

Modified biochar in tropical environments: trends, applications and future perspectives

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ABSTRACT: Tropical soils face challenges related to degradation, contamination, climatic stressors, and nutrient depletion. Sustainable soil management strategies are required, and modified biochar (MB) has emerged as a relevant material for agriculture, environmental remediation, and carbon (C) sequestration. This bibliometric and functional synthesis reports research on modified and doped biochars applied under tropical conditions between 2020 and 2025. A total of 79 studies from the Web of Science Core Collection (WoS) and Scopus databases were analyzed to elucidate relationships between countries, biomass feedstocks, modification strategies, pyrolysis conditions, and application objectives. An increase in publications was observed after 2022, with China, India, and Brazil leading scientific production. Agricultural and forestry residues predominate as raw materials, while pyrolysis temperatures between 300-500 °C are commonly reported. Metal- and mineral-based modifications are the most frequent strategies, particularly for contaminant immobilization and water remediation, whereas soil fertility applications often rely on unmodified or minimally MB. Across applications, MB frequently outperformed pristine materials in function-specific applications, with individual studies reporting approximately two- to three-fold improvements in sorption capacity or reaction kinetics and contaminant removal efficiencies exceeding 90 %. Agronomic responses were more context-dependent, with some researchers reporting improvements in nutrient availability, nutrient-use efficiency, biomass, or crop yield of varying magnitude depending on the modification strategy and soil conditions. Despite these advances, critical knowledge gaps persist regarding long-term stability.

Keywords: biomass conversion, carbon sequestration, doped biochar, tropical soils

Introduction

Tropical regions host a large share of global agricultural production and play a strategic role in global food security (Oakley and Bicknell, 2022). These regions encompass vast natural ecosystems, rapidly expanding urban areas, and industrial and mining landscapes that are increasingly affected by soil degradation and contamination (García et al., 2024). However, highly weathered tropical soils, particularly Oxisols and Ultisols, exhibit inherent limitations that constrain agricultural productivity and environmental sustainability. In general, these soils are highly weathered and characterized by low natural fertility, high acidity, aluminum (Al) toxicity, low availability of nutrients, and intense nutrient leaching, in addition to frequent physical degradation such as compaction and erosion.

The mineralogical composition of highly weathered tropical soils has major implications for nutrient dynamics. Iron (Fe) and Al oxyhydroxides strongly adsorb phosphate through ligand-exchange reactions and the formation of inner-sphere surface complexes, which reduces phosphorus (P) availability to plants and increases fertilizer requirements (Kaur et al., 2026). Phosphorus may also become occluded within oxide aggregates or precipitate with Fe and Al, particularly over long periods (Alleoni et al., 2026). Therefore, the high P-fixation capacity, variable-

charge behavior, and strong dependence of surface reactivity on soil pH distinguish many tropical soils from less-weathered soils and directly influence the performance of soil amendments.

Agricultural expansion, combined with population growth, urbanization, mining activities, and land-use intensification, has exacerbated these constraints and intensified pressures associated with climate change, leading to losses of soil organic matter (SOM), reduced soil biodiversity, and increased environmental contamination (Glaser et al., 2002). In this context, tropical regions face the challenge of maintaining soil functions across agricultural, natural, urban, and industrial environments, balancing food production, ecosystem conservation, and human health under scenarios of climate variability, rising temperatures, and more frequent extreme weather events.

The intensive use of mineral fertilizers and soil amendments has been the primary strategy deployed to overcome chemical constraints in agricultural soils (Zhong et al., 2010). However, this approach may be inefficient over the long-term and generate adverse environmental impacts, such as the contamination of surface and groundwater, greenhouse gas emissions, and disruptions in soil biogeochemical cycles (Awwal et al., 2025). In highly weathered soils, fertilizer-use efficiency may be further reduced by phosphate fixation, nutrient leaching, and interactions with

reactive Fe and Al oxyhydroxides surfaces. In non-agricultural contexts, such as urban and mining-impacted soils, contamination by potentially toxic elements (PTEs) and organic pollutants further constrains soil functionality and poses risks to ecosystems and human populations. Consequently, alternative strategies that promote long-term improvements in soil quality while minimizing environmental and health risks are increasingly required (Menegat et al., 2022; Chen et al., 2025).

Biochar, a porous, carbon-rich material produced by the pyrolysis of biomass under limited oxygen conditions (Chandrasekaran et al., 2024), has emerged as a promising technology within this framework. Its application to soils has been widely investigated due to its potential for long-term carbon (C) sequestration, thereby contributing to climate change mitigation through the stabilization of C in soil, as well as its beneficial effects on soil physical, chemical, and biological properties. In tropical soils, biochar applications may increase soil pH, reduce Al toxicity, enhance cation exchange capacity, improve water and nutrient retention (Ernest et al., 2024), and stimulate microbial activity (Lopes et al., 2024). These effects are particularly relevant in the context of climate change, as improved soil structure and water retention may enhance the resilience to droughts and intense rainfall events (Oishy et al., 2025).

Beyond agronomic benefits, biochar also offers important environmental and socioeconomic advantages, particularly in tropical regions. The biomass used as feedstock for biochar production is highly diverse and includes agricultural, forestry, agro-industrial, and urban residues, such as sugarcane [*Saccharum officinarum* (L.)] bagasse, rice [*Oryza sativa* (L.)] husk, wood residues, coconut [*Cocos nucifera* (L.)] shells, and organic sludges. This diversity poses biochar as a key component of circular economy strategies, enabling the conversion of locally available waste materials into value-added soil amendments while simultaneously reducing waste accumulation and associated risks of environmental contamination (Wenga et al., 2025).

The performance of biochar in soils is strongly dependent on its physicochemical properties, which are governed by feedstock type, pyrolysis conditions, and interactions with the soil environment (Tomczyk et al., 2020). In highly weathered tropical soils, conventional biochar may present limitations, such as low immediate nutrient availability, limited affinity for specific contaminants, or reduced effectiveness under intense leaching conditions (Shyam et al., 2025). Moreover, conventional, unmodified biochars may exhibit limited capacity to immobilize PTEs or organic contaminants commonly reported in tropical agricultural, urban, and mining-impacted soils. These constraints have motivated the development of biochar modification and doping strategies aimed at enhancing its functional performance.

Biochar doping or modification involves the incorporation of chemical materials or functional compounds into the biochar structure before, during, or after pyrolysis. These approaches seek to tailor properties such as surface area, surface charge, functional group composition, and affinity for nutrients or contaminants (Murtaza et al., 2024). Biochars modified with metals, metal oxides, mineral salts, or alkaline materials have demonstrated improved nutrient retention, enhanced immobilization of potentially toxic metals, and effective soil acidity correction.

