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Review Article

Medicinal Plant Waste as a Sustainable Feedstock for Bioenergy and Climate Change Mitigation

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Abstract
The development of the herbal medicine and pharmaceutical sectors has generated increasing amounts of medicinal plant waste (MPW), much of which remains underutilized or is disposed of through unsustainable practices such as open burning and landfilling. MPW contains substantial amounts of lignocellulosic biomass, positioning it as a promising feedstock for renewable energy production and climate change mitigation. This review synthesizes information on the physicochemical properties of MPW and focuses on thermochemical conversion routes, including torrefaction, pyrolysis, gasification, and hydrothermal carbonization. Studies indicate that thermochemical conversion can yield 30–55 wt% bio-oil and 20–35 wt% biochar, while achieving cold gas efficiencies of 55–70%. Hydrothermal treatment can produce hydrochar with carbon contents of 55–65% and higher heating values of 18–23 MJ kg^{-1}. Furthermore, MPW-derived biochar can contribute to carbon sequestration of approximately 2–3 t CO_2-eq per tonne of dry feedstock while enhancing soil water retention and nutrient availability. However, the large-scale valorization of MPW faces several challenges, including feedstock variability, technical constraints, environmental risks, and policy gaps. Recent advances in catalyst design and life cycle assessment provide opportunities to overcome these barriers and improve the sustainability and efficiency of MPW valorization. Overall, the valorization of MPW supports the transition toward a circular bioeconomy, renewable energy, and climate action, thereby contributing directly to Sustainable Development Goal 7 (Affordable and Clean Energy) and Sustainable Development Goal 13 (Climate Action).

Keywords: Bioenergy, Biomass valorization, Circular bioeconomy, Climate mitigation, Medicinal plant waste, Thermochemical conversion

1 Introduction

There is a growing dependence on herbal medicines, nutraceuticals, and plant-based pharmaceuticals globally in recent decades, primarily due to their preference by consumers as natural medicines and the increasing use of traditional medicine in formal health care. This development has generated large quantities of cultivation, harvesting, processing, and solvent extraction of medicinal plant waste (MPW). For example, China generates approximately 60–70 million tonnes of Chinese medicinal herb residues annually [1], [2]. The by-products, leaves, stems, roots, bark, and post-extraction biomass are simply burned or landfilled too frequently, which causes local air pollution and wastes a potentially valuable resource [3], [4]. Surveys centered on the remnants of traditional Chinese medicine, such as reports on the magnitude of the issue and diversity of the emergent utilization possibilities, highlight the necessity of managed valorization pathways [3].

MPW is lignocellulosic in nature, containing cellulose (30 – 50%), hemicellulose (15 – 30%), and lignin (10 – 25%), and it also contains bioactive compounds such as phenolics, alkaloids, and terpenoids that affect the conversion performance [5], [6]. This duality generates its own problems and opportunities: the inhibitory metabolites can be used to suppress microbial digestion, but energy-rich polymers are quite compatible with thermochemical processes, which generate fuels and carbonaceous solids [5], [6]. Increased heating values of similar residues are generally between 14 and 20 MJ/kg, which contributes to using them as solid biofuels or as inputs to liquid and gaseous energy carriers [7]-[9].

Asia leads in medicinal and aromatic plant processing, with China and India being the main contributors geographically. The existing literature on the residues of herbal processing in both nations proves that large amounts of biomass are underutilized and, at the same time, they are in the proximity of industrial hubs, thus making it ideal to deploy decentralized conversion systems [5], [10]. Recent experimental research in India, among others, has shown that the medicinal processing waste of plant wastes can be converted to biogas to produce electricity [10].

The importance of MPW in its valorization is also consistent with the circular bioeconomy and global sustainability concerns. Because of its lignocellulosic makeup and leftover bioactive compounds, MPW is an excellent candidate for thermochemical conversion methods like pyrolysis, gasification and hydrothermal carbonization. These techniques turn MPW into useful products such as bio-oil, syngas, and solid carbon materials like biochar or hydrochar. Of these, biochar has stood out for its versatile environmental perks. When mixed into soil, it boosts fertility, helps retain nutrients, and locks away carbon for the long haul through stable sequestration [11]. Given these benefits, current research increasingly views biochar as a viable negative emission technology, underscoring its role in fighting climate change and supporting sustainable carbon management [12], [13].

This review thus explores the nature of MPW and its supply, surveys conversion pathways with thermochemical routes being of primary interest and provides insights on the environmental and economic impact, aiming at arriving at the technical and policy-level actions required to responsibly scale the valorization of MPW. To complement this qualitative review, a bibliometric analysis was conducted to capture the evolution of this field, revealing emerging research themes, keyword trends, and the geographic distribution of scientific output.

2 Bibliometric Analysis

To map out how research on medicinal plant biomass and its role in renewable energy has evolved, we performed a bibliometric analysis focused on three main goals. First, we tracked publication trends to see how the field has grown over the years. Second, we identified the core research themes and pinpointed emerging topics that are starting to gain traction. Finally, we looked at the broader landscape of the work—examining who is writing the papers, which regions are most active, where the funding is coming from, and which specific research areas are leading the way.

This study conducts a bibliometric analysis using Scopus data. The dataset was exported in CSV format and analyzed using VOSviewer software version 1.6.0, with a focus on keyword co-occurrence analysis to identify emerging research themes and methodological trends [14]. In the VOSviewer map, nodes signify analytical objectives. The larger a node, the greater its significance. The nodes with high occurrence frequencies were positioned in the middle [15]. The keyword co-occurrence analysis was conducted with at least five iterations to examine these links. Furthermore, any word that failed to offer information regarding the topic, such as "Review" or "priority journal" was eliminated. Consequently, the quantity of nodes was diminished without compromising the results relevance.

The keywords "medicinal plant", "energy" and "renewable energy" were merged in Scopus data to capture both direct and interdisciplinary studies at the interface of medicinal biomass utilization for renewable energy production and the analysis was conducted using the "article title, abstract, keywords" option. Additional keywords related to waste and residues were tested; however, their limited occurrence reflects the emerging nature of this research domain rather than methodological exclusion. Data were gathered between 2000 and 2025. Only whole years were taken into consideration; documents released in 2026 were not included. A total of 121 papers were examined. This supplied enough data for the bibliometric study, including financing, areas of expertise, authorship, and the geographic distribution of publications. Scopus was selected as the primary database due to its broader multidisciplinary coverage compared to WoS and its structured, exportable metadata, which ensures compatibility with bibliometric software such as VOSviewer [16]. Google Scholar was not used, as it lacks systematic peer-review filtering and reliable export functions, and often contains duplicate or inconsistent records. Combining Scopus with WoS was also considered but was not pursued, as it would introduce substantial duplication requiring manual deduplication without significantly improving thematic coverage for this specific research niche.

2.1 *Publication trend analysis*

The bibliometric screening of Scopus-indexed publications was presented using the keywords "medicinal plant", "energy", and "renewable energy". The annual distribution of documents on the topic of "medicinal plant waste for bioenergy and climate mitigation" reveals an unstable increase in research interest over time (Figure 1). From 2006 to 2012, the number of publications remained very low, never exceeding five per year. A gradual increase is observed from 2013 onwards, with notable peaks in 2020 and subsequent years. The data indicate a sharp surge in research output in 2025, reaching 20 documents, which highlights the maturation and consolidation of research on medicinal plant waste as a valuable resource for sustainable energy solutions.

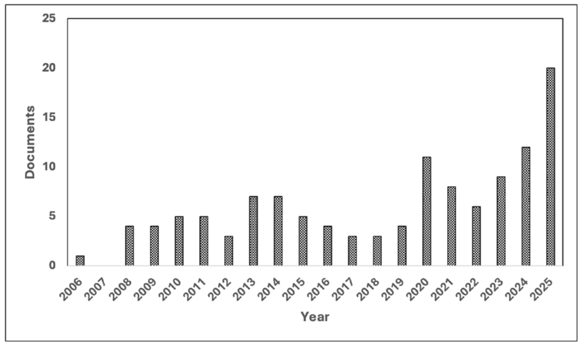

Figure 1: Yearly distribution of documents on medicinal plant waste for bioenergy generation during 2006-2025.

Based on the document type shown in Figure 2, journal articles constitute the largest group with 54 documents. A significant number of reviews (29) and book chapters (16) illustrate the integration of knowledge and synthesis of advancements in medicinal plant feedstock, processes, etc. The conference papers (13) reveal that the authors are involved with the scientific community and are sharing new findings.

The subject area distribution in Figure 3 shows that most of the research on this topic is concentrated in environmental science, agricultural and biological science, energy, and engineering. This trend confirms that the majority of research carried out aims to promote the use of medicinal plant waste as a sustainable feedstock for the production of different types of bioenergy. As an example of a document published in an environmental science journal, consider the research article by Nayak *et al.,* [10]. In this paper, the authors examine the use of medical plant wastes from *Carica papaya, Azadirachta indica,* and *Ocimum tenuiflorum* along with *Justicia adhatora*, for energy generation using

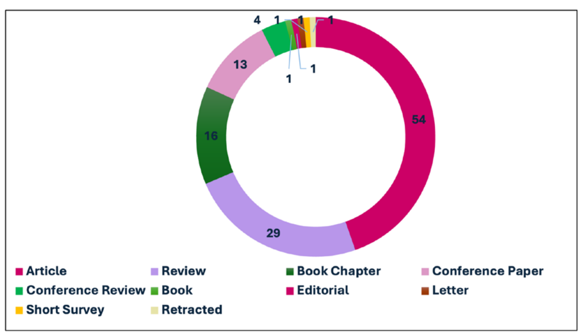

Figure 2: Distribution of the analyzed data according to the document type.

