara*) are toxic to livestock and some also have pharmacological potential [68]. Sesquiterpenes such as caryophyllene, germacrene-D, bicyclgermacrene, humulene, and copaene, among others, are also enriched in other species, including *L. montevidensis*, *L. trifolia*, *L. indica*, *L. radula*, and *L. involucrata* [92]. The compounds are often the major components of essential oils and have been associated with insecticidal, allelopathic, antifungal, and antimicrobial activity [93]. It is important to note, put simply, that chemotaxonomic differences are reflected in species-specific terpenoid signatures that predict potential bioprospecting of natural pesticides and bioactive intermediates [94].

3.2.2. Phenolics and Flavonoids

Phenolic compounds and flavonoids are widely distributed across the genus and confer substantial antioxidant and anti-inflammatory benefits in *Lantana* species [95]. Numerous species have also been reported to contain metabolites such as luteolin, apigenin, verbascoside, quercetin analogs, rutin, and chlorogenic acid, including *L. camara*, *L. involucrata*, *L. Trifolia*, and *L. radula* [91]. The diversity of phenolic acids and phenylpropanoid glycosides across species justifies their application in allelochemical interactions, oxidative stress alleviation, and the design of biomedical, functional, and biopesticide formulations [96].

3.2.3. Other Bioactive Compounds

Phytochemical studies of *Lantana* species, which are broad-spectrum, have yielded several other compounds, including alkaloids, saponins, tannins, steroids, iridoid glycosides, diterpenes, and triterpenoid glycosides [85]. Even though some of these molecules can be intrinsically toxic, they may be used in both pharmaceuticals and antimicrobial preparations, as well as in value-added bioproducts. Particularly diverse pools of minor metabolites are found in species such as *L. urticoides* and *L. radula*, and they are associated with their abundant antiplasmodial, insect-repellent, or cytotoxic activity [97]. Table 2 represent the brief summary of bioactive components of *Lantana* Species.

Table 2. Extractive Profiles across Major *Lantana* Species.

<i>Lantana</i> Species	Major Terpenoids (Triterpenoids and Sesquiterpenes)	Phenolics and Flavonoids	Other Bioactive Compounds	Characteristic Notes/Bioactivity	Ref.
<i>L. camara</i>	Pentacyclic triterpenoids caryophyllene, germacrene-D, bicyclgermacrene	Luteolin, apigenin, verbascoside, phenolic acids	Saponins, alkaloids, tannins, glycosides	Highly diverse metabolite spectrum; strong allelopathic and insecticidal activity; most studied species.	[90]

Table 2. Cont.

<i>Lantana</i> Species	Major Terpenoids (Triterpenoids and Sesquiterpenes)	Phenolics and Flavonoids	Other Bioactive Compounds	Characteristic Notes/Bioactivity	Ref.
<i>L. montevidensis</i>	Sesquiterpenes: caryophyllene, copaene, β -bourbonene	Flavonoids (luteolin derivatives), phenolic glycosides	Low–moderate alkaloids, tannins	Essential oil richer in sesquiterpenes; noted for strong antimicrobial and herbicidal properties.	[93]
<i>L. involucrata</i>	Triterpenoids (lantadene variants), germacrene-type sesquiterpenes	Verbascoside, chlorogenic acid, rutin	Steroidal glycosides, tannins	Higher phenolic content compared to other species; strong antioxidant potential.	[94,95]
<i>L. urticoides</i>	Triterpenoids (ursane- and oleanane-type), humulene, caryophyllene	Quercetin, catechin, phenolic acids	Tannins, saponins	Known for strong anti-inflammatory extracts, the essential oil composition differs with shrub age.	[96,97]
<i>L. trifolia</i>	Sesquiterpenes (germacrene-D, α -humulene, monoterpenoids (limonene)	Verbascoside-rich flavonoid glycosides	Alkaloids, saponins	Documented medicinal uses; rich in antioxidant phenolics; exhibits notable antifungal activity.	[98,99]
<i>L. radula</i>	High triterpenoid concentration; Bicyclic and tricyclic sesquiterpenes	Phenolic acids, flavones	Triterpenoid glycosides, tannins	Leaves produce sticky resin rich in defense-related compounds; strong insect-repellent activity.	[100,101]

The major strength common to many *Lantana* species is the ability to grow and develop with low agricultural requirements. This environmental stability makes them suitable as non-competitive biomass feedstocks, particularly when traditional crops are limited by environmental conditions [102].

3.3. Edaphic Adaptability

The majority of species within this genus exhibit high tolerance to a broad range of soils, including nutrient-deprived, sandy, lateritic, and degraded soils [28]. They are also capable of functioning without fertilization, unlike domesticated biomass crops; in fact, excess nutrient supply commonly shifts biomass partitioning toward vegetative rather than floral growth [103]. This plasticity enables *Lantana* species, including *L. camara*, *L. montevidensis*, and *L. trifolia*, to take over the disturbed or marginal landscapes with little human intervention.

3.3.1. Low Water Requirements

The common trait among *Lantana* species is their ability to survive and grow in water-limited conditions. Late-flowering species, in particular *L. camara* and *L. urticoides*, are highly drought-tolerant and do not require irrigation to thrive; they can be introduced into semi-arid and dry ecosystems [104]. This characteristic is especially beneficial in areas with limited water, as it reduces competition with other biomass sources, such as water-intensive agriculture [105].

3.3.2. Low Management Obligations

Pest, pathogen, and herbivore resistance in *Lantana* species reduces the need for management inputs dramatically [106]. Vegetative regeneration, high growth rate, and environmental persistence are factors that lead to their proliferation in uncontrolled locations. *Lantana* therefore grows and amasses without intervention in the best agricultural land or the use of rigorous crop protection technologies [28]. The ecological power of *Lantana* species can be largely explained by their invasiveness, which preconditions their use as reliable and efficient biomass sources.

3.3.3. Phenotypic Plasticity

Lantana species exhibit high phenotypic plasticity, with individuals assuming dense shrub forms in semi-open habitats and climbing forms in dense forest habitats [45]. This adaptability enhances their survival across a broad range of ecological niches and helps them establish a permanent biomass [107].

3.3.4. Allelopathic Interactions

Lantana plants produce a wide range of allelochemicals in the rhizosphere, which suppress the germination and growth of surrounding plant species [108]. Although this negatively affects native ecosystems, the high production of secondary metabolites enables *Lantana* species to establish dense monospecific communities [109]. Such dominance contributes to a relatively uniform and abundant biomass supply in invaded regions, thereby supporting biomass valorization and extractive recovery applications.

3.3.5. Tolerance to Abiotic Stress

It exhibits excellent heat, salinity, drought, and fire tolerance, as seen in species of the genus [110]. Post-disturbance growth of *L. camara*, particularly *L. urticoides* and *L. radula*, is rapid and sustains a continuous biomass supply, diminishing seasonal variations in feedstock availability.

4. Pre-Treatment Strategies—Physiological, Chemical, and Biological

All *Lantana* species need a combination of pretreatment regimes (Lignin condensation, crystalline cellulose, dense vascular bundles, and phenolic carbohydrate complexes) to be integrated so that sub-products can be converted effectively downstream (Figure 3) [59]. Though *L. camara* is the most studied, because there are cross-species anatomical similarities, it can be generalized; scaled pretreatment models can also be used.