However, their performance depends on the intended application and soil mineralogy. For example, alkaline or calcium- (Ca) and magnesium (Mg)-modified biochars may alleviate soil acidity and improve P availability, whereas Fe- and Al-modified biochars may increase phosphate sorption and may therefore be more suitable for controlling P losses than for directly supplying plant-available P (Zahedifar et al., 2026). Similarly, oxide-modified biochars may provide additional reactive sites for contaminant immobilization, but their effectiveness may vary with soil pH, competing ions, and the abundance of native Fe and Al oxyhydroxides (Fakhar et al., 2025). These features are particularly relevant under tropical conditions characterized by the combined challenges of climate-driven stressors and environmental contamination (Soares et al., 2024).

Biochar modification is of strategic importance in tropical regions, as it enables the design of materials better adapted to local edaphoclimatic conditions. Biochars enriched with Ca, Mg, Fe, or manganese (Mn), for example, may serve as soil amendments, nutrient sources, and remediation agents for contaminated soils. Nevertheless, modification strategies should consider weathering intensity, mineralogical composition, soil pH, oxide abundance, and the dominant nutrient or contaminant-retention mechanisms (Soares et al., 2026a, b). Such considerations are essential to avoiding unintended effects, including excessive P immobilization, limited nutrient release, or reduced accessibility of biochar sorption sites following interactions with native minerals. In addition, modification strategies can promote more stable interactions between SOM and microbial communities, potentially extending the persistence and effectiveness of biochar-induced benefits over time while enhancing the long-term stabilization of both C and contaminants in soils (Ma et al., 2023; Sun et al., 2023).

Over the past decade, research on modified biochar (MB) in tropical regions has expanded rapidly and unevenly across countries, feedstock types, modification strategies, and application fields, largely driven by growing concerns related to climate change mitigation, soil degradation, and environmental contamination (Beesley et al., 2011;

Chandrasekaran et al., 2024). However, the existing bibliographic references remain fragmented, with limited efforts to systematically integrate information on how these dimensions are interconnected. In particular, relationships between geographic origin, biomass selection, modification approaches, pyrolysis conditions, tropical soil mineralogy and target applications are often examined in isolation, hindering a comprehensive understanding of dominant methodological patterns and remaining knowledge gaps.

In this context, this review aims to systematically synthesize and map scientific literature on doped and modified biochars in tropical regions, with emphasis on the relationships between countries of origin, feedstock classes, modification strategies, pyrolysis conditions, and application fields, within the broader challenges of climate change mitigation and environmental contamination control. Particular attention is given to how the characteristic weathering intensity, mineralogy, variable-charge behavior, and P-fixation capacity of tropical soils may influence the effectiveness of modified biochars. By integrating bibliometric indicators with multidimensional graphical analyses, we seek to identify dominant methodological trends, emerging research directions, and persistent knowledge gaps, thereby supporting the development of more effective, context-adapted biochar-based solutions for sustainable agriculture and environmental remediation in tropical environments.

Methodology of research

Review design and information sources

A bibliometric and functional review was conducted to examine publication trends, research focus, production characteristics, modification strategies, and applications of MB associated with tropical countries. The bibliographic references' search, screening, and study-selection procedures were structured following the PRISMA 2020 reporting guidelines (Page et al., 2021) to improve the transparency and reproducibility of the review process.

The search was conducted on the Web of Science Core Collection (WoS) and Scopus databases between 15 Dec 2025 and 19 Jan 2026. These databases were selected because of their broad coverage of peer-reviewed scientific literature in environmental sciences, agriculture, soil science, and related research fields. Only original peer-reviewed scientific articles were considered eligible for inclusion.

The search was restricted to articles published between Jan 2020 and Dec 2025 in order to provide a focused synthesis of recent developments in engineered and functionally enhanced biochars. Although biochar research emerged in the early 2000s, earlier studies primarily focused on production

processes and the performance of pristine biochars. More recently, research has increasingly shifted toward modification strategies such as mineral impregnation, metal or metal-oxide loading, chemical activation, surface functionalization, and heteroatom doping. The 2020-2025 period was therefore selected to capture the recent expansion and diversification of these approaches and their emerging agricultural and environmental applications.

Search strategy

The literature search was performed using multiple combinations of keywords related to modified biochar, tropical environments, and agricultural and environmental applications. Rather than applying a single standardized search string, different combinations of terms were used in WoS and Scopus to broaden the retrieval of potentially relevant studies. Boolean operators AND and OR were used to combine the search terms.

The search terms included *"biochar"*, *"modified biochar"*, *"enriched biochar"*, *"doped biochar"*, *"pyrolysis"*, *"adsorption"*, *"remediation"*, *"soil"*, *"amendment"*, *"water treatment"*, *"carbon sequestration"*, *"tropical region"*, *"tropical"*, and *"tropical soil"*. Search combinations included, for example, *"modified biochar"* AND *"soil"* AND *"tropical"*, *"modified biochar"* AND *"tropical soil"*, *"soil remediation"* AND *"tropical"* AND *"soil"*, and *"tropical soil"*. OR operators were used where appropriate to retrieve alternative terms describing related modification strategies or application categories. The same general search approach was applied to both databases. The search was limited to original scientific articles published between 2020 and 2025.

Eligibility criteria and study selection

The database searches initially identified 3,228 records. Records retrieved from WoS and Scopus and from the different keyword combinations were exported and combined into a single Microsoft Excel 2022 (Microsoft Corp.) database. Duplicate records were identified and removed manually in Microsoft Excel using spreadsheet filters and individual cross-checking of article titles, authors, and bibliographic information. Records retrieved more than once because they were indexed in both databases or identified through keyword combinations were merged and counted only once. No automated tools were used for duplicate removal or study screening.

Studies were considered eligible when they: (i) were original peer-reviewed scientific articles published between 2020 and 2025; (ii) investigated modified, enriched, functionalized, or doped biochar; (iii) addressed at least one agricultural or environmental application relevant to the scope

of the review, including soil amendment, nutrient management, contaminant remediation, water or wastewater treatment, C sequestration, or related applications; and (iv) met the predefined geographical criterion for association with a tropical country.

The geographical screening was based primarily on the institutional affiliation of the first and/or corresponding author. For the purposes of this review, tropical countries were defined as countries located wholly or partly within the tropical zone, between the Tropic of Cancer (23.5° N) and the Tropic of Capricorn (23.5° S). An article was considered associated with a tropical country when the first author and/or corresponding author was affiliated with a research institution located in a tropical country. In addition, when the geographical location of the experiment was explicitly reported in the "Materials and Methods" section of the original article, the country where the study was conducted was also verified and considered during geographical screening.

For multinational publications involving authors from institutions in more than one country, the affiliation of the first and/or corresponding author was used as the primary criterion for country classification. When authors from more than one tropical country were involved, the relevant country affiliations were retained for the geographical analysis, while the article itself was counted only once in the total number of studies. Institutional affiliations and experimental locations, when available, were therefore manually examined to confirm the association of each study with a tropical context.

Studies were excluded when they: (i) were duplicate records; (ii) were review articles, conference papers or abstracts, book chapters, editorials, or other publication types rather than original scientific articles; (iii) did not investigate modified or doped biochar within the scope of the review; (iv) did not meet the predefined geographical criterion; or (v) were published outside the 2020-2025 period.