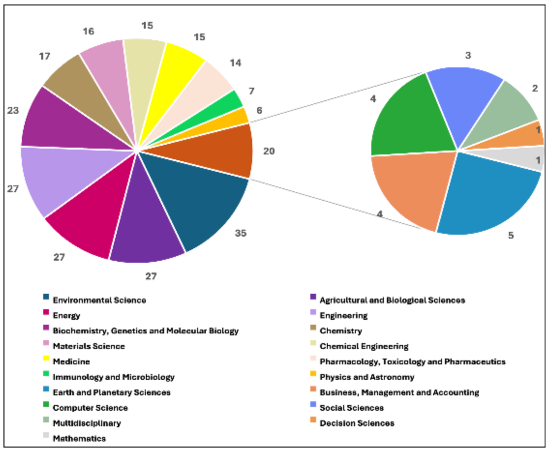

Figure 3: Distribution of the analyzed data in terms of subject area; numbers reflect the total publications for each subject area.

biomethanation. The maximum methane yields for *Carica papaya* and *Azadirachta indica* were 7130 mL and 7850 mL, respectively. Notably, *Azadirachta indica* exhibits an average methane content of 74%, which is the principal factor contributing to enhanced biogas production. Biogas production was monitored using a flow meter over a period of 90 days, yielding an average output of around 560.37 m^3/day. Subsequently, the chemical fraction of energy was transformed into mechanical energy within a regulated combustion system via a heat engine, which was then used to generate electrical power.

In terms of territory contribution, Figure 4 repres ents India as the first contributor in this research topic with 42 publications. China reveals an important engagement with 11 papers, followed by the United States with 10 publications. However, important contributions were observed in Egypt (8), Saudi Arabia (6), and the United Kingdom (6), which reflect a focus on valorization of medicinal plant waste and renewable energy.

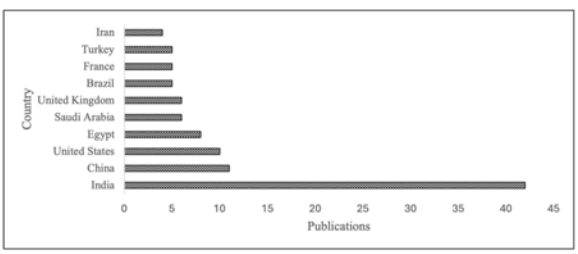

Figure 4: Countries' contribution to bioenergy production from medicinal plant research worldwide.

2.2 *Keywords analysis*

The keyword co-occurrence network shown in Figure 5 gives a clear observation of research trends. The examination of keywords shows that "medicinal plant" and "renewable energy" are the most important research areas. "medicinal plant" (occurrence = 26) and "renewable energy" (occurrence = 28) are the most important and central keywords in the research landscape. The map reveals five interconnected clusters representing key research themes in medicinal biomass utilization for renewable energy production and climate mitigation.

Cluster 1 (red) groups keywords such as biomass, biofuel, fermentation, lignin, and lignocellulose, highlighting the conversion of plant-based and medicinal residues into bioenergy. Cluster 2 (green) centers on renewable energy, biodiesel, phytoremediation, and energy resources and "greenhouse gas," emphasizing the role of medicinal plants as sustainable energy sources and climate mitigation. Cluster 3 (blue) assembles terms related to biodegradation, bioremediation, renewable resources, and sustainability, reflecting biological processes that support the valorization of waste. Cluster 4 (yellow) focuses on plant extracts, chemistry, green synthesis, and catalysis, illustrating eco-friendly conversion pathways and the valorization of bioactive compounds. Finally, Cluster 5 (purple) connects themes such as medicinal plants, plants (botany), agriculture, and biotechnology, highlighting the biological and agronomic foundation that links medicinal biomass production to energy and environmental applications. Indeed, the bibliometric analysis reveals a deficiency of documents on this

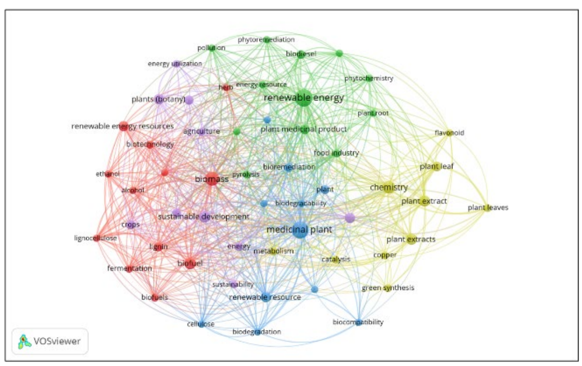

Figure 5: VOSviewer map of keyword co-occurrence based on the study's keywords, showing five thematic clusters (colors correspond to clusters discussed in Section 2.2).

topic, indicating that research in this field is still in its early stages. Medicinal plant waste can serve as a sustainable feedstock for bioenergy generation. However, further research is needed to address key challenges associated with its large-scale application, process efficiency, and overall sustainability.

3 Characteristics and Availability of Medicinal Plant Waste

Medicinal plant waste (MPW) has turned out to be an underutilised but important biomass to consider in the framework of renewable energy and circular bioeconomy. With the recent growth of herbal medicine industries worldwide, a large volume of biomass is produced as a by-product in the cultivation, harvesting, post-harvest management, and the extraction of bioactive compounds through industries. Uncontrolled emissions of these residues also contribute to greenhouse gas (GHG) emissions by burning them openly or undergoing uncontrolled decomposition. Nevertheless, they are promising physicochemical feedstocks in the conversion to bioenergy.

3.1 *Physicochemical composition*

MPW is mostly lignocellulosic, composed of cellulose (30 – 50%), hemicellulose (15 – 30%), and lignin (10 – 25%) [5], [6]. Polysaccharides that can be hydrolyzed to fermentable sugars include cellulose and hemicellulose, and lignin is responsible for high energy density but is not degradable by microbes. Secondary metabolites like polyphenols, alkaloids, flavonoids, terpenoids and saponins are also found in the residual fraction. These chemicals affect bioenergy conversion processes. Polyphenols could be used as fermentation inhibitors, whereas some terpenes could increase the activity of microorganisms under simulated conditions [15].

MPW has a higher heating value (HHV) of 14 – 20 MJ/kg, which is equivalent to the conventional agricultural residues such as rice straw (17 – 20 MJ/kg) and sugarcane bagasse (17 – 20 MJ/kg) [18-20]. This calorific potential indicates high levels of suitability for thermochemical conversion, like pyrolysis and gasification. Nevertheless, differences between species and nutrient conditions warrant standardisation of characterisation for use in industrial applications**.** In addition to heating value, the composition of MPW, particularly its cellulose, hemicellulose, lignin, and ash content, plays an important role in determining its behaviour during thermochemical conversion. Biomass with higher cellulose and hemicellulose contents generally promotes volatile release and bio-oil formation during pyrolysis, while higher lignin content contributes to increased biochar yield due to its thermally stable structure. The typical physicochemical composition of medicinal plant waste compared with selected agricultural residues is summarized in Table 1.

3.2 *Variability across species and processes*

MPW does not have a homogeneous structure but depends on plant species, mode of cultivation, time of harvest and processing [8]. As an example, *Curcuma longa* (turmeric) residues have a high starch and polyphenolic content when compared to *Azadirachta indica* (neem), which has high triterpenoid and limonoid content. The residues of herbal extraction are usually incomplete in the removal of the target metabolites yet might have an inhibitory compound that makes downstream fermentation complex [21].

Table 1: Typical physicochemical composition of medicinal plant waste compared with selected agricultural residues.

Biomass type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	HHV (MJ/kg)	Key secondary metabolites	Reference
Medicinal plant waste (general)	30 – 50	15 – 30	10 – 25	14 – 20	Polyphenols, alkaloids, terpenes	[3], [4]
Rice straw	32 – 47	19 – 27	5 – 24	15 – 18	Silica, phenolics	[10]
Sugarcane bagasse	32 – 44	19 – 24	25 – 32	17 – 20	Waxes, tannins	[17]
Herbal extraction residues (e.g., neem, papaya)	28 – 46	16 – 29	12 – 26	15 – 19	Flavonoids, terpenoids	[18]

There are also environmental factors that have an effect on the quality of biomass, including the type of soil, irrigation methods, and climate. It has been demonstrated that MPW gathered in dry areas tends to contain more lignin, which decreases digestibility but improves thermal resistance in the process of pyrolysis [22], [23]. Composition also changes during extraction: solvent-based extraction can potentially be left with inhibitory residues, whereas extraction using supercritical CO_2 retains lignocellulosic integrity [5]. The major constituents of MPW and their effects on biochemical and thermochemical conversion technologies are summarized in Table 2, highlighting how feedstock composition influences the selection of an appropriate valorization pathway [24].

3.3 *Global availability*

Asia is the most important region in terms of medicinal plant production, as India and China lead in commercial production. A total of 1,178 medicinal plant species are recorded in trade in India, of which 242 species are traded in quantities exceeding 100 metric tonnes per year, while the annual demand for medicinal plants was estimated at approximately 512,000 metric tonnes in 2014 – 2015 [36]. The large traditional medicine industry in China also generates substantial amounts of herbal by-products, with approximately 60 – 70 million tonnes of Chinese medicine residues reportedly discharged annually [1]. Africa and Latin America are some other areas that make significant contributions to traditional medicine,

Table 2: Effects of major medicinal plant waste constituents on conversion technology selection.