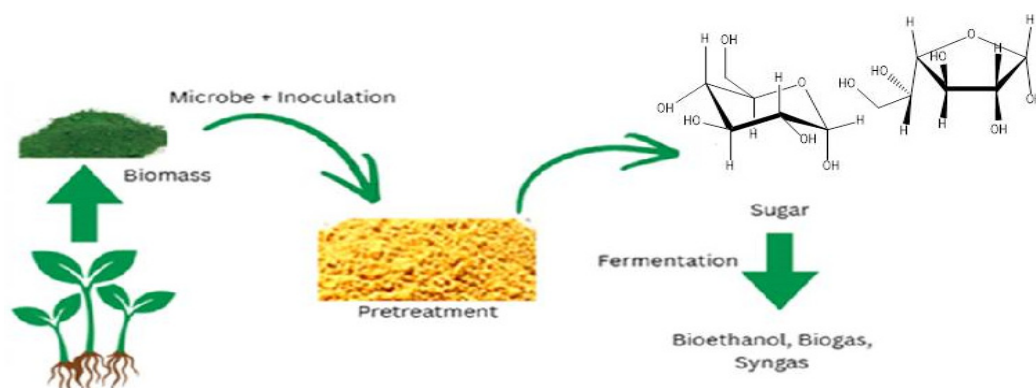


Figure 3. Schematic Flow chart for the pretreatment process.

4.1. Physical Pretreatment

All *Lantana* species generally require physical pretreatment due to the rigid, lignified nature of their stems, their tough bark, and their heterogeneous particle morphology. Size reduction methods such as chipping, milling, and shredding are commonly employed, particularly for species with thicker stems, including *L. camara*, *L. urticoides*, and *L. radula* [111]. These processes reduce particle size, increase surface area and porosity, and facilitate enhanced enzyme penetration during subsequent hydrolysis steps [112]. Steam explosion is another effective pretreatment approach, especially for species possessing denser xylem tissues such as *L. camara* and *L. trifolia* [113]. This treatment improves the solubility of hemicellulose, disrupts lignin–carbohydrate complexes, and enhances the accessibility of biomass for enzymatic hydrolysis and thermochemical conversion processes [113,114]. Microwave- and ultrasound-assisted disruption techniques are also applied in specific cases, particularly for *L. montevidensis*, which contains resin-rich leaves with hydrophobic extractives that may inhibit hydrolysis [115]. These methods help decrease cellulose crystallinity and accelerate reaction rates, thereby improving biomass digestibility. In addition, hot-water pretreatment or autohydrolysis is suitable for species such as *L. involucrata* and *L. radula*, which have relatively lower lignin content in young shoots. This approach aids in removing hemicellulose and enhances the release of fermentable sugars [116].

Overall, physical pretreatment significantly enhances heat and mass transfer efficiency, improves hydrolysis kinetics, and increases the overall conversion efficiency of *Lantana* biomass across different species [117].

4.2. Chemical Pretreatment

However, the lignin content, aromatics, and phenolic cross-linkages in the majority of *Lantana* species are very high, making chemical pretreatments essential. Chemical pretreatment methods are widely used to improve the bioconversion efficiency of *Lantana* biomass by enhancing lignin removal and increasing the accessibility of cellulose and hemicellulose. Dilute acid pretreatment with H_2SO_4 and HCl is particularly effective for xylan-rich species, including *L. trifolia* and *L. radula* (Table 3) [118]. This approach promotes hemicellulose solubilization and increases the release of fermentable sugars for ethanol production. However, the process conditions must be carefully controlled to avoid the formation of inhibitory by-products during hydrolysis [118]. Alkaline delignification using NaOH , KOH , or $\text{Ca}(\text{OH})_2$ is highly advantageous for species with rigid, lignin-rich biomass, such as *L. camara* and *L. urticoides* [119]. These treatments enhance the enzymatic susceptibility of cellulose microfibrils by inducing biomass swelling and removing phenolic and lignin barriers, thereby improving hydrolysis efficiency. Organosolv pretreatment is particularly suitable for species containing high levels of extractives, such as *L. montevidensis* leaves and *L. camara* bark [120]. In addition to effective lignin removal, this method enables the recovery of high-purity lignin that can be further utilized in the production of biopolymers and resins [120]. Advanced solvent-based pretreatments involving ionic liquids (ILs) and deep eutectic solvents (DES) have also demonstrated high efficiency in delignification and cellulose dissolution across various *Lantana* species [121]. These solvents are especially effective for species rich in polyphenolic compounds, including *L. trifolia* and *L. involucrata* [122], thereby improving biomass digestibility and facilitating downstream bioconversion processes. Chemical pathways play an important role in overcoming lignin-rich barriers and maximizing the liberation of fermentable sugars across all *Lantana* species feedstocks [123].

Table 3. Comparative Pretreatment Strategies and Conversion Outcomes for Different *Lantana* Species.

<i>Lantana</i> Species	Pretreatment Method	Main Purpose	Yield	Reference
<i>L. camara</i>	Dilute acid pretreatment	Improved sugar release	Fermentable sugar yield: ~180–200 mg g ^{−1} biomass	[118]
<i>L. camara</i>	Pyrolysis	Biofuel production	Bio-oil (50–65%), biochar (18–28%)	[119]
<i>L. urticoides</i>	Alkaline pretreatment	Lignin removal	Improved saccharification	[119]
<i>L. trifolia</i>	Acid pretreatment	Hemicellulose solubilization	Reducing sugars (33.34%)	[120]
<i>L. montevidensis</i>	Organosolv pretreatment	Lignin extraction	Improved digestibility	[120]
<i>L. involucrata</i>	Hot water pretreatment	Hemicellulose removal	Enhanced sugar release	[121]
<i>L. radula</i>	Ultrasound pretreatment	Improves enzyme penetration	Better biomass digestibility	[122]

4.3. Biological Pretreatments

Biological pretreatments offer a biologically neutral alternative to delignifying all *Lantana* species; however, the reaction rate is slower than that of physical–chemical methods. These biological pretreatment approaches have attracted increasing attention for the sustainable valorization of *Lantana* biomass owing to their eco-friendly nature and selective lignin-degrading capabilities. White-rot fungi, including *Phanerochaete*, *Trametes*, and *Pleurotus* species, are particularly effective against guaiacyl–syringyl lignin structures commonly present in *L. camara* and *L. trifolia* [124]. These fungi selectively degrade lignin while causing minimal cellulose loss, thereby improving the accessibility of structural carbohydrates for downstream conversion processes. Brown-rot and soft-rot fungi are better suited to partially delignified tissues or leaf biomass, especially in species such as *L. radula* and *L. involucrata*, which possess relatively softer stem structures [125]. These fungal systems enhance biomass porosity and facilitate improved enzymatic accessibility. In addition, enzymatic cocktails containing cellulases, hemicellulases, and laccases play an important role in biomass saccharification. Such specialized enzyme systems effectively hydrolyze cellulose-rich stems of *L. urticoides* and resinous leaves of *L. montevidensis*, while laccases assist in degrading phenolic compounds and reducing hydrolysis inhibitors [126]. Microbial consortia and consolidated bioprocessing (CBP) strategies have also shown promise for simultaneously accelerating hydrolysis and fermentation [127]. These approaches are particularly useful for *Lantana* species with high volatile oil content, where microbial degradation contributes to biomass detoxification and enhanced fermentability. Furthermore, bioaugmentation techniques improve the activity of naturally occurring decomposer microorganisms in the environment, thereby supporting decentralized biomass pretreatment systems. Such strategies may be especially beneficial for community-level biomass valorization in regions dominated by *L. radula* or *L. involucrata* [128].