Duplicate removal, publication-type screening, and geographical filtering were performed manually in Microsoft Excel using spreadsheet filters and individual verification of the records. Titles, abstracts, and author keywords of the remaining articles were subsequently screened to determine their relevance to the objectives of the review. The screening and eligibility assessment were performed by two reviewers. No automated screening or machine-learning tools were used during the selection process.

Following duplicate removal and assessment against the predefined eligibility criteria, 79 original peer-reviewed scientific articles were included in the final bibliometric and functional synthesis. The complete study-selection process, including identification, duplicate removal, screening, exclusion, eligibility assessment, and final inclusion, is summarized in the PRISMA 2020 flow diagram.

Data collection and classification

Data from the 79 eligible articles were manually extracted and compiled into a structured Microsoft Excel database. Data extraction was performed by two reviewers independently. Information not explicitly reported in the original articles was not inferred and was recorded as not available (NA).

The information extracted from each article included publication year, country, institutional affiliation, biomass feedstock, target application, modification or doping strategy, pyrolysis conditions, and other relevant experimental information available. Information relevant to the functional synthesis, such as the reported performance of modified and unmodified biochars, was also extracted when explicitly provided by the original studies. All records were individually checked to identify inconsistencies or ambiguous entries, and categorical variables were standardized before analysis, including the harmonization of synonymous terms describing feedstocks, applications, and modification strategies.

Biomass feedstocks were grouped into five categories according to their origin: (i) agricultural residues, (ii) forestry and wood residues, (iii) animal residues, (iv) urban or industrial residues, and (v) aquatic or marine residues. Modification strategies were classified according to their dominant functional approach, encompassing heteroatom doping, metal or metal-oxide loading, mineral-based impregnation, chemical activation or surface oxidation, carbon-based composites, biological or microbial modification, and composting. Reported pyrolysis temperatures were grouped into four ranges (< 300, 300-500, 500-700, and > 700 °C) to facilitate comparisons across the reviewed literature.

Individual articles could report more than one feedstock, modification strategy, or application. Therefore, multiple categorical occurrences were allowed for a single article when more than one category was explicitly reported. Consequently, the total number of categorical occurrences used in some frequency-based analyses exceeds the total number of individual articles included in the review ($n = 79$). For example, values such as $n = 172$ -173 reported for some categorical analyses represent the total number of classified occurrences rather than independent studies. Thus, a single article could contribute to more than one category, and these occurrences should not be interpreted as separate studies.

Functional synthesis

The functional synthesis was descriptive and was not designed as a quantitative meta-analysis. Quantitative performance values were extracted directly from individual articles when they were relevant to

illustrate the performance of specific biochar modification strategies or applications. Therefore, these values represent study-specific outcomes obtained under the experimental conditions of the respective original studies and do not represent averages, pooled estimates, or overall effect sizes across the reviewed literature.

The reviewed studies differed substantially in feedstock type, pyrolysis conditions, modification procedures, experimental design, application rates, target contaminants or crops, environmental conditions, and response variables. Because of this methodological and experimental heterogeneity, quantitative results were not statistically pooled across studies, and no meta-analysis, subgroup analysis, meta-regression, or sensitivity analysis were performed.

Accordingly, quantitative values presented in the functional synthesis were explicitly attributed to the respective individual studies and used only to illustrate the magnitude of responses reported under specific experimental conditions. Similarly, when inferential statistical expressions such as $p < 0.05$ were reported, they referred exclusively to statistical analyses performed and reported by the original study cited and not to statistical analyses conducted across studies in the present review.

Bibliometric analysis and data visualization

Descriptive analyses were used to quantify the frequencies of individual variables and their combinations. Temporal trends in publication output, journals contributing to the field, geographical distribution of research, feedstock categories, modification strategies, pyrolysis conditions, and application categories were evaluated from the compiled database.

Relationships between categorical variables were explored using Sankey diagrams, which illustrate the distribution of categorical occurrences across countries, feedstock categories, applications, modification strategies, and pyrolysis temperature ranges. Flow widths represent the frequency with which each pathway occurred in the compiled dataset, allowing for dominant research directions and less-explored combinations to be identified.

Bubble plots were used to further investigate relationships between biochar application, feedstock category, and modification strategy. Each bubble represents a unique combination of categorical variables, and its size is proportional to the frequency of that combination within the compiled dataset. Numerical labels were added to larger clusters to facilitate interpretation.

All data processing, descriptive analyses, and visualizations were performed using Python 3.11, primarily with the *pandas*, *numpy*, and *matplotlib* libraries, executed within the Spyder 6 environment.

Assessment of bias and certainty of evidence

No formal study-level risk-of-bias assessment, reporting-bias assessment, or certainty-of-evidence grading was performed because the present study was designed as a bibliometric and descriptive functional review rather than as a meta-analysis of intervention effects. Similarly, no pooled effect measures were calculated because quantitative outcomes were not statistically synthesized across studies. The quantitative results discussed in the functional synthesis were used as study-specific examples and were interpreted within the methodological and experimental context of the respective original articles.

Expansion and geographical distribution of research on modified biochar in tropical regions

The global distribution of scientific publications on MB under tropical conditions highlights a strong concentration of research output in a limited group of countries with high publication intensity (Figure 1). China clearly dominates the scientific production, standing out as the main contributor, followed by Brazil, India, and Indonesia. Together, these countries account for a substantial share of the studies published between 2020 and 2025, reflecting their robust research capacity and the strategic importance of biochar-based technologies for addressing soil degradation, contamination, and C management challenges in tropical agroecosystems.

Other Asian countries, particularly India and several Southeast Asian nations, also exhibit substantial research output, reinforcing the regional concentration of studies (Figure 1). This geographic pattern reflects the growing reliance on MB as a practical and versatile strategy to enhance soil fertility, to immobilize PTEs, and mitigate environmental impacts in areas dominated by highly weathered soils, intensive agricultural systems, and increasing pressure from industrial and mining activities (Miyan, 2015; Sartori et al., 2019; Katsir et al., 2024).

In South America, Brazil stands out as the main contributor to research on MB in tropical soils, reflecting its consolidated expertise in tropical soil science and sustainable agriculture. This prominence is closely associated with the extensive occurrence of highly weathered soils and the growing demand for soil amendments capable of enhancing fertility and reducing contamination risks (Srivastava et al., 2024).