Major constituent or compound group	Effect on conversion processes	Implication for technology selection	References
Cellulose and hemicellulose	These polysaccharides can be hydrolysed into fermentable sugars, although pretreatment is generally required to improve their accessibility to enzymes and microorganisms. Hemicellulose is readily degraded during torrefaction, while both components contribute to volatile and bio-oil formation during pyrolysis.	Suitable for fermentation or anaerobic digestion following appropriate pretreatment, as well as for torrefaction and pyrolysis.	[5], [25], [26], [27], [28], [29]
Lignin	Lignin is resistant to microbial degradation and reduces the biodegradability of lignocellulosic MPW. Its thermally stable and energy-rich structure contributes to fixed-carbon and char formation.	Lignin-rich MPW is generally more suitable for pyrolysis or gasification unless effective delignification or pretreatment is applied before biochemical conversion.	[17], [19], [28], [29]
Phenolic compounds, including flavonoids and tannins	Phenolic compounds released or retained during processing and pretreatment may inhibit fermentative microorganisms and reduce biochemical conversion efficiency. During pyrolysis, residual organic compounds may also contribute to the formation of aromatic derivatives in the resulting products.	Detoxification, dilution, microbial adaptation, or co-digestion may be required before biochemical conversion. Thermochemical conversion may be considered when inhibitory concentrations are high, although product upgrading may be necessary.	[25], [27], [30], [31]
Terpenoids and residual essential-oil compounds	Monoterpenes can inhibit anaerobic digestion depending on their identity and concentration. Nevertheless, residues remaining after essential-oil extraction have been successfully processed through anaerobic digestion and gasification.	Residual essential-oil content should be characterized before technology selection. Anaerobic digestion may be applied when inhibitory compounds are sufficiently removed or controlled, whereas thermochemical conversion may be preferable for residues with high residual volatile-compound contents.	[22], [32], [33]
Alkaloids, saponins, and other secondary metabolites	These compounds may remain in MPW after extraction, but their individual and concentration-dependent effects on MPW conversion have not been sufficiently quantified.	Feedstock-specific screening is required before selecting biochemical conversion. Strong claims concerning their inhibitory or beneficial effects should be avoided unless supported by experimental data.	[3], [24]
Ash and mineral constituents, including potassium, chlorine, silica, and sulfur	High mineral content can contribute to slagging, fouling, agglomeration, corrosion, and other operational problems during high-temperature conversion.	High-ash MPW may require washing, demineralization, blending, additives, or ash-tolerant reactor configurations before thermochemical conversion.	[34], [35]

although quantitative information on waste production is still scattered [24].

Herbal industries are rapidly expanding, implying an increasing trend in the availability of MPW. This is, however, impaired by poor reporting systems and the absence of integrated biomass databases, thus hampering accurate quantification. The available quantitative data by country or region are summarised in Table 3. Because several reported values represent medicinal plant demand or trade rather than direct waste generation, they should be interpreted as indicators of potential MPW availability.

3.4 *Energy and environmental potential*

The biochemical composition and calorific value of MPW render the energy feedstock a renewable source of energy that can be converted in various conversion directions. Experiments on anaerobic digestion of neem and papaya residues claimed that the output of methane was more than 60%, and the payback period is less than ten years [10]. Herbal extraction residues have produced biochar containing over 70% carbon after pyrolysis, and are capable of producing energy and long-term storage of carbon [37].

The use of MPW also reduces environmental risks caused by poor disposal. As an example, the uncontrolled degradation of residues containing polyphenols and other substances emits methane and nitrous oxide, both of which are strong greenhouse gases [12], [38]. By channeling such wastes into regulated bioenergy systems, the emissions are minimized, and by-products like biofertilisers are produced.

3.5 *Integration into circular bioeconomy*

Circular economy principles are very consistent with the valorisation of MPW. Other secondary products that the residues can provide include bioplastics, natural pesticides, and activated carbon, in addition to energy. Integration of MPW valorisation and herbal processing centres would create decentralised bioenergy in the rural population, encouraging access to energy, as well as diversification of livelihoods [39]. This conceptualised solution is considered particularly crucial in meeting SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). The conceptual flow of medicinal plant waste (MPW) generation and its valorisation pathways within a circular bioeconomy framework is illustrated in Figure 6.

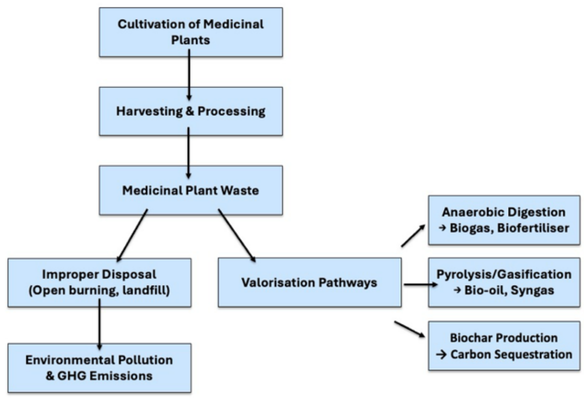

Figure 6: Conceptual flow of medicinal plant waste (MPW) generation and valorisation pathways.

Table 3: Reported quantitative indicators and data gaps relevant to medicinal plant waste availability by country or region.

Region	Reported quantitative information	Data category	Relevance to MPW availability	Reference
India	1,178 medicinal plant species recorded in trade; 242 species traded at quantities exceeding 100 metric tonnes/year; approximately 512,000 metric tonnes of annual demand in 2014–2015	National trade and demand	Proxy indicator of potential residues generated during medicinal plant processing	[36]
China	Approximately 60–70 million tonnes of Chinese medicine residues discharged annually	Direct residue-generation estimate	Indicates substantial national availability of MPW	[1]
Africa and Latin America	No consolidated regional quantitative estimate of MPW generation was identified	Regional data gap	Medicinal plants contribute substantially to traditional medicine, but waste-generation information remains limited and scattered	[24]

MPW occurs in the harvesting and processing of medicinal plants. When not disposed of properly (e.g., by open burning or landfilling), MPW causes environmental pollution and greenhouse gas emissions [3], [4]. Alternatively, the anaerobic digestion, pyrolysis, and gasification valorization routes can be used to convert MPW into renewable carriers of energy (biogas, bio-oil, and syngas) and co-products (biofertiliser and biochar) [3], [4]. Biochar also offers long-term potential in carbon sequestration, which fits the MPW utilisation with the circular bioeconomy and mitigation of climate change.

4 Biochemical Conversion of Medicinal Plant Waste (MPW)

Medicinal Plant Waste (MPW), such as herbal extraction residues, processing residues, and unused herbal parts make up a huge biomass waste product from the pharmaceutical, herbal medicine, and essential oil industries [40], [41]. Normally, these wastes contain high levels of biodegradable organic materials such as cellulose, hemicellulose, proteins, and secondary metabolites; thus, they can be easily degraded and converted biochemically. The rise in herbal extraction residues has pushed the research into biochemical routes that can be used to obtain energy while at the same time reducing the pollution caused by the disposal of these wastes [42]. A summary of the main biochemical conversion pathways utilized for medicinal plant waste and their corresponding results as reported in the literature.

4.1 *Anaerobic digestion and biomethanation*

Anaerobic digestion is one of the most widely used biochemical processes for the valorization of MPWs, as this process can convert complex organic materials into biogas under oxygen-free conditions [43], [44]. The wastes of medicinal plants have exhibited good anaerobic biodegradability, thus producing stable biogas through the appropriate operational conditions of anaerobic digestion processes. The waste of herbal and medicinal plant materials has also shown good biogas production capacity, which is rich in methane and can be used to produce electricity through the anaerobic digestion process [10].

The application of biomethanation technology in the processing of waste matter of medicinal plants may also serve as a means of mitigating the effects of greenhouse gases, considering that the wastes are converted into a usable gas [45]. The enrichment of methane gas can also be achieved through the process of upgrading biogas, which makes it even more appropriate for use as a source of energy [10]. This also validates anaerobic digestion as a key biochemical process in processing MPW.

Co-anaerobic digestion is another method that can be employed as a means of improving the efficiency of anaerobic digestion, especially when MPW is employed as a substrate [46]. The employment of a combination of plant herbs and sawdust or animal manure serves as a means of improving the nutrient balance during anaerobic digestion. The employment of a combination of plant herbs and animal manure serves as a means of diluting some of the inhibitory substances present in some of the employed medicinal plants [47]. The relationship between medicinal plant waste characteristics and the selection of appropriate biochemical conversion routes is schematically illustrated in Figure 7.

4.2 *Pretreatment and fermentation-based conversion*

The biochemical conversion efficiency of MPW is significantly affected by the lignocellulosic composition of the material, particularly those residues obtained from extraction procedures. The pretreatment of the waste is critical to break the cell wall structure of the rigid plant material, making it accessible to the hydrolyzing microorganisms or enzymes [48], [49]. Various pretreatment procedures, such as chemical, physical, and enzymatic treatment, were tested on a mixture of forestry waste and aromatic-medicinal plant waste, showing improved hydrolysis efficiency compared to untreated wastes [25].

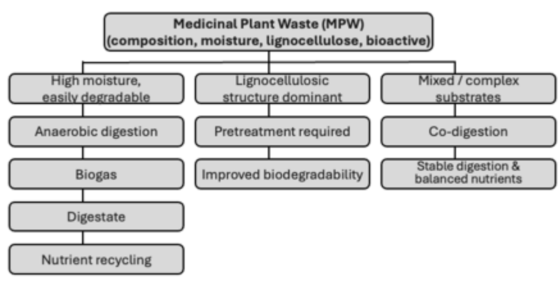

Figure 7: Conceptual framework linking medicinal plant waste characteristics to anaerobic digestion–based biochemical conversion routes.