Biological pretreatment increases sustainability and minimizes chemical load, but optimizing residence time, moisture, and inoculum density is species-specific [129]. Table 3 represent the comparative summary of various pretreatment and conversion strategies adopted to various *Lantana* species for biorefinery applications and correlation between pretreat-

ment techniques, their main goals and the resulted conversion efficiencies such as increased sugar release, lignin removal, biomass digestibility, bio-oil production and improved saccharification results in the context of sustainable biofuel and bio-based product generation.

5. Combined Pretreatment Plan of All the Lantana Species

A hybrid pretreatment approach is considered the most suitable strategy for *Lantana* species. While these species share certain compositional similarities, they differ significantly in structural toughness, lignin distribution, and biomass recalcitrance. Typically, the pretreatment process begins with physical size-reduction methods, such as milling or steam explosion, which increase surface area and improve biomass accessibility [111]. This is generally followed by selective chemical delignification using alkaline reagents, ionic liquids (ILs), or deep eutectic solvents (DESs), which aid in lignin removal and enhance cellulose availability for downstream conversion processes [121,122]. Finally, enzymatic hydrolysis or biological polishing treatments, such as fungal delignification, may be applied to degrade residual lignin further and improve fermentable sugar release [126]. The integration of these pretreatment strategies can significantly improve biomass digestibility, conversion efficiency, and overall process performance for multi-species *Lantana* biorefineries.

This multi-step approach maximizes access to cellulose, inhibits the formation of inhibitors, balances cost-effectiveness, maintains sustainability, and can adapt to compositional changes in *Lantana* species [130]. These hybrid strategies have demonstrated the greatest efficiency in converting to bioethanol, biogas, syngas, biochar, and platform chemical value-added products across all species.

6. Bioenergy Conversion Pathways from Lantana Species

Thermochemical conversion technologies are Pyrolysis, gasification, combustion, and torrefaction. Pyrolysis is one of the pathways identified to produce several *Lantana* species (e.g., *L. montevidensis*, *L. trifolia*, *L. urticoides*, *L. involucrata*, and *L. radula*) into high-value bioenergy carriers (Table 4) [131]. Although lignocellulosic structures differ across species, many are considered desirable as fuels. They typically have a middle- to high-energy density, contain high concentrations of volatile constituents, and exhibit undesirable levels of nitrogen and sulfur, making them attractive as fuels for thermally based conversion systems [132]. The distribution of the products of pyrolysis is reported to be 50–65% bio-oil, 18–28% biochar, and 10–15% non-condensable gases, but varies from study to study based on the process conditions and reactor design: the bio-oils are typically characterized by energy contents of the sort 30–33 MJ kg^{−1} with similar proportions of carbon [133]. *L. camara* and *L. urticoides* have a larger amount of lignin-based aromatic fractions, *L. trifolia* and *L. montevidensis* have a slightly lighter pyrolytic liquid due to a higher percentage of leaf-stem ratios [134].

Gasification of *Lantana* biomass produces syngas with a lower heating value of about 5.8–6.5 MJ Nm^{−3}, making it suitable for thermal and distributed power applications [135]. Comparative combustion studies across *Lantana* species show that emissions of sulfur, nitrogen, and ash are lower than those from coal and certain agricultural residues, which may also be attributed to lower levels of sulfur, nitrogen, and ash in most species. However, site-specific uptake can also result in slightly elevated mineral levels in *L. radula* and *L. involucrata* [136].

Torrefaction enhances the grindability, hydrophobicity, and energy density of all the investigated species, thereby reducing logistics costs and making them more suitable for co-firing systems [137]. Thermochemical pathway coupling is a strategically important need for transforming a range of *Lantana* species into renewable energy vectors. In this context, *Lantana* species also facilitate biomass clearance at the grassland level and mitigate the

ecological risks associated with their invasiveness [138]—a biochemical route to producing biofuels. Lignocellulosic biomass from *Lantana* species can be converted into biofuels via a series of biocatalyzed reactions, primarily producing bioethanol and biogases [139]. These pathways are typical of the pretreatment, hydrolysis, and microbial transformation stages and have been well investigated in *Lantana* species due to the abundance of cellulose and hemicellulose, as well as the availability of non-food biomass.

A requirement of biochemical transformation of *Lantana* species is hydrolysis, which would follow the pretreatment. It was shown that the acid pretreatment, along with enzyme hydrolysis, was extremely effective in solubilizing structural carbohydrates and generating fermentable sugars [140]. Reported studies indicate that *Lantana* species biomass dilute acid hydrolysis can achieve the first total sugar concentration in the range of approximately 180–200 mg per pound of dry biomass, after which an enzyme hydrolysis would proceed to generate a greater concentration of sugars in the range of about 0.14–0.23 kg of dry biomass, depending on the enzyme compounds and microbial strains applied [141]. Other enzyme delignification techniques are very high yielding, up to 85–90%, with reducing sugar yields of up to 700 mg/kg of dry biomass under optimal conditions, even in the absence of subsequent fermentation [142].

Anaerobic digestion is another significant biochemical process for valorizing *Lantana* species into biogas, particularly methane. Experimental studies on optimized conditions for the anaerobic factors involved in the digestion of *Lantana* species biomass have demonstrated a cumulative methane volume of a few liters per batch, proportional to the substrate load [143]. There is also the use of cellulolytic and fermentation-based cellulolytic microbe consortia, which are proposed to significantly enhance the production of methane and quality of the biogas, where the yield of methane is approximately 249 L kg^{−1} of the volatile solids, and methane content is approximately 55–65% in the case of ideal performance [144].

Table 4. Comparison of thermochemical and biochemical conversion pathways for *Lantana* biomass.

Conversion Process	Operating Temperature	Main Products	Important Features	Ref.
Pyrolysis	350–700 °C	Bio-oil, biochar, gases	Produces high bio-oil yield (50–65%) with energy content of 30–33 MJ kg ^{−1}	[131–134]
Gasification	700–1000 °C	Syngas (H ₂ , CO, CH ₄)	Generates combustible syngas suitable for heat and power applications	[135,136]
Combustion	800–1000 °C	Heat energy	Shows lower sulfur and ash emissions compared with coal	[136]
Torrefaction	200–320 °C	Torrefied biomass	Improves biomass energy density, storage, and grindability	[137]
Hydrolysis	30–60 °C	Fermentable sugars	Enhances sugar release for downstream bioethanol production	[138]
Enzymatic Delignification	30–50 °C	Reducing sugars	Achieves high lignin removal and improved saccharification efficiency	[142]
Anaerobic Digestion	35–55 °C	Biogas/methane	Produces methane-rich biogas under optimized conditions	[143,144]
Fermentation	30–37 °C	Bioethanol	Converts fermentable sugars into bioethanol after detoxification	[145]

The biochemical conversion processes of the *Lantana* species are very useful, depending on the extent of pretreatment and detoxification. During pretreatment, it is important to break the lignin-hemicellulose framework and open up cellulose to eliminate compounds

that inhibit acid hydrolysis, which is achieved through detoxification [59]. In *Lantana* species hydrolysates, common inhibitors include phenolic compounds and furan-based products such as hydroxymethylfurfural (HMF) and furfural, which must be minimal or absent before fermentation by microbes, or they can block the production of other products [145].