Brazilian contributions are further supported by the large availability of agricultural, forestry, and agro-industrial residues suitable for biochar production. Brazil generates hundreds of millions of tons of lignocellulosic biomass residues annually (e.g., sugarcane bagasse and straw, rice husk, coffee (*Coffea* sp.) husk, coconut shell, and forestry residues), with total agricultural waste estimated at approximately

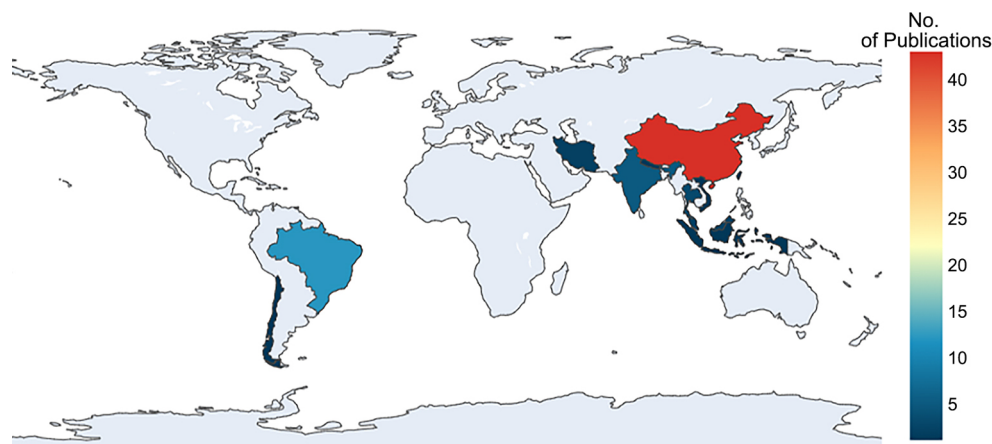


Figure 1 – Global distribution of publications on modified biochar by tropical countries between 2020 and 2025. Countries are colored according to publication intensity, with warmer tones representing higher research output. China leads the global production of studies on modified biochar, followed by Brazil, India, Indonesia, and other nations in Southeast Asia and South America. The geographic pattern reflects the rapid expansion of research on biochar functionalization, such as mineral impregnation, surface oxidation, and iron modification, driven by increasing interest in soil remediation, soil fertility, carbon sequestration, and pollutant immobilization in tropical environments.

600 million tons per year, making it one of the largest global producers of such residues (Alves et al., 2023). For the sugarcane sector alone, researchers estimate an agronomic availability of approximately 157 million tons of fresh residues annually, with a dry-basis reuse potential of approximately 19.6 million tons, reflecting the unparalleled scale of biomass resources available for thermochemical conversion and carbon-rich material production in Brazil (Forster-Carneiro et al., 2013).

According to Brazilian biomass inventories, sugarcane bagasse consistently ranks among the most abundant agro-industrial by-products, reflecting the country as the world's largest sugarcane producer (Cuervo et al., 2024). This large and diversified biomass supply not only ensures feedstock availability at scale, but also enables the selection and modification of distinct raw materials, which is essential to the development of engineered and doped biochars with a wide range of physicochemical properties. Such versatility allows biochar formulations to be tailored to specific soil constraints and contamination scenarios (Novotny et al., 2015; Aluthge et al., 2025).

Overall, the spatial distribution of articles suggests that research on MB in tropical regions is largely driven by countries where agroecosystems are both environmentally vulnerable and economically strategic, thereby underscoring the global relevance of this material for sustainable soil management. This trend reflects the need for scalable, low-cost, and multifunctional solutions capable of addressing soil degradation, contamination, and C management in tropical settings.

Furthermore, based on the bibliometric analysis of publications retrieved from the WoS and Scopus databases, the distribution of papers across peer-

reviewed scientific journals demonstrates a strong interdisciplinary profile in studies addressing MB in tropical environments (Figure 2). Publications are mainly concentrated in journals related to chemical engineering, environmental sciences, agronomy, and soil science, indicating that advances in this field are strongly driven by the integration of material engineering approaches with soil and environmental applications, highlighting the applied and technological orientation of this research field.

The Chemical Engineering Journal stands out as the leading publication outlet, indicating a strong emphasis on process optimization, material engineering, and pollutant removal mechanisms. High publication frequencies are also observed in journals such as Biochar, Environmental Research, Agronomy, and Journal of Cleaner Production, highlighting the relevance of MB to sustainable agriculture, environmental remediation, and circular economy-oriented approaches.

In addition, a substantial number of studies are published in journals focused on soil and water pollution control, including Water, Air, & Soil Pollution, Journal of Water Process Engineering, and Bioresource Technology Reports. The presence of publications in specialized soil and plant science journals further demonstrates the growing interest in biochar modification as a strategy to improve soil quality and nutrient dynamics under tropical conditions. Overall, the diversity of publication outlets confirms that research on MB is predominantly application-driven, with strong links to environmental engineering, soil remediation, and sustainable agricultural practices.

The temporal evolution of publications on MB reveals a clear intensification of research activity after 2022 at the global scale and within tropical regions

(Figure 3). While a gradual increase was observed between 2020 and 2021, the period from 2022 onwards is marked by a pronounced acceleration in the number of publications. At the global level, this post-2022 acceleration suggests an increasing recognition of MB as a multifunctional material for soil remediation, nutrient management, and C sequestration (Gui et al., 2025). The sharp rise in publications in 2024 and 2025 indicates a consolidation of research efforts and a transition toward broader application-oriented studies.

Notably, the contribution of studies conducted in tropical regions increases disproportionately after 2022, highlighting the growing focus on environments

where soil constraints are more severe. This trend reinforces the relevance of MB as key technology for addressing emerging environmental challenges in tropical agroecosystems.

Biomass availability and production pathways shaping biochar development in tropical countries

The production and application of biochars in tropical and subtropical regions are strongly influenced by local biomass availability, technological capacity, and targeted end uses. Understanding how these factors interact is crucial for interpreting current research trends and identifying realistic pathways for large-scale implementation. In this context, the Sankey diagrams provide an integrated perspective on how countries, feedstock classes, production conditions, modification strategies, and applications are interconnected.

Patterns linking countries, biomass sources, and pyrolysis conditions indicate a clear dominance of agricultural residues as the primary feedstock for biochar production, particularly in countries with extensive agricultural systems such as China and Brazil (Figure 4). This predominance reflects the wide availability of crop residues, processing by-products, and lignocellulosic wastes, which are generally low-cost and easily accessible (O’Laughlin and McElligott, 2009). Forestry and wood residues appear as the second most important feedstock class, highlighting their relevance in regions where agricultural and forest-based activities coexist.

Across countries and feedstock classes, pyrolysis temperatures between 300 and 500 °C are the most frequently reported, followed by the range of 500-700 °C (Figure 4). This distribution suggests a preference for production conditions that balance energy efficiency with the generation of biochars possessing suitable physicochemical properties for environmental applications (Antal and Grønli, 2003). Moderate temperatures favor the retention of oxygen-containing functional groups and, in some cases, nutrients, which are particularly relevant for soil-related uses and contaminant immobilization (Keiluweit et al., 2010).

Higher temperatures, on the other hand, are less commonly adopted and are typically associated with studies aiming to enhance attributes often linked to adsorption performance and long-term C sequestration such as aromaticity, surface area, and structural stability (Brantley et al., 2015). The association between feedstock type and pyrolysis temperature reflects practical considerations, as agricultural residues are generally processed at lower to intermediate temperatures. At the same time, woody biomasses tolerate and often benefit from higher thermal treatments.