Hydrothermal pretreatment has also been cited as an effective method for improving the biodegradability of herbal extraction residues before anaerobic digestion. This method increases the yield of biogas because it increases the organic materials for anaerobic microbes [26]. This demonstrates the significance of pretreatment in optimizing biochemical conversion for MPW.

Fermentation-based routes also offer opportunities for valorization of MPW for other purposes, other than biogas production. The lignocellulose fraction of residues from medicinal and aromatic plants can be hydrolyzed and converted to bioethanol by appropriate microbial systems [50]. The efficiency of bioethanol production is affected by pretreatment and selection of appropriate microorganisms, as seen by the efficiency of fungal and bacterial strains for bioethanol production [27].

4.3 *Integrated biological valorization and by-product recovery*

The biochemical change of MPW also provides the possibility for the development of value-added products through the use of biotransformation methods [51]. For instance, the use of the process of solid-state fermentation on the residues of Chinese herbal medicinal substances has been found to influence the antioxidant and antimicrobial activities through biochemical transformations, particularly phenolic compounds [52]. This demonstrates the possibility of MPW being converted to useful materials, in addition to the possibility of its conversion to energy products [51].

The residues obtained after the digestion process must be managed to ensure the maximum possible recovery. The digestate is rich in stabilized organic matter and plant nutrient resources, which can be recovered by the process of composting or separation of the liquid and solid fractions of the digestate [47]. The processes of anaerobic digestion and composting are successful in the recovery of plant nutrients and energy, resulting in the production of compost of suitable quality [53].

Herbal residues have also been considered as supplements in anaerobic fermentation processes associated with animal feed and silage. The use of herbal residues in silage fermentation influences the process of fermentation and the composition of microbial populations [54]. Some herbal supplements have been linked to lower methane and carbon dioxide production in in vitro ruminal fermentation processes, indicating the possible use of MPW in the reduction of greenhouse gases in livestock production systems [55]. Differences in fermentation products and microbial populations further support the biochemical function of herbal residues in anaerobic conditions.

At a broader level, the importance of biochemical conversion in the valorization of medicinal and herbal residues into useful products has been highlighted through integrated valorization frameworks. Similar approaches have been highlighted for the valorization of herbal and biomedical residues through green biochemical pathways for the reduction and valorization of herbal and biomedical wastes [1]. The biochemical valorization of organic biomedical wastes also shows the scope and applicability of biochemical approaches for the production of value-added products from biomedical wastes [55]. In addition, the biochemical valorization of specific herbal residues, such as tobacco, shows the dual scope and application of herbal residues for bioenergy and bioactive compound production [56].

Generally speaking, biochemical conversion routes possess considerable potential for the sustainable valorization of medicinal plant waste in terms of energy production, functional products, and nutrient reuse [42]. The combination of anaerobic digestion, fermentation, pretreatment, and various biological treatments provides the basis for the valorization of MPW from an environmental problem into a resource in the context of circular economy approaches [40]. The main biochemical conversion pathways applied to medicinal plant waste, along with their process characteristics and reported outcomes, are summarized in Table 4.

Properties of medicinal plant waste vary based on the type and processing history of the waste. Biodegradable medicinal plant waste can be anaerobically digested directly, while lignocellulosic material is better pretreated to make it more biodegradable. Anaerobic digestion of mixed or complex medicinal plant waste can be optimized by co-anaerobic digestion. Digestate from anaerobic digestion of medicinal plant waste can be recycled.

5 Thermochemical Conversion of Medicinal Plant Waste

5.1 *Conversion route*

Thermochemical conversion is a group of technologies that utilize heat, pressure, and controlled atmospheres to convert biomass to energy carriers,

Table 4: Main biochemical conversion routes applied to medicinal plant waste.

Medicinal plant residue	Biochemical conversion route	Process characteristics	Main product	Reported main-product yield	Reference
Ashwagandha (*Withania somnifera*), Yavani (*Trachyspermum ammi*), Draksha (*Vitis vinifera*), and Amla (*Phyllanthus emblica*) processing residues	Anaerobic digestion	Batch digestion at 35 °C and a food-to-inoculum ratio of 0.75	Biomethane	Biomethane potential of 0.55–0.90 g CH_4-COD/g CODfed; the highest value of 0.90 g CH_4-COD/g CODfed was obtained from *W. somnifera* residue	[43]
Papaya (*Carica papaya*) and neem (*Azadirachta indica*) processing residues	Biomethanation	Anaerobic digestion over a 60-day retention period	Biogas and methane	*C. papaya*: 11,320 mL biogas and 7,130 mL methane; *A. indica*: 10,610 mL biogas and 7,850 mL methane	[10]
Ginkgo biloba urban pruning waste	Pyrolysis	Charcoal	Biogas and methane	27.33–32.05%	[57]
Amla (*Phyllanthus emblica*) processing residue co-digested with food waste	Anaerobic co-digestion	Food waste-to-amla residue ratio of 11:1 based on total COD; hydraulic retention time of 30 days	Methane	Methane production was 22% greater than the combined methane production from the corresponding single-substrate digesters	[46]

chemical precursors, and carbonaceous solids. Specifically, these methods include torrefaction, pyrolysis, gasification, as well as hydrothermal carbonisation (HTC), which are of interest for medicinal plant waste (MPW), which, in most cases, is lignocellulosic but has a residual amount of phytochemicals and mineral material left as a result of herbal extraction. Traditional methods of MPW disposal, such as open burning or landfilling, not only lead to the emission of greenhouse gases but also waste the resource with high energetic potential [7]. In comparison with biochemical routes, thermochemical approaches are not as sensitive to the inhibitory impact of phenolics, alkaloids, and terpenoids, which makes them more resilient to heterogeneous feedstocks. Moreover, these reactions can be designed to yield a portfolio of products: syngas to combined heat and energy, bio-oil to be further converted to liquid fuels and biochar or hydrochar that can be used to improve the soil and reduce carbon emissions [58], [57]. Recent studies have further emphasized the role of biomass-derived biochar as a stable carbon sink in soils, highlighting its long-term climate mitigation potential [57]. The adoption of thermochemical units within medicinal plant processing centres can result in the formation of a decentralised and circular bioeconomy where waste is recycled into energy and agricultural inputs. Recent progress in catalytic systems and reactor design, along with intensification of the process, keeps broadening the ability to use thermochemical conversion to a wide range of waste materials, including MPW [19]. Therefore, the roles and the potential of the four key thermochemical paths in MPW valorisation are discussed in this section, including their mechanisms, products, environmental impact, and prospects. An overview of the principal thermochemical conversion pathways applicable to medicinal plant waste and their corresponding energy products is presented in Figure 8.

Depending on the operating conditions, MPW can be converted through torrefaction, pyrolysis, gasification, or hydrothermal carbonisation, producing various types of energy carriers (torrefied biomass, bio-oil, syngas, hydrochar) with uses in fuel production, generation of power, and carbon storage.

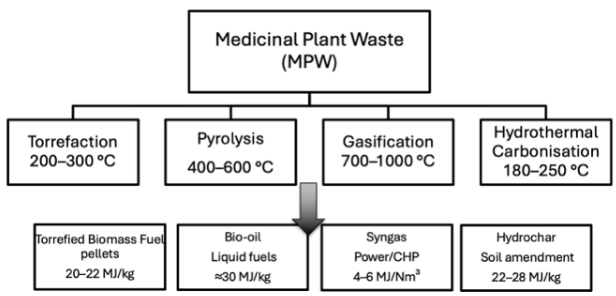

Figure 8: Overview of thermochemical conversion pathways for medicinal plant waste (MPW).

5.2 *Torrefaction*

Torrefaction is a gentle thermochemical process at 200 – 300°C in either inert or oxygen-limited conditions with emphasis on the reduction of biomass to stable solid fuel. Hemicellulose degrades preferentially by this process while cellulose and lignin are mostly maintained, and hence a lower moisture content, a high fixed carbon content and improved fuel characteristics are obtained during this process. In medicinal plant waste (MPW), torrefaction increases hydrophobicity, grindability and storage stability, which are necessary for the production of residue from dispersed herbal processing. Based on the temperature and residence time, solid mass yields can range from 70 – 90% with HHV increasing to ~20 – 22 MJ/kg [7], [28]. The partial removal of volatile components also improves combustion behavior and energy density. Torrefied MPW may form pellets for co-firing purposes or may be used as pretreated feedstock to facilitate gasification or pyrolysis that might improve devolatilization properties. Nevertheless, feedstock heterogeneity, in ash content and residual phytochemicals in particular, might result in different mass loss profiles and energy densification efficiency. More optimization, suited for particular MPW streams, is necessary. On the whole, torrefaction provides a fairly uncomplicated and light-weight upgrading technique for residues of medicinal plants, thereby enabling their incorporation into decentralised bioenergy systems.

5.3 *Pyrolysis*

Pyrolysis is the process of heating biomass with no oxygen and normally at temperatures of 400 – 600°C to form bio-oil, syngas, and biochar. In the case of MPW, pyrolysis is specifically important due to the high lignin and bioactive content, which determines the composition of the products. A catalytic pyrolysis of herbal medicine waste was performed by Lee *et al.,* [30] with Pt/activated carbon catalysts, where it was observed that the formation of harmful benzyl derivatives was inhibited at 500°C, generating cleaner bio-oil. In a similar study, Paudel [57] established that medicinal and ornamental plant residues pyrolyzed produced biochar, which contained stable carbon structures that could be used as carbon storage in soils. General biomass pyrolysis studies report typical yields of 35 – 55% bio-oil and 20 – 30% biochar, with oil heating values around 30 MJ/kg [7]. However, MPW-derived oils remain highly oxygenated and require upgrading through catalytic cracking or hydrodeoxygenation to be used as transport fuels [59]. The biochar fraction, conversely, has shown strong potential as a soil amendment that can immobilise heavy metals and improve soil fertility, offering co-benefits for agricultural sustainability [12].