Overall, *Lantana* species may be considered a potential non-food lignocellulosic biomass for biofuel production. Although their conversion processes are relatively costly and complex, biochemical conversion processes can achieve very significant increases in conversion efficiency with good optimization of pretreatment, hydrolysis, and microbial methods. The biochemical valorization of the *Lantana* species has significant potential to become a sustainable biofuel when integrated into well-integrated biorefinery models and also to contribute to the restoration of invasive species issues and environmental protection (Figure 4).

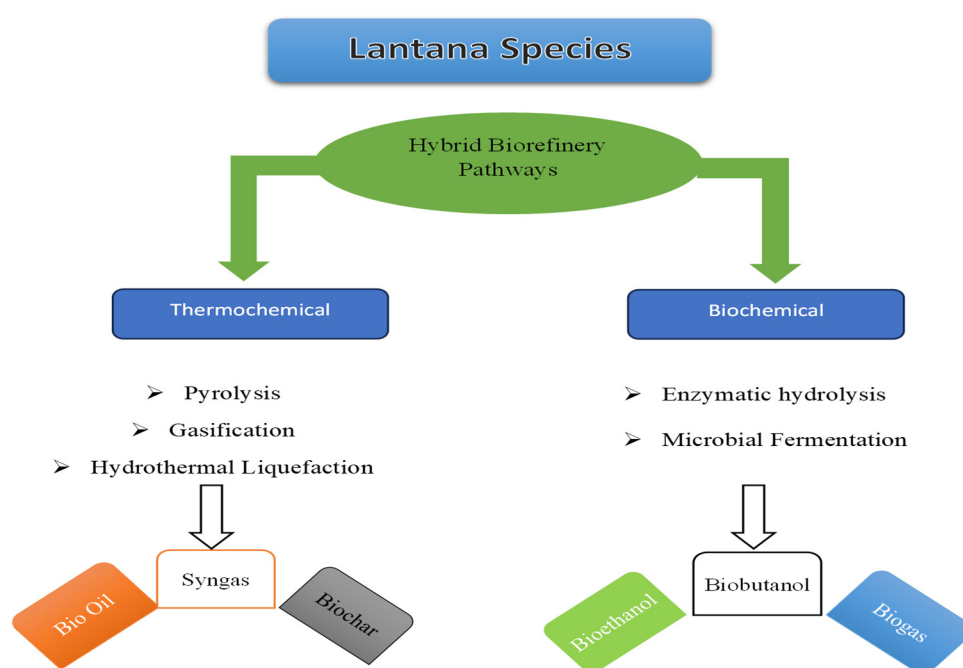


Figure 4. Bioenergy Pathways from *Lantana* Species.

7. Advanced Hybrid Integrated Biorefinery Concepts and Value-Added Products Beyond Energy

7.1. Biochar and Fabricated Biochar

Biorefinery systems combining thermochemical and biochemical conversion routes have been proposed as effective approaches for achieving better energetic and chemical valorization of various *Lantana* species [79]. Although *L. camara*, *L. montevidensis*, *L. urticoides*, *L. trifolia*, *L. involucrata*, and *L. radula* are compositionally heterogeneous, all species have a lignocellulosic skeleton that is well applicable to the integrated processing platforms such as pyrolysis, gasification, hydrothermal liquefaction, torrefaction, enzymatic hydrolysis, fermentation, anaerobic digestion, and microbial upgrading [32].

Figure 5 illustrates the thermochemical conversion of biomass through processes such as pyrolysis, gasification, combustion, and torrefaction under controlled temperature and oxygen conditions.

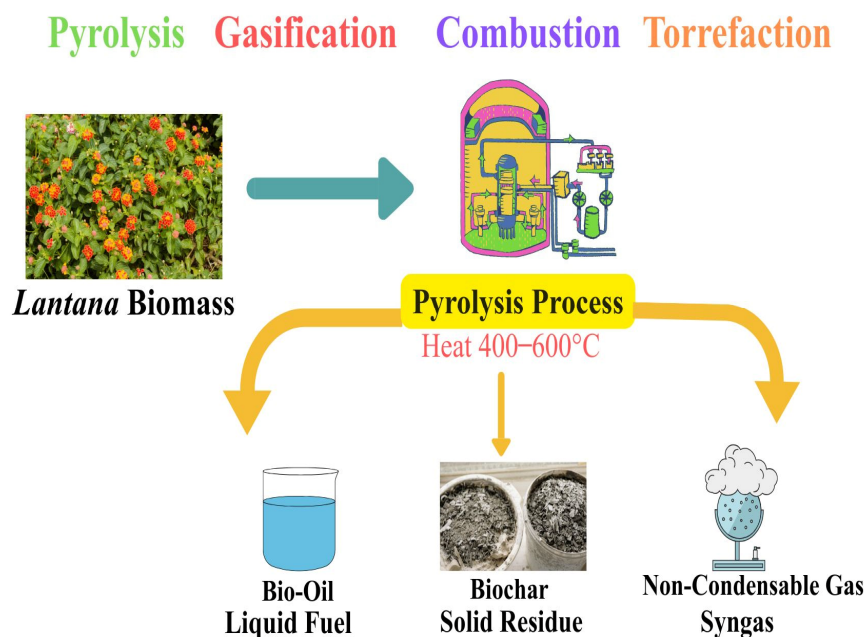


Figure 5. Schematic diagram of the Pyrolysis Process.

Hybrid systems maximize carbon recovery and minimize waste generation and process inefficiency by coordinating the use of lignin-rich and carbohydrate-rich portions of biomass. For instance, species like *L. camara* and *L. urticoides*, which are rich in lignin, are more suitable for thermochemical conversion routes to syngas and bio-oil, while others, such as *L. trifolia* and *L. montevidensis*, with higher cellulose content, are better suited to biochemical routes of fermentative biofuel production [146]. In these integrated pathways, bioethanol, biobutanol, biogas, syngas, platform chemicals, and carbon-rich biochar enable the production of carbon-positive, circular biorefinery systems [33].

Pyrolysis of *Lantana* biomass to obtain metal-doped and nanocomposite engineered biochar, which has the potential to enhance catalytic integration of these hybrid systems, is an area of strong interest [147]. Figure 6 illustrates the production of engineered or nanostructured biochar from biomass via thermochemical carbonization under oxygen-limited conditions, followed by physical and chemical activation with steam, reactive gases, chemical agents, and mechanical size reduction.

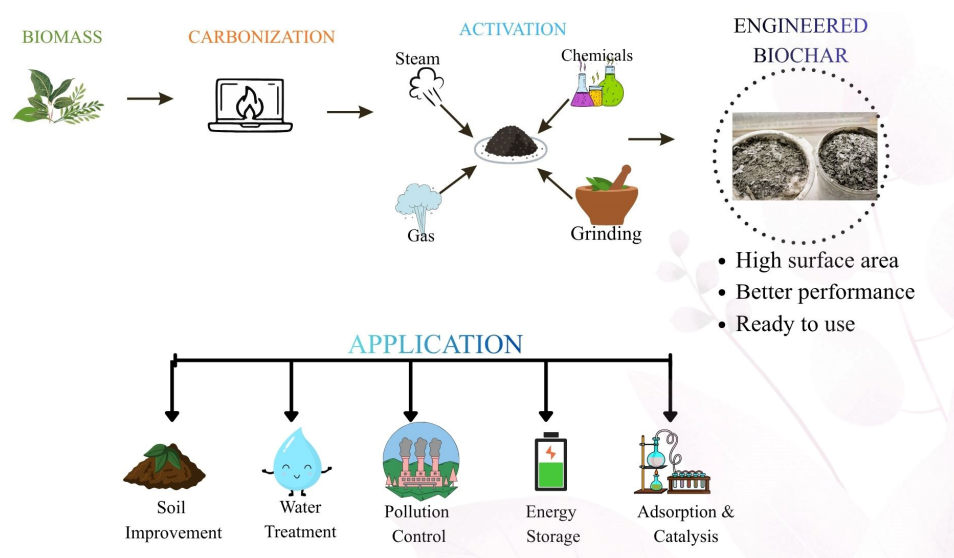


Figure 6. Preparation route of engineered nanocomposite biochar.