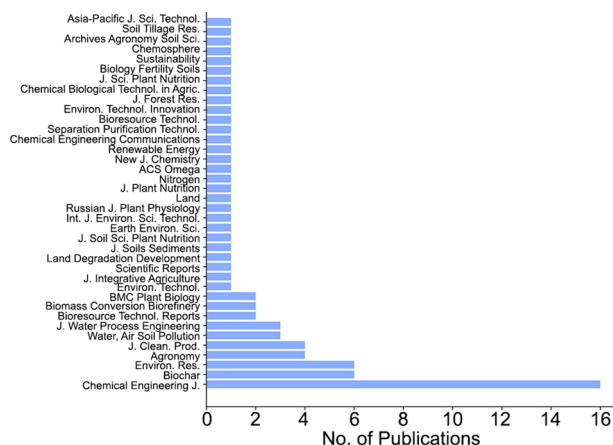


Figure 2 – Number of articles in scientific journals on modified biochar under tropical conditions (2020-2025).

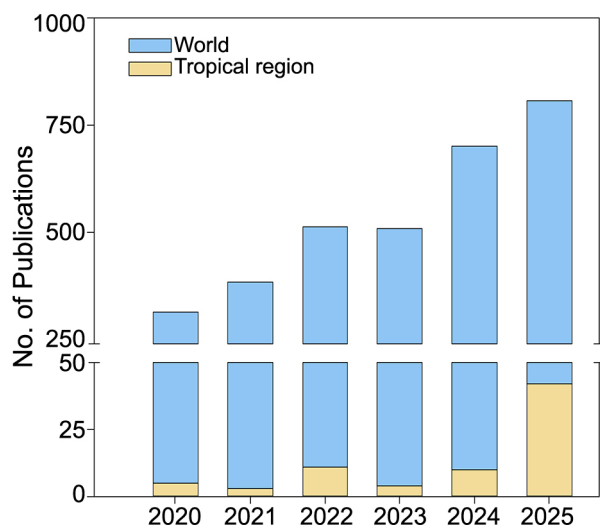


Figure 3 – Annual number of publications on modified biochar in the world (light blue) and modified biochar in tropical regions (yellow) produced between 2020 and 2025. A consistent increase in total research output is observed over the years, with a marked rise in papers on modified biochar published after 2023.

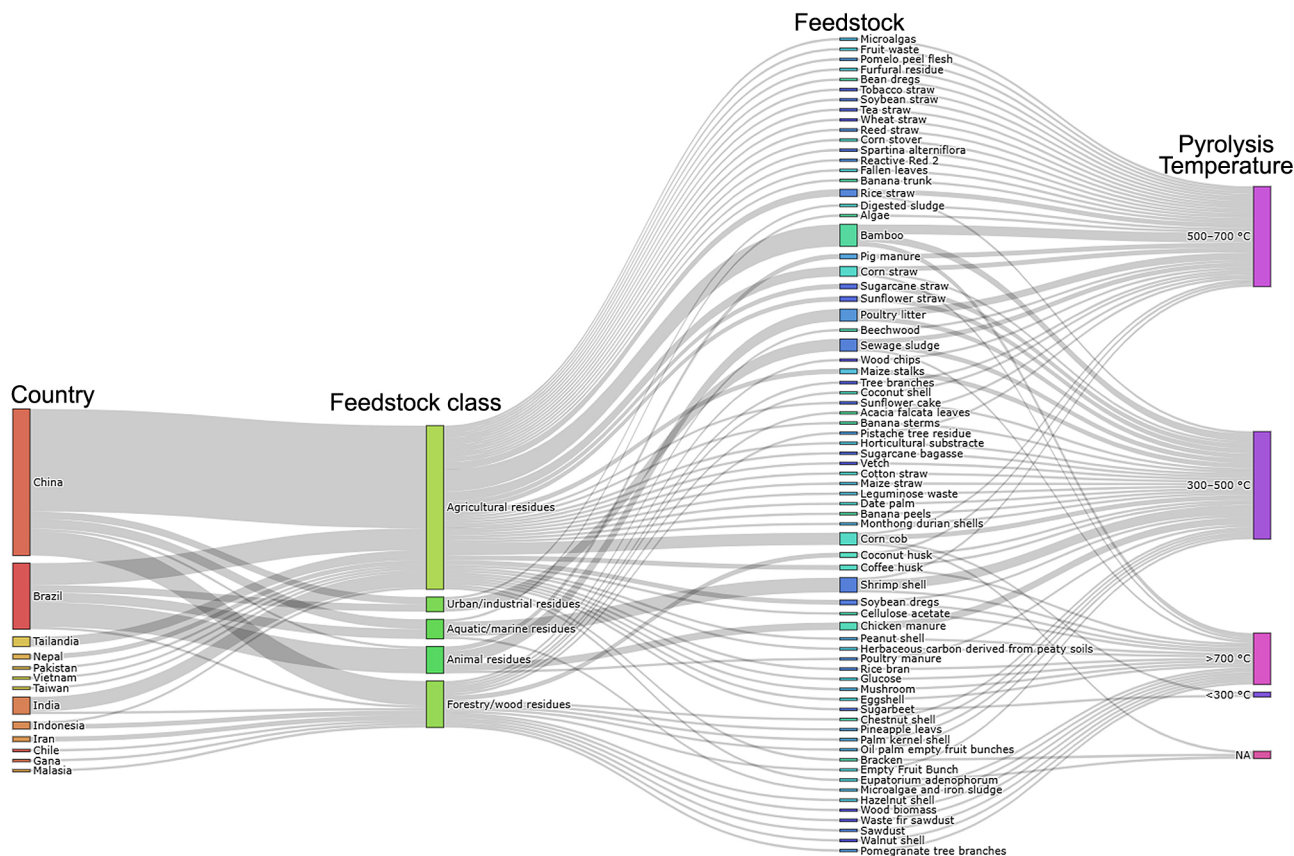


Figure 4 – Sankey diagram of relationships between countries, feedstock class, individual feedstocks, and pyrolysis temperature ranges used in biochar production. The width of each flow is proportional to the number of studies reporting a given pathway. Feedstocks are grouped into major classes (agricultural, forestry/wood, animal, aquatic/marine, and urban/industrial residues), highlighting dominant biomass sources across countries and their association with specific pyrolysis temperature ranges (< 300, 300–500, 500–700, and > 700 °C). NA = not available.

In addition to production conditions, the relationship between biomass availability and chemical modification strategies reveals how research priorities align with material characteristics and technological accessibility (Tan et al., 2015). Agricultural and forestry residues remain the most frequently modified feedstocks, indicating that chemical enhancement is preferentially applied to abundant and well-characterized materials (Figure 5). Among the reported approaches, metal and metal oxide impregnation clearly predominate, especially in studies conducted in China and, to a lesser extent, Brazil. This trend reflects a strong research focus on improving biochar performance for the immobilization of inorganic contaminants such as potentially toxic metals (Beesley et al., 2010).