5.4 *Gasification*

Gasification is a high-temperature process (700 – 1,000°C) under limited oxygen or steam that converts biomass into syngas, a mixture of CO, H_2, CO_2, and CH_4. For MPW, gasification offers the advantage of tolerating lignin-rich and structurally complex residues that are otherwise challenging to ferment. Typical syngas yields are reported as 2 – 3 Nm^3/kg biomass, with heating values of 4 – 6 MJ/Nm^3, depending on the oxidising medium [7]. As Demirbas [19] emphasized, catalytic gasification with dolomite, olivine, or nickel-based catalysts can greatly decrease tar formation, which is one of the major barriers to a stable quality of syngas. Though the data on the specifics of MPW are scarce, its mineral-enriched ash presents problems of slagging and fouling, which require either the use of pretreatment or catalyst selection strategies. The possible uses of the MPW-derived syngas are either direct usage in combined heat and power (CHP) systems, or improvement through Fischer–Tropsch synthesis into more advanced liquid biofuels that fit the needs of the aviation sector. Gasification, therefore, is a technologically advanced route that has high potential in the valorisation of medicinal residues to produce high-value energy carriers.

5.5 *Hydrothermal carbonisation (HTC)*

Hydrothermal carbonisation (HTC) has become a particularly competitive approach to wet feeds like MPW, which usually retain moisture in their state following extraction. HTC transforms biomass into a carbon-rich hydrochar and an aqueous phase of soluble organics, conducted at 180 – 250°C in pressurised water. John and Omorogie [60] reviewed the mechanisms of HTC and highlighted its capacity to generate hydrochar yields of 55–70%, with calorific values of 22 – 28 MJ/kg. Sivaranjanee *et al.,* [61] further noted that HTC can achieve yields up to 94% under optimised conditions, while also producing a liquid fraction that can be coupled with anaerobic digestion to recover methane. Liu and Zhang [62] demonstrated that HTC provides a circular economy opportunity by producing hydrochar for soil application while simultaneously recovering energy from high-moisture biomass streams. For MPW, which is often discarded in slurry form near processing hubs, HTC avoids costly drying and transforms residues into a storable, transportable, and carbon-rich solid. This positions HTC as one of the most promising routes for decentralised, low-emission valorisation of herbal residues. Typical operating conditions, product yields, and energy values associated with thermochemical conversion processes are summarized in Table 5.

5.6 *Emissions control, energy balance, and integration*

Although thermochemical conversion offers high energy yields, it also generates emissions that must be carefully managed. Nitrogenous compounds in MPW can lead to NO_x formation, while residual minerals such as sulfur contribute to SO_x, and incomplete combustion can release VOCs and particulates. Osman *et al.,* [12] conducted a life-cycle assessment of biochar systems and emphasised that emissions control technologies, including catalytic oxidisers, wet scrubbers, and baghouse filters, are critical to ensuring net environmental benefits. Huang *et al.,* [3], focusing on traditional Chinese medicine residues, further argued that emissions management is a prerequisite for scaling herbal waste utilisation in urban areas. Thermochemical systems, when combined with medicinal processing centres, can be energy efficient since the gases produced in the syngas or pyrolysis can be focused on driving the herbal drying and extraction processes, and bio-oil can be utilised instead of industrial fuel oil. In addition, the hybrid systems involving a mixture of HTC with anaerobic digestion of aqueous layers optimise energy recovery and minimise the discharge of effluents [60]. These combined structures support the argument that thermochemical conversion is a solution that is circular, resolving energy requirements, waste management, and emission reduction at the same time.

5.7 *Opportunities and future challenges*

The potential of thermochemical conversion of MPW is not limited to energy recovery and thus can be discussed in the context of climate change mitigation, rural development, and integration into the circular economy. Biochar and hydrochar are sources of both long-term sequestration of carbon and enhancement soil quality, as verified by Biswal and Balasubramanian [65], who determined the global climate mitigation capability of biochar and discovered that it was able to counter the huge carbon emissions. In particular, Koul *et al.,* [6] pointed out that MPW is a promising lignocellulosic feedstock since this type of residue is abundant in Asia, with herbal medicine industries producing millions of tonnes of residues per year. Nevertheless, obstacles are still present. The conversion efficiency and quality of products vary due to feedstock heterogeneity in the form of plant species, cultivation, and extraction methods. The

Table 5. Quantitative performance of thermochemical conversion of medicinal plant residues.

Process	Plant residue	Operating conditions	Main product	Reported quantitative outcome	Reference
Torrefaction	Mixed herbal medicine waste	230–290 °C under N_2; additional treatments at 260 °C under CO_2 and O_2	Torrefied solid fuel	Equilibrium moisture uptake decreased from 24.48% to 15.22%, while the comprehensive combustibility index increased approximately 3–5-fold compared with untreated waste	[63]
Pyrolysis	*Ginkgo biloba* urban pruning waste	400–600 °C following oven-drying pretreatment	Charcoal	Charcoal yield of 27.33–32.05% and maximum energy yield of 46.75%	[57]
Gasification	Oregano (*Origanum onites*) and lavender (*Lavandula angustifolia*) essential-oil distillation residues	700–900 °C; dry-air flow rate of 0.05–0.40 L/min in an updraft fixed-bed reactor	Syngas	Gas yield of 0.2–1.0 Nm^3/kg for oregano residue and 0.4–1.4 Nm^3/kg for lavender residue; maximum H_2 content of approximately 40%	[32]
Hydrothermal carbonisation	Mixed herbal medicine waste	220 °C for 2 h at a liquid-to-solid ratio of 15:1	Hydrochar	Hydrochar yield of 45.15% and energy recovery of 68.7%, and HHV of 22.41 MJ/KG	[64]

presence of high levels of ash that include potassium, chlorine, and silica compounds may lead to slagging and the deactivation of catalysts during the high-temperature operation [19]. Economically, small, decentralised facilities have a low chance of reaching economies of scale, and financial viability will rest on favourable policy-developed frameworks like feed-in tariffs, carbon credit recognition, or biochar certification schemes. Furthermore, techno-economic analysis (TEA) and life-cycle assessment (LCA) specifically aimed at MPW are scarcely provided, which obstructs policy and investment decision-making [24], [66], [67]. These gaps could be addressed through sequential characterisation of feedstocks, synthesis of impurity-tolerant catalysts, and streamlined LCA/TEA systems [19], [24], [66], [67]. With these obstacles cleared, MPW thermochemical valorisation has the potential to be a building block of sustainable waste-to-energy approaches in the global context [24], [66], [67].

To facilitate a direct comparison between the two principal conversion pathways discussed in this review, Figure 9 presents a comparative overview of biochemical and thermochemical conversion routes for medicinal plant waste (MPW). The figure summarizes their principal technologies, major products, reported advantages, limitations, and potential integration within a circular bioeconomy framework, providing a concise perspective on their respective roles in sustainable MPW valorization.

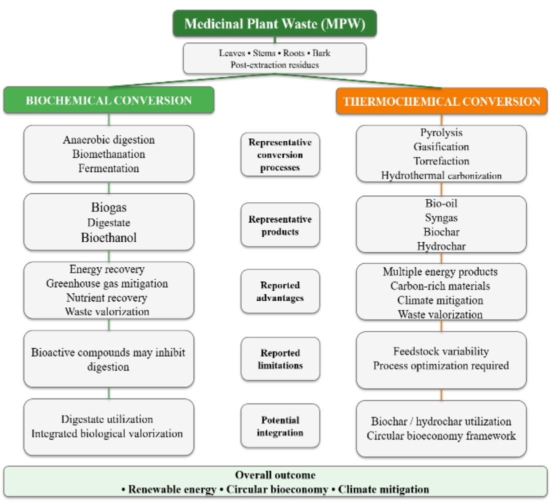

Figure 9: Comparative overview of biochemical and thermochemical conversion pathways for MPW.

6 Limitations and Challenges of Medicinal Plant Waste (MPW) Valorization

The field of medicinal plant waste (MPW) valorization is highly promising in converting the available herbal and pharmaceutical industry wastes into bioenergy and bioproducts. However, in reality, a number of technical, environmental, economic and policy-related issues still restrict its large-scale implementation. The identification of these barriers is essential to determining the requirements of the research and developing supportive policies.

6.1 *Feedstock variability and composition*

One of the major obstacles to the valorization of MPW is its heterogeneity. The chemical composition of MPW is diverse with regard to plant species, plant part (leaf, stem, bark, or rhizome) and extraction method in pharmaceutical processing [3], [6]. As an example, secondary metabolites like alkaloids, flavonoids, and phenolics are commonly left behind in residues of industrial activities of traditional medicine. Although useful as pharmacological agents, these compounds may reduce the activity of microbes in biochemical operations [5] or decrease the quality of bio-oil in pyrolysis [29]. A similar biological example was also documented in *Arabidopsis thaliana,* whereby expression of bacterial $yoeB_{spn}$ toxin genes negatively affected plant growth until these toxin genes were neutralized by antitoxin expression. This helps to understand that toxic biomolecules may interfere with biological systems, and it is necessary to have detoxification or pretreatment methods in MPW valorization [68]. This variability makes the process design challenging and hard to guarantee equal yields.