These activation processes improve pore development, surface functionality, electrical conductivity, and adsorption capacity, thereby enhancing the physicochemical properties and multifunctional performance of biochar for environmental remediation, catalysis, and electrochemical energy storage applications. Fe_3O_4 , TiO_2 , ZnO , MgO , Al_2O_3 , Y_2O_3 , and ZSM-5 are transition metals, metal oxides, and zeolitic phases, respectively, with significantly improved catalytic activity, which is attributed to enhanced surface area, hierarchical pore architecture, redox active sites, tunable acidity–basicity, and improved electron-transfer properties within the biochar modified with them [148]. These catalytic systems have been prepared using several synthesis techniques such as wet impregnation, co-precipitation, hydrothermal deposition, or sol–gel modification [147,148]. In a series of reported studies, impregnating the biomass with metal precursor at Biochar: metal Precursor ratios of 1:2 to 1:1 and pyrolyzing at temperatures ranging from 500 to 800 °C were observed to be effective methods for producing highly porous catalytic biochar with improved physicochemical stability [149]. In another study, the Fe-loaded biochar produced at 700 °C exhibited significantly larger graphitic carbon domains and a higher concentration of surface-active iron oxide phases, leading to superior catalytic pyrolysis properties for aromatization and deoxygenation reactions [150].

Advanced characterization techniques were used to examine the structural properties of modified biochar, including BET surface area analysis, X-ray diffraction (XRD), scanning and transmission electron microscopy (SEM/TEM), Raman spectroscopy, FTIR spectroscopy, and X-ray photoelectron spectroscopy (XPS) [149,150]. BET analysis reveals that the surface areas of the pristine biochar are low (generally lower than 100 m² g^{−1}). However, the activated and nanocomposite biochars appear to have much larger surface areas (above 500 m² g^{−1}), a consequence of enhanced pore development and activation efficiency [149]. The same goes for pore volume and distribution, where BET analysis can also provide information and directly relates to adsorption performance and access to the catalytic material. XRD is commonly used to identify and characterize crystallographic phases and confirm the successful incorporation of metal oxides and zeolitic structures, including ZSM-5, into the biochar matrix via characteristic diffraction peaks [149,150]. The peak height ratio (ID/IG) of the D and G peaks provides Raman spectroscopy with a measure of the degree of graphitization, allowing defects in carbon materials to be quantified and separating domains of graphitic carbon from disordered carbon structures. All these analytical techniques provide insights into the surface elemental composition and the oxidation states of catalytically active metal species, for example, Fe(II)/Fe(III) species in Fe_3O_4 -supported biochar systems, and validate successful metal loading and catalytically active surface formation in these systems [150]. The surface morphology, pore architecture, dispersion, and particle size distribution of nanometer-sized metal oxides were revealed by SEM and TEM analysis within porous carbon matrices, which increase the accessibility of the catalysts and the distribution of active sites [149,150]. Advanced FTIR spectroscopy is also used to detect oxygen-related functional groups and surface chemical interactions that control adsorption, catalysis, and electron transfer in engineered biochar systems.

Additionally, ZSM-5-modified and metal-oxide-functionalized biochar offers catalytic activity to improve catalytic cracking, hydrodeoxygenation, tar reforming, hydrogenation, and aromatization reactions, resulting in superior bio-oil quality and cleaner synthesis gas production during thermochemical conversion [150]. Catalytic upgrading using Fe-, Ni-, and ZSM-5-modified biochar catalysts during pyrolysis of lignocellulosic biomass at 500–700 °C has been reported to enhance aromatic hydrocarbon selectivity by approximately 30–45% while reducing oxygenated compounds by 25–40%, primarily due to improved deoxygenation, cracking, and aromatization reactions [150–152].

Moreover, stability tests suggest that several of the metal-doped and nanocomposite biochar catalysts retain their catalytic activity of almost 70–90% after 4–6 reaction cycles due to coke deposition, pore blockage, etc., though there is gradual deactivation through coke deposition, surface carbon deposition, metal agglomeration, and pore blockage, which is a big operational thermal resistance to the application of these biochar catalysts [152,153]. Surface area, pore collapse, changes in crystallinity, and oxidation-state changes in active metal species have all been observed in spent catalysts using BET, XRD, SEM/TEM, TG, and XPS analyses [153]. Catalytic performance has been restored and catalyst life extended by altering catalyst surfaces through regeneration techniques such as thermal oxidation, calcination, steam treatment, and solvent washing to remove coke that has formed and to recover catalytic sites [154]. These results demonstrate the key roles of catalyst durability, catalyst regeneration effectiveness, and extended operational stability in enhancing the techno-economic feasibility of catalytic biorefinery systems.

In biochemical pathways, nanostructured biochar catalysts can be used as immobilization matrices for enzymes, as support carriers for microbes, and as electron-shuttling materials to increase the efficiencies of saccharification, fermentation, and anaerobic digestion processes [151]. Cellulose breakdown microorganisms, such as *Clostridium thermocellum*, *Trichoderma reesei*, and metabolically engineered *Saccharomyces cerevisiae*, immobilized on a metal-modified biochar surface enhance substrate accessibility, enzyme stability, and microbial electron transfer, which aid consolidated bioprocessing (CBP) and simultaneous saccharification and fermentation (SSF) systems [151]. These catalytic interfaces can significantly reduce exogenous enzyme loading and processing time across a variety of *Lantana* feedstocks [147,151].

At the same time, transition-metal-modified biochar, such as Ni-, Co-, Fe-, and Mo-based biochar, exhibits high hydrocracking, deoxygenation, and hydrogenation activity during the thermochemical upgrading process [152]. These catalytic systems enhance fuel stability, tar conversion efficiency, fuel aromaticity, and calorific value without producing significant amounts of residual tar, while also selectively producing valuable intermediates [153]. A combination of thermochemical and biochemical processes also enables the conversion of bioorganic residues into biohydrogen, VFAs, and platform chemicals, enabling near-complete carbon utilization in integrated biorefining processes for *Lantana*.

Lantana biomass is especially appealing for emerging wet-processing technologies, such as hydrothermal carbonization (HTC) and supercritical water gasification (SCWG), due to its naturally high moisture content [155].

In addition to energy use, the metal- and nanocomposite-modified biochars derived from *Lantana* species exhibit multifunctional capabilities for environmental remediation, agriculture, and electrochemical applications. The FeMn, CuZnO, TiO₂, FeNi, CoMn, and CuO composites are effective at capturing and redox-mediated electron transfer of dyes, heavy metals, and organic pollutants [156]. Moreover, conductive transition-metal biochars have the potential to serve as porous electrode materials for supercapacitors, batteries, and fuel cells, owing to their high conductivity, charge-storage capacity, and structural stability [157].