Other modification strategies, including heteroatom doping, chemical activation, and the development of carbon-based composites, have also been reported but with lower frequency (Figure 5). These approaches are generally associated with increased surface area, enhanced porosity, and

greater surface reactivity; however, they often involve higher costs, more complex processing steps, and stricter experimental control (Rajapaksha et al., 2016). As a result, such strategies tend to be explored more intensively in regions with stronger laboratory infrastructure and higher research investment. Feedstock derived from aquatic, animal, or urban and industrial residues appears less frequently in MB, which may be related to their compositional heterogeneity, logistical challenges, or regulatory constraints.

When biochar applications are taken into account, soil-related uses emerge as the dominant pathway across countries and feedstock classes (Figure 6). Biochar applications as soil amendment to improve soil fertility and C sequestration account for a substantial proportion of the reported studies. This prevalence reflects not only agronomic demand but also the relative simplicity and scalability of soil applications, which generally require fewer technological inputs and face fewer regulatory barriers than more specialized uses (Jeffery et al., 2011).

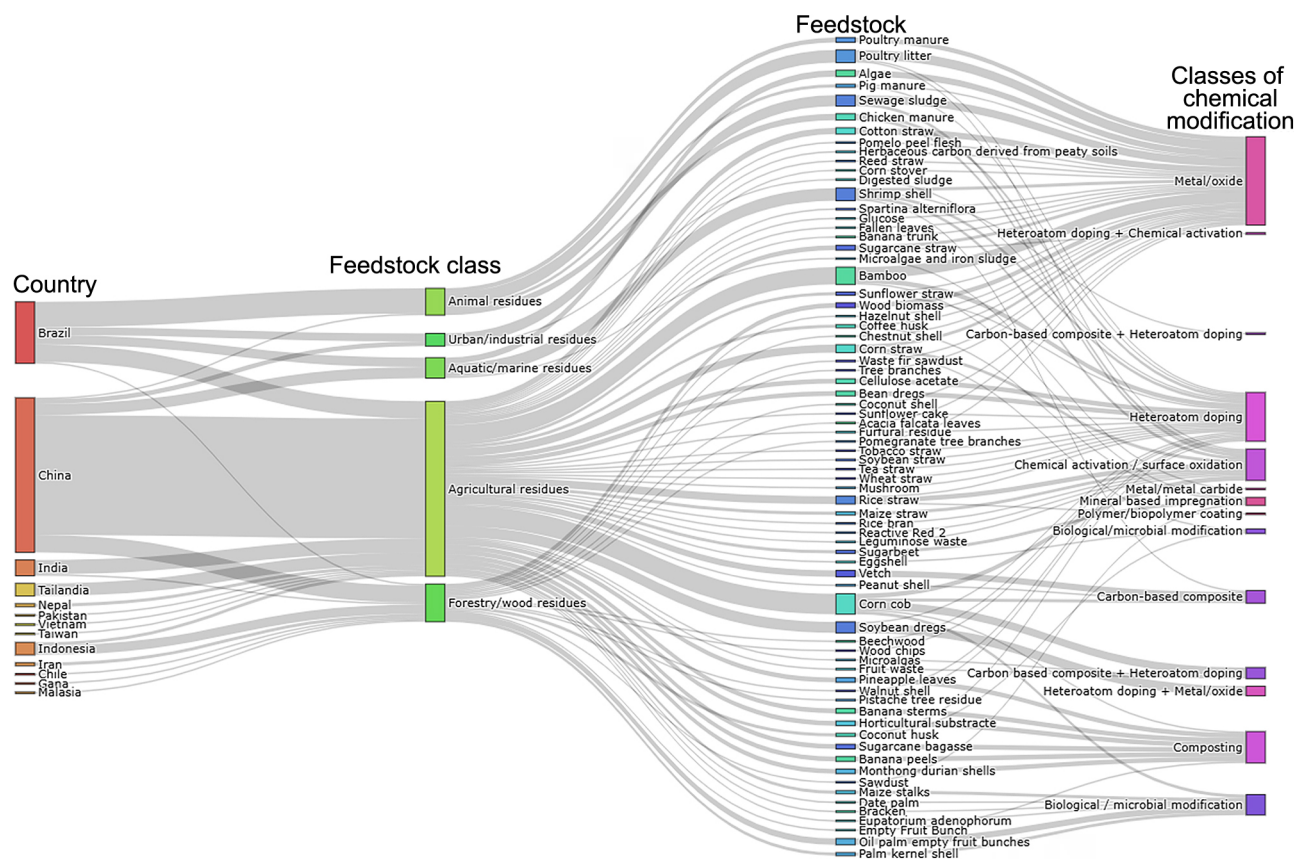


Figure 5 – Sankey diagram of relationships between countries, feedstock class, individual feedstocks, and classes of biochar modification reported in scientific papers. The width of each flow is proportional to the number of studies associated with a given pathway. Feedstocks are grouped into major classes (agricultural, forestry/wood, animal, aquatic/marine, and urban/industrial residues), highlighting how different biomass sources from distinct countries are preferentially combined with specific modification strategies, including metal/oxide loading, heteroatom doping, chemical activation or surface oxidation, carbon-based composites, biological/microbial modification, and composting.

Environmental remediation, particularly the removal of organic and inorganic contaminants from water, also represents an important application category (Figure 6). These uses are closely associated with chemically MB and are more commonly reported in countries with access to advanced analytical tools and experimental facilities (Inyang et al., 2010). In contrast, applications related to catalysis, wastewater treatment systems, or integration into bioenergy processes are less frequent. Such applications often require higher material consistency, strict performance criteria, and integration into existing industrial infrastructure, which can limit their feasibility in regions with structural or economic constraints.

Overall, the combined interpretation of production conditions, modification strategies, and applications indicates that biochar research is primarily shaped by the interplay between local resource availability and technological capacity. Agricultural residues form the backbone of biochar production worldwide, supporting a wide range of

modification approaches and end uses. However, increasing complexity in biochar engineering and diversification of applications are closely linked to the availability of infrastructure, expertise, and institutional support. These findings underscore the importance of context-specific strategies for biochar development, particularly in tropical and subtropical regions, where aligning feedstock availability, technological feasibility, and realistic application pathways is essential for sustainable implementation.

Alignment between biochar modification strategies and intended applications

The strategies for biochar modification in tropical regions are closely aligned with the methodological choices rather than planned experimentation. When production parameters, feedstock classes, and modification approaches are examined together, clear patterns emerge, linking how biochars are produced and modified to deal with the environmental problems they are intended to solve (Figures 7-9).