6.2 *Technical challenges in conversion*

The thermochemical or biochemical conversion pathways experience certain bottlenecks. High ash and alkali concentrations in MPW may lead to slagging, fouling, and corrosion in reactors in thermochemical processes [34]. Pyrolysis oils are unstable and acidic, which must be upgraded at high cost prior to utilization as transport fuels [9]. Tar and particulates are commonly present in the gasification products and require advanced clean-up systems [19]. In biochemical pathways, the remaining phytochemicals prevent enzymes and microbes, decreasing fermentation or digestion efficiency [69]. These technical limitations increase the costs of operation and lower the reliability.

6.3 *Environmental and safety concerns*

Environmentally, valorization systems are supposed to regulate air emissions, wastewater and solid residues. Unless treated, nitrogen-containing MPW can be combusted or gasified to produce NOx, SOx, or chlorine-based pollutants [34]. The by-product of hydrothermal carbonization is a liquid containing high levels of organics, which requires subsequent treatment and then disposal [3]. Furthermore, when implementing biochar or hydrochar products in soils, a prerequisite is that they fulfill the safety criteria, being free of heavy metals or polycyclic aromatic hydrocarbons (PAHs) [11], [70].

6.4 *Economic and logistical constraints*

Feedstock and logistics tend to limit the valorization of MPW in an economical manner. The scale of medicinal plant waste is generally low and scattered across processing units, making it expensive to collect and transport [71]. The bulk density and seasonality of biomass are also low, which further raises the cost of supply chains. Smaller operations might not have the economies of scale that enhance competitiveness, and even the processes of catalytic hydrotreating or tar reforming demand a high capital investment [7]. Consequently, the majority of projects are left at pilot or demonstration levels.

6.5 *Policy and market barriers*

The standards and policy frameworks on MPW valorization are poorly developed. The residues of herbal industries in certain nations are considered to lie in their regulatory "grey areas," which are not defined as either biomass or waste [3]. This generates confusion and deters private investment. There are also barriers to the market: bio-oil and syngas have to compete with cheap fossil fuels, and biochar products do not have a unified international standard, which restricts their use in agriculture and carbon markets [11]. Incentives are frequently created for large-scale energy crops or forestry residues, but not for small, distributed resources such as MPW, even in the presence of supportive policies.

6.6 *Knowledge and research gaps*

Lastly, knowledge gaps exist that hinder development. There are not many life cycle assessment (LCA) and techno-economic assessment (TEA) studies on MPW valorization, and it is hard to measure the environmental profit and economic viability [12]. Integrated systems are also not well demonstrated, including hydrothermal carbonization with anaerobic digestion, to maximize the recovery of value [19]. The agronomic advantages and long-term stability of MPW-derived biochar also require further investigations, particularly in tropical soil conditions like those in Asia, where the majority of the biomass is produced. The key limitations and challenges associated with medicinal plant waste valorization across technical, environmental, economic, and policy domains are summarized in Table 6.

7. Conclusion and Future Perspectives

The waste of medicinal plants (MPW) can no longer be viewed as a small by-product of the herbal and pharmaceutical industries but as a valuable biomass resource, which can be used to promote the production of renewable energy, mitigate climate change, and transform the bioeconomy to go circular. Due to the lignocellulosic composition and the remaining bioactive compounds, MPW can be readily processed in terms of thermochemical and biochemical conversion to a wide range of energy carriers, including bio-oil, syngas, biochar, and hydrochar. These products not only replace fossil fuels but also have other environmental co-benefits, such as improvement in soil fertility and long-term sequestration of carbon. MPW valorization is a viable contribution to the realization of global climate and the United Nations Sustainable Development Goals through the reduction of uncontrolled residues and the decrease of greenhouse gas emissions.

However, the review also reveals that there are still numerous obstacles to the large-scale implementation of MPW valorization technologies. The heterogeneous structure of MPW makes it more difficult to design the process, optimize yields and control the product quality. In most cases, technical obstacles such as tar formation during the process of gasification, pyrolysis bio-oil instability and microbial inhibition during fermentation are still unresolved. Operation is further complicated by environmental hazards of nitrogen- and chlorine-rich feedstocks that result in the formation of NOx, SOx and corrosive ash. Economic obstacles are also urgent since the dispersed and small scale of the MPW supply chains contribute to higher costs of collection and lower economies of scale. These issues are worsened by poor policy frameworks, low market standards, and inadequate

Table 6. Key limitations and challenges of medicinal plant waste (MPW) valorization across technical, environmental, economic, and policy domains.

Category	Main Challenges	References
Feedstock variability	Heterogeneous composition; presence of inhibitory compounds (alkaloids, phenolics)	[3], [6]
Technical issues	Slagging/fouling in thermochemical reactors; unstable bio-oil; tar contamination; enzyme inhibition	[9], [19], [29]
Environmental concerns	NOx, SOx, VOC emissions; wastewater from HTC; contaminants in biochar/hydrochar	[3], [11], [34], [70]
Economic constraints	High transport cost; small scale of residue generation; expensive upgrading technologies	[7], [71]
Policy/market barriers	Lack of regulatory clarity; limited standards for biochar; weak incentives for small-scale valorization	[11]
Knowledge gaps	Limited LCA/TEA studies; insufficient field validation of biochar benefits	[5], [12]

life cycle and techno-economic evaluation of the MPW systems. Unless specific interventions are implemented, MPW valorization may only stay a laboratory demonstration instead of becoming a solution that can be scaled and utilized in practice.

Moving forward, further development will rely on coherent approaches based on technology innovation, effective analysis, and accommodating governance. A study needs to be conducted to provide rapid and consistent tools to characterize feedstock faster, and to design impurity-tolerant catalysts and reactors that might reduce fouling, tar, and corrosion. A combination of conversion systems that couple processes, i.e., hydrothermal carbonisation and anaerobic digestion or pyrolysis and nutrient recovery, may be more energy efficient and value stream diversified. Meanwhile, high-resolution life cycle and techno-economic analysis, especially in tropical and small-scale environments with the highest MPW, is necessary to quantify the real environmental benefits and to make investment decisions. The policy instruments will have to change in order to acknowledge MPW as a renewable resource, to develop certification programs for products like biochar and to give incentives to distributed biomass systems. It is also essential that products derived through MPW be validated at farm and community scales to achieve agronomic gains, develop farmer trust and create rural economic engagement.

Provided that these measures are followed, MPW valorization can become not only a research field of study, but a common solution to climate and energy problems. Asia, being the center stage of medicinal plant industries in the world, is in a position to spearhead this change. Finally, the example of turning medicinal plant residues into renewable energy and a carbon sink is a demonstration of the transition from a linear paradigm of waste to the circular bioeconomy, where resources are used to their limits. In this way, MPW valorization not only addresses pressing waste management and energy challenges but also delivers tangible contributions to sustainability, climate resilience, and community development.

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Authors Contribution

F.A.B: Writing – original draft, supervision, validation, investigation, data curation. M.M.M: Investigation, data curation, formal analysis. H.A: writing – original draft, investigation, data curation, formal analysis. K.L: writing – original draft, data curation, conceptualization. C.S: writing – original draft, formal analysis, conceptualization. H.E.B: supervision, validation, investigation, data curation.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

References

[1] Q. Lu and C. Li, "Comprehensive utilization of Chinese medicine residues for industry and environment protection: Turning waste into treasure," *Journal of Cleaner Production*, vol. 279, Art. no. 123856, Jan. 2021, doi: 10.1016/j.jclepro .2020.123856.

[2] J. Luo, R. Yang, F. Ma, W. Jiang, and C. Han, "Recycling utilization of Chinese medicine herbal residues resources: Systematic evaluation on industrializable treatment modes," *Environmental Science and Pollution Research*, vol. 30, no. 12, pp. 32153–32167, Mar. 2023, doi: 10.1007/s11356-023-25614-4.

[3] C. Huang, Z.-X. Li, Y. Wu, Z.-Y. Huang, Y. Hu, and J. Gao, "Treatment and bioresources utilization of traditional Chinese medicinal herb residues: Recent technological advances and industrial prospect," *Journal of Environmental Management*, vol. 299, Art. no. 113607, Dec. 2021, doi: 10.1016/j.jenvman.2021.113607.

[4] M. Alexandri, S. Christaki, K. Gkatzionis, I. Mourtzinos, and E. Tsouko, "Residual biomass from major aromatic and medicinal flora of the Mediterranean: Challenges towards sustainable integration into food systems within the circular bioeconomy," *Trends in Food Science & Technology*, vol. 139, Art. no. 104123, Sep. 2023, doi: 10.1016/j.tifs.2023.104123.

[5] C. Sawatdeenarunat, K. C. Surendra, D. Takara, H. Oechsner, and S. K. Khanal, "Anaerobic digestion of lignocellulosic biomass: Challenges and opportunities," *Bioresource Technology*, vol. 178, pp. 178–186, Feb. 2015, doi: 10.1016/j.biortech. 2014.09.103.

[6] B. Koul, M. Yakoob, and M. P. Shah, "Agricultural waste management strategies for environmental sustainability," *Environmental Research*, vol. 206, Art. no. 112285, Apr. 2022, doi: 10.1016/j.envres.2021.112285.

[7] P. Basu, *Biomass Gasification, Pyrolysis and Torrefaction*, 3rd ed. London, U.K.: Academic Press, 2018.

[8] N. Gao, J. Du, W. Yang, Y. Li, and N.Chen, "Biomass-based shape-stabilized composite phase-change materials with high solar–thermal conversion efficiency for thermal energy storage," *Polymers*, vol. 15, no. 18, Art. no. 3747, Sep. 2023, doi: 10.3390/polym15183747.