The hybrid thermochemical–biochemical bio-refinery approach for integrating metal- and nanocomposite-engineered biochars significantly enhances the valorization potential of *Lantana* biomass [158]. These systems simultaneously deliver a range of outcomes, including renewable energy, catalytic upgrading, environment, carbon sequestration, sustainable material outputs, and a transformation of invasive biomass into a renewable carbon resource that supports circular bioeconomy processes and global sustainability goals, such as SDG 7, SDG 12, and SDG 13 (Figure 7) [159].

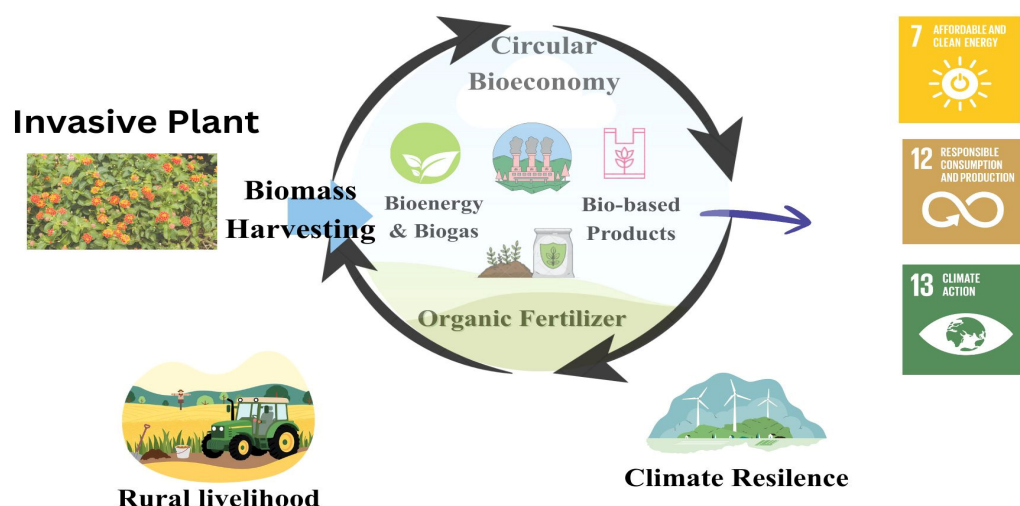


Figure 7. Circular bioeconomy approaches for sustainable valorization of *Lantana* biomass.

7.2. Biopolymers and Biocomposites

Combination bio-refineries, implemented across various *Lantana* species such as *L. camara*, *L. montevidensis*, *L. trifolia*, *L. urticoides*, *L. involucrata*, and *L. radula*, are beginning to rebrand these invasive shrubs as competitive lignocellulosic feedstocks for the sustainable production of bioplastics and higher-level biomaterials [160].

The high content of cellulose and hemicellulose in these species enables easy hydrolysis and fermentation into monomeric sugars, which are used to produce the most important biopolymers, including polyhydroxyalkanoates (PHA) and polylactic acid (PLA) (Figure 8) [161].

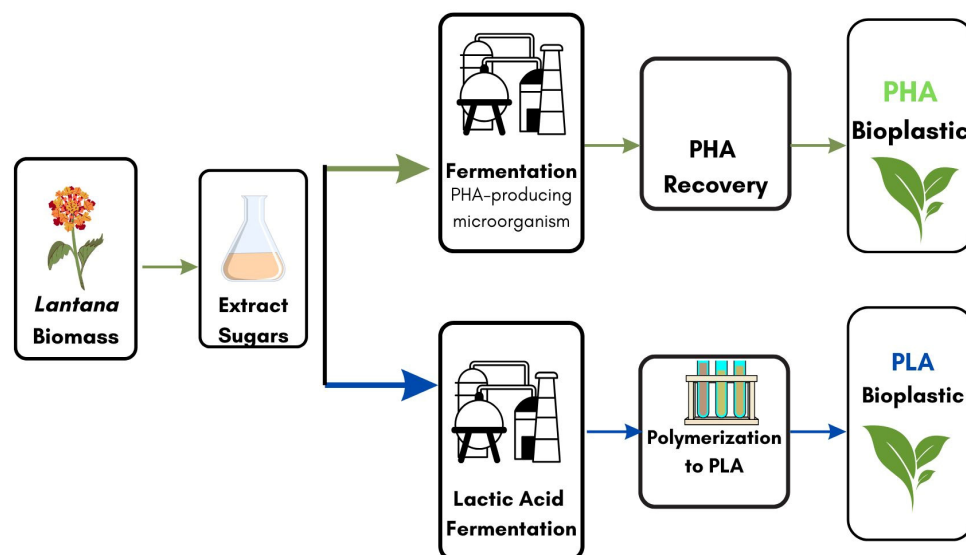


Figure 8. Production Route of PHA/PLA From *Lantana*-Derived Sugars.

Innovations in recently developed pretreatment methods, such as acid-assisted autoclaving, have greatly improved the efficiency of enzymatic saccharification across a variety of *Lantana* taxa, yielding up to 132 mg/g of total reducing sugars per gram of biomass [162]. These fermentable sugars serve as the biochemical basis for PHA and PLA, and the remaining lignin-enriched fractions can be used directly as reinforced materials and biodegradable polymer scaffolds [163]. Consequently, biorefineries in *Lantana* species can naturally facilitate a two-way system in which the biochemical production of monomers and the fabrication of composite materials occur in parallel, enabling a circular, near-zero-waste

processing scheme [38]. However, the work is mostly restricted to laboratory research, underscoring the need for techno-economic optimization, pilot-scale testing, and stringent life-cycle analysis to assess the commercial feasibility of PHA and PLA production using *Lantana* species as feedstocks [164].

In addition to the valorization of lignocellulosic materials, a cascading biorefinery concept is further enhanced by the co-extraction of high-value secondary metabolites. Other species, such as *L. camara*, *L. involucrata*, and *L. radula*, provide abundant sources of triterpenoids (e.g., lantadene A, oleanolic acid), flavonoids (e.g., quercetin), and phenolic compounds [165]. Optimal extraction of these phytochemicals before or alongside biomass conversion improves overall resource use and economic output per unit of biomass, and aligns with the vision of a circular bioeconomy [166]. The history of incorporating phytochemical recovery into fermentation-based polymer production as precursors, and the creation of fiber-reinforced composites, highlights the potential of *Lantana* species as a multipurpose feedstock [167].

In this scenario, PHA and PLA will serve as building blocks for new-generation sustainable biomaterials. PHA is a biopolymer produced by microorganisms under nutrient-restrictive, carbon-enriched conditions, with high biodegradability, high thermal stability, and adjustable mechanical properties [168]. Their affinity for *Lantana* species sugars puts them in a good position for use in packaging, biomedical equipment, and high-performance composites [168]. PLA, manufactured by fermenting sugars to produce lactic acid, which is then polymerized, provides high tensile strength, transparency, compostability, and processability, and can be used as films, fibers, for additive manufacturing, and as an additive [169]. Pre-treated *Lantana* biomass is a promising source of fermentable sugars, and the production of lactic acid is an efficient reaction with PLA, with *Lantana*-based biorefineries potentially producing PLA in large quantities and making it a commercially promising resource [143].