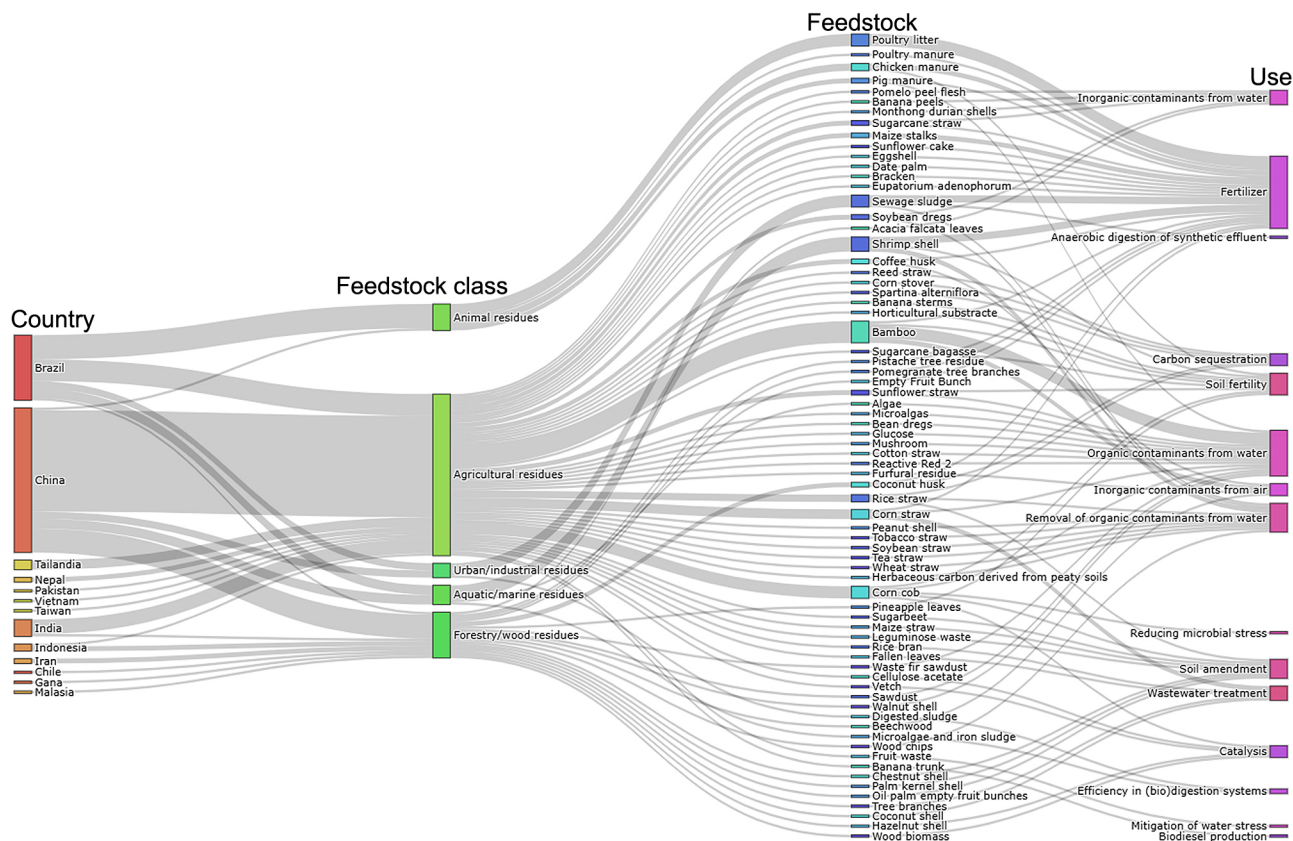


Figure 6 – Sankey diagram of relationships between countries, feedstock class, individual feedstocks, and biochar application. The width of each flow is proportional to the number of studies reporting a given combination. Feedstocks are grouped into five major classes (animal, agricultural, forestry/wood, urban/industrial, and aquatic/marine residues), highlighting dominant biomass sources across countries and their preferential allocation to specific applications, such as soil fertility, contaminant removal from water and air, carbon sequestration, wastewater treatment, and catalysis.

The distribution of pyrolysis temperatures among the modification classes highlights the role of temperature as a structuring parameter in the choice of biochar for application in tropical regions (Figure 7). Instead of acting as an outcome variable, pyrolysis temperature appears to function as a methodological framework within the specific modification strategies that are innovative. Biochars produced at low temperatures, most commonly between 300 and 500 °C, are frequently associated with mineral impregnation, incorporation of metals or metal oxides, and alkaline enrichment. These temperature ranges favor the retention of oxygen-containing functional groups and surface heterogeneity, which are essential to cation exchange, surface complexation, and electrostatic interactions (El-Naggar et al., 2021). Such properties are particularly relevant in tropical soils and contaminated environments, where acidity, nutrient loss, and metal mobility are constant challenges (Soares et al., 2021).

At higher pyrolysis temperatures, typically above 500 °C, the alteration strategies tend to focus on chemical activation, surface oxidation, heteroatom

doping, and the formation of carbon-based functional structures. These approaches are generally related to applications that require high surface area, well-developed porosity, and a stable structural framework, such as the adsorption of organic contaminants, wastewater treatment, and catalytic processes (Amen et al., 2020; Elkhaila et al., 2022). The association between higher temperatures and these alteration strategies reflects functional requirements and technological limitations, since elevated temperatures facilitate pore development and structural reorganization of the C matrix (Oginni and Singh, 2020). However, the overlap observed among temperature ranges across different alteration classes suggests that temperature alone does not imply functionality, reinforcing the importance of considering pyrolysis conditions in conjunction with feedstock characteristics and post-production treatments.

The practical implications of these production patterns become more evident when analyzed together (Figure 8). Biochar applications cluster around specific combinations of feedstock class and modification strategies, indicating a strong functional logic underlying

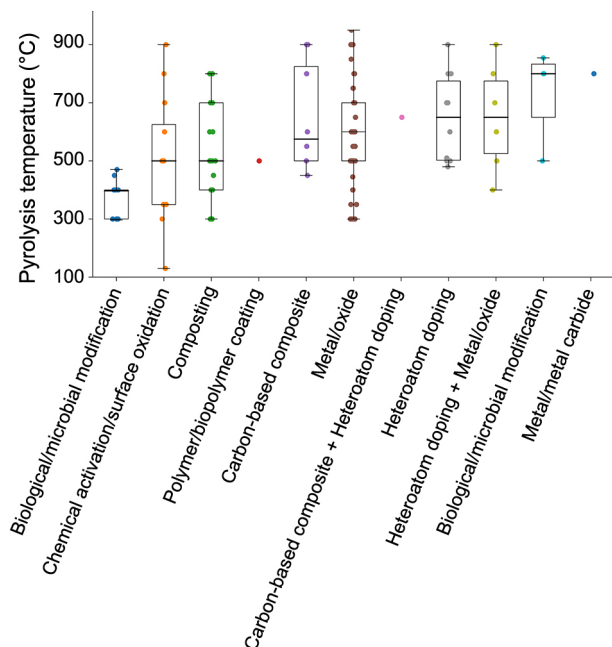


Figure 7 – Distribution of pyrolysis temperatures reported for biochars subjected to modification (doping) classes. Boxplots summarize the median (central line) and interquartile range (IQR, box), with whiskers representing the typical temperature ranges adopted across studies, and individual points indicating values reported in individual papers.

material selection. The biochars applied for soil fertility improvement and conditioning purposes are predominantly derived from agricultural and forestry residues and, most often, modified through mineral- or alkaline-based approaches (Kabir et al., 2023; Shyam et al., 2025). This reflects an alignment between locally abundant biomass resources, relatively simple modification techniques, and the typical chemical limitations of tropical soils, particularly acidity and low nutrient retention capacity (Soares et al., 2020).