[9] A. V. Bridgwater, "Review of fast pyrolysis of biomass and product upgrading," *Biomass and Bioenergy*, vol. 38, pp. 68–94, Mar. 2012, doi: 10.1016/j.biombioe.2011.01.048.

[10] K. Nayak, V. Kumargouda, and K. Kumar, "Investigation of medicinal plant processing waste for electricity generation through biomethanation," *Biotechnology for the Environment*, vol. 1, Art. no. 4, Jul. 2024, doi: 10.1186/s44314-024-00004-3.

[11] J. Lehmann and S. Joseph, Eds., *Biochar for Environmental Management: Science and Technology*. London, U.K.: Routledge, 2015.

[12] A. I. Osman, M. Farghali, and A. K. Rashwan, "Life cycle assessment of biochar as a green sorbent for soil remediation," *Current Opinion in Green and Sustainable Chemistry*, vol. 46, Art. no. 100882, Apr. 2024, doi: 10.1016/j.cogsc.2024. 100882.

[13] R. K. Shrestha *et al.*, "Biochar as a negative emission technology: A synthesis of field research on greenhouse gas emissions," *Journal of Environmental Quality*, vol. 52, no. 4, pp. 769–798, 2023, doi: 10.1002/jeq2.20475.

[14] O. Öztürk, R. Kocaman, and D. K. Kanbach, "How to design bibliometric research: An overview and a framework proposal," *Review of Managerial Science*, vol. 18, no. 11, pp. 3333–3361, Nov. 2024, doi: 10.1007/s11846-024-00738-0.

[15] B. Markscheffel and F. Schröter, "Comparison of two science mapping tools based on software technical evaluation and bibliometric case studies," *COLLNET Journal of Scientometrics and Information Management*, vol. 15, no. 2, pp. 365–396, Dec. 2021, doi: 10.1080/09737766 .2021. 1960220.

[16] P. C. García, M. J. Fernández-Rodríguez, R. Borja, J. M. Mancilla-Leytón, and D. de la Lama-Calvente, "Research trends in the recovery of by-products from organic waste treated by anaerobic digestion: A 30-year bibliometric analysis," *Fermentation*, vol. 10, no. 9, Art. no. 446, Sep. 2024, doi: 10.3390/fermentation10090446.

[17] Z. Sun et al., "Deciphering the impact of lignin on anaerobic digestion: Focus on inhibition mechanisms and methods for alleviating inhibition," *ACS Omega*, vol. 9, no. 44, pp. 44033–44041, 2024 , doi: 10.1021/acsomega.4c04375.

[18] A. Demirbas, "Progress and recent trends in biofuels," *Progress in Energy and Combustion*

Science, vol. 33, no. 1, pp. 1–18, Feb. 2007, doi: 10.1016/j.pecs.2006.06.001.

[19] S. K. Sansaniwal, K. Pal, M. A. Rosen, and S. K. Tyagi, "Recent advances in the development of biomass gasification technology: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 363–384, May 2017, doi: 10.1016/j.rser.2017.01.038.

[20] H. El Bari and A. Barakat, Eds., *Biogas in the Circular Economy: Technology, Production and Applications*. Oxford, U.K.: Woodhead Publishing, 2025.

[21] Y. Xi et al., "Enhanced anaerobic biogas production from wheat straw by herbal-extraction process residues supplementation," *Frontiers in Bioengineering and Biotechnology*, vol. 9, 2021, doi: 10.3389/fbioe.2021.623594.

[22] K. Hjouji, R. Haldhar, A. A. Alobaid, M. Taleb, and Z. Rais, "Maximizing resource recovery: Anaerobic digestion of residual biomass from essential oil extraction in four aromatic and medicinal plants," *Industrial Crops and Products*, vol. 216, Art. no. 118820, Sep. 2024, doi: 10.1016/j.indcrop.2024.118820.

[23] Z. Zafar *et al*., "The change in growth, osmolyte production and antioxidant enzymes activity explains the cadmium tolerance in four tree species at the saplings stage," *Forests*, vol. 13, no. 9, Art. no. 1343, Aug. 2022, doi: 10.3390/f13091343.

[24] S. Marcelino, P. D. Gaspar, and A. Paço, "Sustainable waste management in the production of medicinal and aromatic plants—A systematic review," *Sustainability*, vol. 15, no. 18, Art. no. 13333, Sep. 2023, doi: 10.3390/su151813333.

[25] A. Bendaoud et al., "Simple and combined pretreatment of a mixture of forestry and aromatic-medicinal plant waste by chemical, physical and enzymatic methods," *Journal of Ecological Engineering*, vol. 24, no. 5, pp. 71–86, May 2023, doi: 10.12911/22998993/160094.

[26] M. Wang, Y. Zhang, S. Yan, B. Yi, W. Niu, and Q. Yuan, "Enhanced biogas yield of Chinese herbal medicine extraction residue by hydrothermal pretreatment," *BioResources*, vol. 12, no. 3, pp. 4627–4638, Jun. 2017, doi: 10.15376/biores.12.3.4627-4638.

[27] A. Bendaoud, A. Belkhiri, A. Hmamou, S. Tlemcani, N. Eloutassi, and A. Lahkimi, "Efficient bioethanol production from lignocellulosic biomass using diverse microbial strains," *Journal of Ecological Engineering*, vol. 25, no. 10, pp. 351–360, Oct. 2024, doi: 10.12911/22998993/191748.

[28] W.-H. Chen, J. Peng, and X. T. Bi, "A state-of-the-art review of biomass torrefaction, densification and applications," *Renewable and Sustainable Energy Reviews*, vol. 44, pp. 847–866, Apr. 2015, doi: 10.1016/j.rser.2014.12.039.

[29] D. Mohan, C. U. Pittman, and P. H. Steele, "Pyrolysis of wood/biomass for bio-oil: A critical review," *Energy & Fuels*, vol. 20, no. 3, pp. 848–889, May/Jun. 2006, doi: 10.1021/ef0502397.

[30] Y. Lee et al., "Catalytic pyrolysis as a technology to dispose of herbal medicine waste," *Catalysts*, vol. 10, no. 8, Art. no. 826, Jul. 2020, doi: 10.3390/catal10080826.

[31] F. Monlau *et al.,* "Do furanic and phenolic compounds of lignocellulosic and algae biomass hydrolyzate inhibit anaerobic mixed cultures? A comprehensive review," *Biotechnology Advances*, vol. 32, no. 5, pp. 934–951, Sep./Oct. 2014, doi: 10.1016/j.biotechadv.2014.04.007.

[32] R. G. Y. Çinçin, A. Öngen, and O. N. Ağdağ, "Essential oil distillation residue as environmentally friendly feedstock in gasification: Effect of dry air flow rate and temperature on gasification performance," *Biomass Conversion and Biorefinery*, vol. 15, pp. 11719–11733, 2025, doi: 10.1007/s13399-024-05951-1.

[33] A. Trujillo-Reyes *et al.,* "Evaluation of toxic effect of monoterpene compounds on anaerobic digestion," *Journal of Environmental Chemical Engineering*, vol. 12, no. 2, Art. no. 112035, Apr. 2024, doi: 10.1016/j.jece.2024.112035.

[34] Y. Niu, H. Tan, and S. E. Hui, "Ash-related issues during biomass combustion: Alkali-induced slagging, silicate melt-induced slagging (ash fusion), agglomeration, corrosion, ash utilization, and related countermeasures," *Progress in Energy and Combustion Science*, vol. 52, pp. 1–61, Jan. 2016, doi: 10.1016/j.pecs.2015.09.003.

[35] S. V. Vassilev et al., "An overview of the organic and inorganic phase composition of biomass," *Fuel*, vol. 94, pp. 1–33, Apr. 2012, doi: 10.1016/j.fuel.2011.09.030.

[36] G. S. Goraya and D. K. Ved, *Medicinal Plants in India: An Assessment of Their Demand and Supply*. New Delhi: National Medicinal Plants Board, Ministry of AYUSH, Government of India,

and Dehradun: Indian Council of Forestry Research and Education, 2017.

[37] Z. H. Weng and A. L. Cowie, "Estimates vary but credible evidence points to gigaton-scale climate change mitigation potential of biochar," *Communications Earth & Environment*, vol. 6, no. 1, pp. 259, 2025, doi: 10.1038/s43247-025-02228-x.

[38] M. Bakraoui et al., "Kinetics study of methane production from anaerobic digestion of sludge and wastewater recycled pulp and paper," *IOP Conference Series: Materials Science and Engineering*, vol. 946, Art. no. 012009, Nov. 2020, doi: 10.1088/1757-899X/946/1/012009.

[39] R. Burton-Tauzer, C. Geronimo, P. Overholser, E. Wallach, and K. R. Fingerman, "Life cycle climate impacts of producing biochar from forest residues via the Takachar reactor," Schatz Energy Research Center, California State Polytechnic Univ., Humboldt, Arcata, CA, USA, Rep., Oct. 2024. [Online]. Available: https://schatzcenter.org/pubs/2024-Takachar-Report_FINAL.pdf

[40] T. Yarin et al., "Valorization of medicinal and aromatic plants waste: Review article," *The Pharma Innovation Journal*, vol. 11, no. 1, pp. 532–537, 2022.

[41] G. Mancuso, S. Habchi, M. Maraldi, F. Valenti, and H. E. Bari, "Comprehensive review of technologies for separate digestate treatment and agricultural valorisation within circular and green economy," *Bioresource Technology*, vol. 409, Art. no. 131252, Oct. 2024, doi: 10.1016/j.biortech.2024.131252.