Taken as a whole, the combination of lignocellulosic transformation, controlled phytochemical recovery, and the production of biopolymers and biocomposites demonstrates how the exploitation of *Lantana* species can both reduce the environmental risks posed by invasive growth and encourage the development of low-carbon, bio-based polymer industries. These multi-product biorefineries are cascading and embody the concepts of circularity, sustainability, and green materials engineering, and they might turn *Lantana* into not a liability to the environment but a strategic industrial feedstock.

7.3. Biochar for Carbon Sequestration

Biomass of invasive shrubs in several species of the genus *Lantana*, including *L. camara*, *L. montevidensis*, *L. trifolia*, *L. urticoides*, *L. involucrata*, and *L. radula*, can be converted into biochar as a possible nature-based indicator of the ultimate carbon sequestration and soil restoration. Slow pyrolysis of these lignocellulosic feeds will continuously provide a high-carbon, aromatic biomass, biochar, which can be maintained in soils for relatively short time frames, stabilizing carbon in the atmosphere in very recalcitrant forms [170]. The comparative analysis of *Lantana* species shows that biochar products contain more than half stubborn carbon, and the application of biochar in fields increases soil organic carbon (SOC), which generally ranges from 1.6% to 1.75% depending on the species and soil type [171].

Biochar produced from *Lantana* biomass is highly effective at stabilizing soil carbon and improving soil fertility [171]. Availability of N, P and K among the treatments are also increased, this implies good ash mineralogy and pH of alkaline soil, and the adsorption capacities of heavy metal ions, in which case, Cd^{2+} and Cu^{2+} , in soils is high due to the formation of high surface areas and oxygenated functional groups during *Lantana*

pyrolysis, and their use in *Lantana* biochar can be applied to soil and water remediation activities [172,173]. The biochar trial conducted on *L. camara*, *L. radula*, and *L. trifolia* shows a high potential for stabilizing the contaminant in degraded or mining-disturbed soils [174].

The field experiments have revealed the synergistic benefits of applying biochars from different taxa of the *Lantana* genus in combination with other inorganic fertilizers [175]. It has been enhanced with a higher SOC, increased cation exchange capacity (CEC), which is, in many cases, 30–40 percent greater and also has more favorable physical traits of the soil, including a reduction in bulk density and a rise in water-defining ability, particularly in semi-arid agroecosystems [176]. These twofold characteristics make *Lantana* species biochar a two-pronged policy to reduce climate change through carbon sequestration and to restore agricultural regeneration by maximizing the exploitation of soil nutrients and structure.

A shift toward long-residence-time biochar driven by invasive *Lantana* species advances a circular bioeconomy paradigm, where ecologically problematic biomass is used as a source of carbon drawdown and soil recovery. The existing multi-species valorization pathway illustrates how it might be meaningful to make a substantial contribution to climate change mitigation, ecosystem restoration, and sustainable land-use in elongated regions overrun by *Lantana* invasion using *Lantana* biochar.

8. Circular Bioeconomy and Sustainability Implications

Most *Lantana* species are fine, non-competitive lignocellulosic feedstocks, as their ubiquity, ecological dominance, and low input requirements combine. *Lantana* biomass does not pose a threat to food and fodder systems; compared with agricultural residues, *Lantana* biomass is a massive accumulator due to the lack of appropriate control measures [177]. The unregulated growth of *Lantana* results in dense biomass accumulation across invaded regions, posing threats to ecology, biodiversity, and fire safety, while also indicating the potential for biomass valorization [178]. The introduction of *Lantana* biomass into biorefinery systems would be effective in: Decentralized production of bioenergy, Production of biomass by biochemical methods, Cleansing of platform chemicals, Reduction in pressure on invasive species, and Circular bioeconomy and low-carbon feedstock development [179].

Thus, the planting of *Lantana* species is highly regarded for its dual benefits: ecological rehabilitation through biomass clearing and sustainable, biobased value-added production.

The concept of producing energy and utilizing the co-products of *Lantana* species can be considered a brilliant example of operationalizing the circular economy, as it enables greater resource use and environmental sustainability [180]. *Lantana* species is an invasive biomass resource with advantages in two ways: first, to ensure energy generation through a thermochemical process, and second, to derive useful co-products that can be exploited in the future [181]. The biomass of *Lantana* species, when transformed to bioenergy through pyrolysis and gasification, or incineration, can not only produce renewable energy but also yield biochar and other co-products, bio-oil, and syngas [182]. Such co-products are used to feed many environmental and industrial processes, in essence facilitating material loops and reducing waste [183]. For example, biochar derived from *Lantana* species could be used for soil improvement and carbon sequestration, thereby improving soil health and stabilizing carbon levels [176]. Simultaneously, bio-oil and syngas can be used as alternative fuels, reducing the reliance on fossil fuels. Circularity would also be encouraged, as the relationship between energy outputs and the co-product stream would be defined, thereby offering synergistic benefits. The application of *Lantana* species biochar in soil remediation enhances energy recovery in tackling land deterioration, providing support for syngas and bio-oil production and aiding a decentralized energy system [184]. In addition, the circular model eliminates environmental issues arising from the continuity of the *Lantana*

species, turning an ecological issue into a resource. This balance between energy yield and co-product quality is to be established by optimizing process parameters, such as temperature and residence time, along with feedstock preparation [185]. These parameters are adjustable to manufacture biochar with agronomic or environmental uses and to achieve the maximum energy conversion efficiency. *Lantana* species-based system and co-product system integration is a holistic, circular approach to sustainable biomass management.

9. Life Cycle Assessment (LCA)

Important insight into the environmental sustainability of invasive biomass valorization through the entire bioenergy conversion chain, from biomass harvesting to pretreatment, energy generation, and co-product utilization, can be provided by the life-cycle assessment (LCA) of *Lantana*-based bioenergy systems [186]. The latest studies show that thermochemical and biochemical conversion routes from *Lantana* biomass can significantly lower GHG emissions compared with fossil-fuel energy routes and traditional cultivated bioenergy crops [187]. These benefits are mostly attributed to the invasive and low-input nature of *Lantana* species, which may occur on degraded or marginal lands and do not compete with food production.

Only a limited number of published LCA studies have examined energy pathways using lignocellulosic bioenergy and biochar systems with GWP reductions of 40–65% compared to a coal- and petroleum-based pathway [188]. The low-carbon-neutral use of *Lantana* biomass, along with methane gas avoided from unmanaged biomass decomposition, significantly enhances its potential for climate mitigation [189]. Furthermore, biochars are produced as stable, carbon-rich co-products in the thermochemical processes of pyrolysis and gasification and can therefore be used for long-term carbon sequestration, making these processes more environmentally friendly [190]. However, studies of broader lignocellulosic biomass indicate that pathways for biochar production and carbon sequestration can make a substantial contribution toward greenhouse gas reduction and storage in the future. However, there is limited, detailed *Lantana*-specific life-cycle assessment (LCA) data, and additional pilot-scale and techno-economic testing are still needed to better characterize the potential for carbon offsets in *Lantana* biochar systems as they are implemented in practical settings [191]. The natural ability of *Lantana* species to grow on degraded lands under reduced irrigation, fertility, and land-use modification provides additional sustainability benefits compared to dedicated energy crops [28]. As a result, indirect land-use change (ILUC) effects are likely to be much smaller for conventional bioenergy feedstocks [192]. Additionally, habitat and biodiversity restoration during invasive species control may provide ecological co-benefits, including SDG 13 (Climate Action) and SDG 15 (Life on Land) [193].