[42] W. Tao, J. Jin, Y. Zheng, and S. Li, "Current advances of resource utilization of herbal extraction residues in China," *Waste and Biomass Valorization*, vol. 12, no. 11, pp. 5853–5868, Nov. 2021, doi: 10.1007/s12649-021-01428-8.

[43] K. Fardad, B. Najafi, S. F. Ardabili, A. Mosavi, S. Shamshirband, and T. Rabczuk, "Biodegradation of medicinal plants waste in an anaerobic digestion reactor for biogas production," *Computers, Materials & Continua*, vol. 55, no. 3, pp. 381–392, Jun. 2018, doi: 10.3970/cmc.2018.01803.

[44] S. Habchi, N. Lahboubi, M. Asbik, and H. E. Bari, "Enhancing biomethane production from food waste using olive pomace hydrochar: An optimization study," *Environmental Advances*, vol. 15, Art. no. 100477, Apr. 2024, doi: 10.1016/j.envadv.2023.100477.

[45] C. K. Jisha, K. Bauddh, and S. K. Shukla, "Phytoremediation and bioenergy production efficiency of medicinal and aromatic plants," in *Phytoremediation Potential of Bioenergy Plants*, K. Bauddh, B. Singh, and J. Korstad, Eds., Singapore: Springer, 2017, pp. 289–318, doi: 10.1007/978-981-10-3084-

[46] S. Panyadee, A. Petiraksakul, and C. Phalakornkule, "Biogas production from co-digestion of *Phyllanthus emblica* residues and food waste," *Energy for Sustainable Development*, vol. 17, no. 5, pp. 515–520, Oct. 2013, doi: 10.1016/j.esd.2013.07.003.

[47] M. Szymańska, H. E. Ahrends, A. K. Srivastava, and T. Sosulski, "Anaerobic digestate from biogas plants—Nuisance waste or valuable product?," *Applied Sciences*, vol. 12, no. 8, Art. no. 4052, Apr. 2022, doi: 10.3390/app12084052.

[48] S. Ledakowicz, "Biochemical processes of lignocellulosic biomass conversion," *Energies*, vol. 18, no. 13, Art. no. 3353, 2025, doi: 10.3390/en18133353.

[49] D. Jose *et al*., "Effective deep eutectic solvent pretreatment in one-pot lignocellulose biorefinery for ethanol production," *Industrial Crops and Products*, vol. 222, Art. no. 119626, Dec. 2024, doi: 10.1016/j.indcrop.2024.119626.

[50] A. B. M. S. Hossain, A. A. Saleh, S. Aishah, A. N. Boyce, P. P. Chowdhury, and M. Naqiuddin, "Bioethanol production from agricultural waste biomass as a renewable bioenergy resource in biomaterials," in *Proceedings of the 4th Kuala Lumpur International Conference on Biomedical Engineering 2008*, N. A. Abu Osman, F. Ibrahim, P. Y. Wan, and H. S. Lim, Eds., Berlin, Germany: Springer, 2008, pp. 240–243, doi: 10.1007/978-3-540-69139-6_77.

[51] H. S. Lim and G. Park, "Biorecycling and valorization strategies of herbal medicine waste: Convergent approaches for the functional food, pharmaceutical, and cosmetic industries," *Journal of Environmental Science International*, vol. 34, no. 6, pp. 333–347, Jun. 2025, doi: 10.5322/JESI.2025.34.6.333.

[52] Y. L. Wen, L. P. Yan, and C. S. Chen, "Effects of fermentation treatment on antioxidant and antimicrobial activities of four common Chinese herbal medicinal residues by *Aspergillus oryzae*," *Journal of Food and Drug Analysis*, vol. 21, no. 2,

pp. 219–226, Jun. 2013, doi: 10.1016/j.jfda.2013.05.013.

[53] M. Cucina et al., “Recovery of energy and plant nutrients from a pharmaceutical organic waste derived from a fermentative biomass: Integration of anaerobic digestion and composting,” *Journal of Environmental Chemical Engineering*, vol. 5, no. 3, pp. 3051–3057, Jun. 2017, doi: 10.1016/j.jece. 2017.06.003.

[54] X. Li et al., “Innovative utilization of herbal residues: Exploring the diversity of mechanisms beneficial to regulate anaerobic fermentation of alfalfa,” *Bioresource Technology*, vol. 360, Art. no. 127429, Sep. 2022, doi: 10.1016/j.biortech.2022. 127429.

[55] X. Li et al., “Exploring the addition of herbal residues on fermentation quality, bacterial communities, and ruminal greenhouse gas emissions of paper mulberry silage,” *Frontiers in Microbiology*, vol. 12, Art. no. 820011, Dec. 2021, doi: 10.3389/fmicb.2021.820011.

[56] P. M. Patil, P. P. Mahamuni, P. G. Shadija, and R. A. Bohara, “Conversion of organic biomedical waste into value added product using green approach,” *Environmental Science and Pollution Research*, vol. 26, no. 7, pp. 6696–6705, Mar. 2019, doi: 10.1007/s11356-018-4001-z.

[57] P. P. Paudel et al., “Energy recovery from *Ginkgo biloba* urban pruning wastes: Pyrolysis optimization and fuel property enhancement for high-grade charcoal productions,” *Biofuels, Bioproducts and Biorefining*, 2025.

[58] K. Shen et al., “Tobacco as bioenergy and medical plant for biofuels and bioproduction,” *Heliyon*, vol. 10, no. 13, Art. no. e33920, Jul. 2024, doi: 10.1016/j.heliyon.2024.e33920.

[59] Z. Jiang, Y. Zeng, R. Guo, L. Lin, R. Luque, and K. Yan, “Recent advances on CO_2-assisted synthesis of metal nanoparticles for the upgrading of biomass-derived compounds,” *Renewable and Sustainable Energy Reviews*, vol. 203, Art. no. 114756, Oct. 2024, doi: 10.1016/j.rser.2024.114 756.

[60] K. I. John and M. O. Omorogie, “Biomass-based hydrothermal carbons for catalysis and environmental cleanup: A review,” *Green Chemistry Letters and Reviews*, vol. 15, no. 1, pp. 162–186, 2022, doi: 10.1080/17518253. 2022. 2028017.

[61] R. Sivaranjanee, P. S. Kumar, and G. Rangasamy, “A recent advancement on hydrothermal carbonization of biomass to produce hydrochar for pollution control,” *Carbon Letters*, vol. 33, no. 7, pp. 1909–1933, 2023, doi: 10.1007/s42823-023-00576-2.

[62] G. Liu and T. Zhang, “Advances in hydrothermal carbonization for biomass wastewater valorization: Optimizing nitrogen and phosphorus nutrient management to enhance agricultural and ecological outcomes,” *Water*, vol. 17, no. 6, Art. no. 800, Mar. 2025, doi: 10.3390/w17060800.

[63] S. Xin, F. Huang, X. Liu, T. Mi, and Q. Xu, “Torrefaction of herbal medicine wastes: Characterization of the physicochemical properties and combustion behaviors,” *Bioresource Technology*, vol. 287, Art. no. 121408, Sep. 2019, doi: 10.1016/j.biortech.2019 .121408.

[64] Y. Luo et al., “Hydrothermal carbonization of herbal medicine waste: Process parameters optimization, secondary char formation and its effect on hydrochar properties,” *Journal of Environmental Management*, vol. 379, Art. no. 124819, Apr. 2025, doi: 10.1016/j.jenvman. 2025.124819.

[65] B. K. Biswal and R. Balasubramanian, “Use of biomass-derived biochar as a sustainable material for carbon sequestration in soil: Recent advancements and future perspectives,” *npj Materials Sustainability*, vol. 3, no. 1, pp. 26, 2025, doi: 10.1038/s44296-025-00066-8.

[66] M. Patel, X. Zhang, and A. Kumar “Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review,” *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 1486–1499, Jan. 2016, doi: 10.1016/j.rser.2015 .09.070.

[67] Z. Yu, H. Ma, X. Liu, M. Wang, and J. Wang “Review in life cycle assessment of biomass conversion through pyrolysis—Issues and recommendations,” *Green Chemical Engineering*, vol. 3, no. 4, pp. 304–312, Nov. 2022, doi: 10.1016/j.gce.2022.08.002.

[68] F. A. Bakar, C. C. Yeo, and J. A. Harikrishna, “Neutralization of bacterial $YoeB_{Spn}$ toxicity and enhanced plant growth in *Arabidopsis thaliana* via co-expression of the toxin-antitoxin genes,” *International Journal of Molecular Sciences*, vol.

17, no. 4, Art. no. 321, Apr. 2016, doi: 10.3390/ijms17040321.

[69] Y. Chen, J. J. Cheng, and K. S. Creamer, "Inhibition of anaerobic digestion process: A review," *Bioresource Technology*, vol. 99, no. 10, pp. 4044–4064, Jul. 2008, doi: 10.1016/j.biortech. 2007.01.057.

[70] S. E. Hale et al., "Quantifying the total and bioavailable polycyclic aromatic hydrocarbons and dioxins in biochars," *Environmental Science & Technology*, vol. 46, no. 5, pp. 2830–2838, 2012, doi: 10.1021/es203984k.

[71] E. Searcy, P. Flynn, E. Ghafoori, and A. Kumar, "The relative cost of biomass energy transport," *Applied Biochemistry and Biotechnology*, vol. 137–140, pp. 639–652, Apr. 2007, doi: 10.1007/s12010-007-9085-8.