The environmental and techno-economic potentials of *Lantana*-based biorefineries, however, are highly site-specific, depending on transportation distance, biomass availability, conversion efficiency, and the allocation method used [194]. Because of *Lantana*'s dispersed and localized biomass distribution, logistical and harvesting costs could be higher, potentially reducing the potential for large-scale centralized processing systems [45,46]. Thus, decentralized and regionally integrated conversion models might be more viable and cost-effective for the valorization of invasive biomass [28,29]. Furthermore, no field-scale emissions data are currently available for LCA studies, biomass productivity is uncertain, system boundaries are not standardized across different taxa of the genus *Lantana*, and there is limited data on species-specific conversion factors (Figure 9) for this genus [195].

Bioenergy systems using *Lantana*, however, offer significant potential for environmental benefits; further techno-economic studies, pilot-scale validation, and region-specific life-cycle assessment are necessary to realistically implement them on a large scale in

industry. The consideration of integrated environmental–economic assessment frameworks, catalyst recyclability analysis, decentralized optimization of biomass supply chains, and standardized LCA methodologies is suggested to understand better the long-term sustainability and commercial viability of *Lantana*-based circular biorefinery systems in the future.

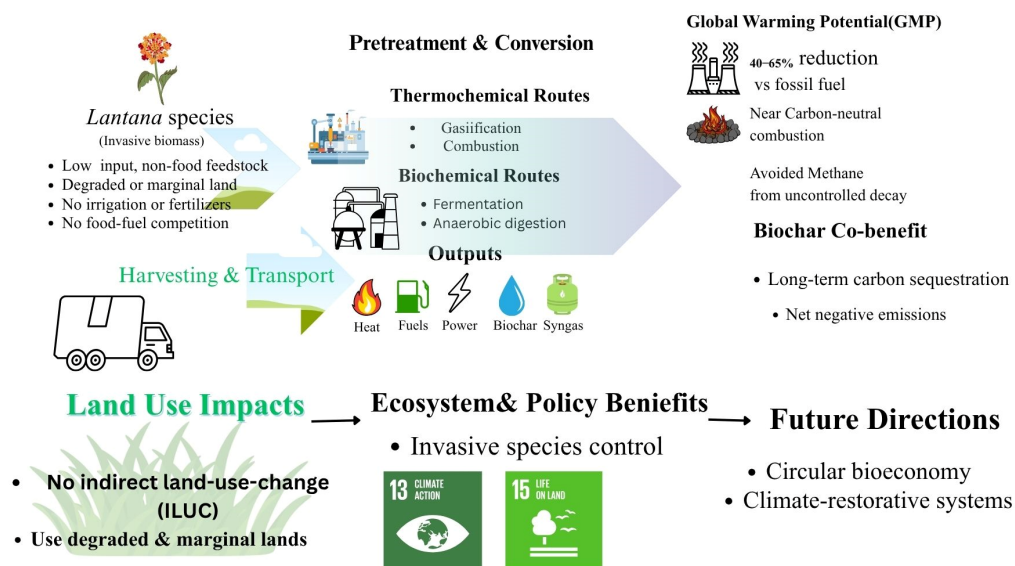


Figure 9. Life Cycle Assessment of *Lantana* species [190,192].

10. Challenges and Bottlenecks

Despite the significant, untapped potential of biomass from *Lantana* species, several technical, economic, and environmental factors hinder the large-scale conversion of *Lantana* species into sustainable bioenergy in an integrated biorefinery system. Adaptability to feedstocks is a major limitation (i.e., extensive variations in the lignin (21–26%), cellulose (35–40%), and hemicellulose (20–25%) composition of various ecotypes and growth conditions interfere with the standardized conversion efficiencies [14]). Also, the biochemical and thermochemical routes are challenged by the recalcitrant lignocellulosic matrix of *Lantana* species, where the highest amount of lignin is present and is further complicated by the presence of secondary metabolites that inhibit the process, such as phenolics and terpenoids, which require energy-intensive pretreatments, hiking the cost and environmental footprint of the processes [194]. The continuous availability of feedstock is also limited by logistical issues, such as the decentralized location of biomass, its high water content, and the lack of instrumented harvesting operations, which only increase the cost of delivered biomass but hamper plant-scale economics [195].

The integrated biorefineries are anchored by continuous feedstock supply, enhanced conversion pathways, and marketable co-products, from a technoeconomic perspective. Nevertheless, systems based on *Lantana* species are susceptible to scale inefficiencies because most existing trials operate at pilot or bench scale and lack strong scaling potential [45]. Addressing invasive biomass is not a favorable policy environment, as there is a lack of infrastructure and policies to promote its use in the industrial sector. Additionally, the initial capital investment (CAPEX) and the low return on investment, compared to traditional bioenergy crops, are high and unlikely to be adopted by the private sector [196]. In addition, insufficient attention is given to how bioenergy produced with *Lantana* species affects the surrounding environment; the life cycle assessment (LCA) of these examples is not thoroughly analyzed [28]. To address those issues, a systems-level approach, including the development of decentralized collection networks, greener pretreatment technologies (such

as ionic liquids or biological delignification), and modular biorefinery designs to transform *Lantana* species into other co-products in the form of biochar, bio-oil, and biopolymers, is called for. Payment for ecosystem services (PES) models should be integrated into policy frameworks to maximize the environmental benefits of *Lantana* removal, thereby making biorefinery systems both economically viable and environmentally sustainable [197].

Finally, to realize the potential of *Lantana* species as bioenergy, future joint innovation is needed across feedstock science, process engineering, supply chain optimization, and sustainability analysis to transform an ecological liability into a renewable bioresource.

11. Conclusions

The utilization of *Lantana* species for biomass in the production of advanced carbon materials and sustainable bioenergy is a promising approach that aligns with the concept of ‘Circular Bioeconomy’ and integrates invasive species management. The wide environmental adaptability and high lignocellulosic content of *Lantana* species provide significant opportunities for thermochemical and biochemical conversion to biofuels, syngas, bio-oil, biohydrogen, and multifunctional biochar-derived materials. But there are still some technological and technical-industrial obstacles to widespread application. The problem of inter-species compositional variability, the low efficiency of pretreatment pathways, catalyst deactivation due to coke deposition and metal agglomeration, lack of pilot-scale validation, high biomass logistics costs, and insufficient techno-economic and life-cycle assessment studies are all major issues.

More efforts should be made to develop stable, recyclable metal- or nanocomposite-engineered biochar catalysts with enhanced redox activity, hierarchical pore structure, and deactivation resistance in future studies. There is also a need for greater focus on the integrated thermochemical–biochemical biorefinery to maximize carbon use while reducing waste. Moreover, artificial intelligence optimization processes, decentralized modular biorefineries, hydrothermal processing, and multifunctional catalytic materials could also enhance conversion efficiency and economic viability. Data collection from in-depth life-cycle assessments, optimization of regional biomass supply chains, and demonstration studies at an industrial scale are also critical for bridging the gap between laboratory scenarios and commercial-scale technologies.

In summary, *Lantana*-based bio-refineries are a sustainable solution to biodiesel, catalytic carbon-based materials, eco-friendly co-products, and other renewable fuel products from invasive plantain biomass. A catalytic reaction engineering initiative that leverages nanocomposite biochar design and circular bioeconomic pathways may truly make the *Lantana* species a model fuel stock for future low-carbon biorefinery applications.

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