In contrast, chemically activated biochars and materials doped with metals or heteroatoms are applied to environmental remediation, water contaminant removal, and wastewater treatment (Figure 8). These biochars are commonly produced from forest, urban, or industrial waste, which are often better suited for high-temperature processing and intensive chemical treatments. The prominence of these combinations highlights the greater functional demands associated with remediation applications, where sorption capacity, surface reactivity, and chemical stability are crucial. In tropical urban and industrial environments affected by metal(oids), organic pollutants, and emerging contaminants, these advanced modification strategies appear to be adopted as a response to complex contamination scenarios, rather than as incremental improvements over unmodified biochars (Ghosh et al., 2022; Kuppam et al., 2024).

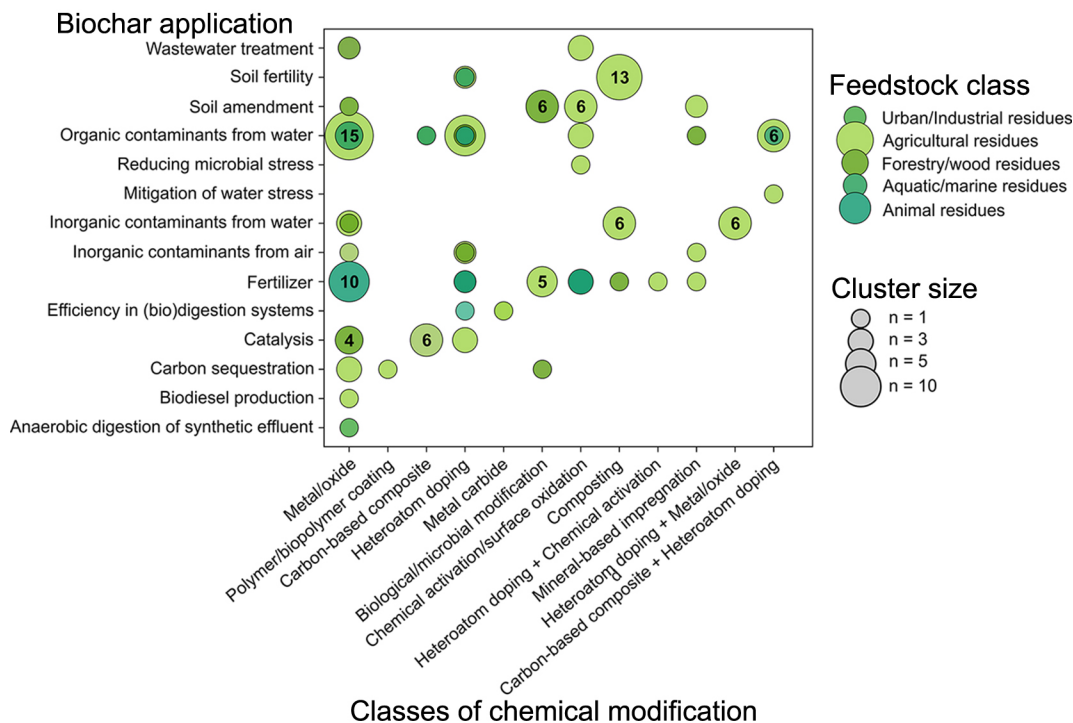


Figure 8 – Bubble plot of the relationships between biochar application, doping class, and feedstock class. Each bubble represents a unique combination of application and modification strategy, with bubble size proportional to the number of studies reporting that combination. Bubble color corresponds to feedstock class based on green tonal variations consistent with the Sankey diagram (agricultural, forestry/wood, animal, urban/industrial, and aquatic/marine residues).

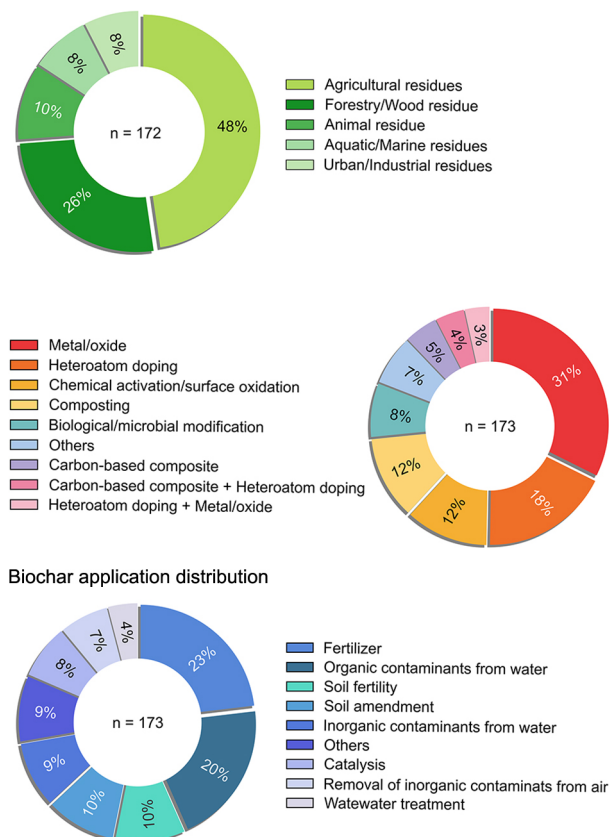


Figure 9 – Categorical distribution of studies included in the bibliometric analysis. Each chart represents a classification scheme, with segment sizes corresponding to the relative percent frequency of each category and the total number of records indicated at the center (n). Note that “n” is greater than the total number of articles evaluated since a number of studies reported more than one biomass feedstock, doping/modification method, and consequently more than one biochar application, which increased the total number of category counts.

Studies carried out in rapidly industrializing tropical countries, such as China, tend to emphasize advanced modification techniques and water-related applications (Meng et al., 2019; Wu et al., 2024), while studies from predominantly agricultural regions, such as Brazil, often focus on soil applications, using simpler modification approaches (Melo et al., 2013; Puga et al., 2016; Gomes et al., 2023; Soares et al., 2023). These differences likely reflect variations in research infrastructure, regulatory pressures, funding availability, and the urgency of environmental issues. Thus, the observed patterns highlight the importance of interpreting biochar research within its broader socio-environmental context, rather than treating modification strategies as universally applicable solutions.

The categorical overview reinforces these observations, summarizing the relative importance of feedstock classes, modification strategies, and

application fields in the literature (Figure 9). Agricultural and forestry residues clearly dominate as feedstocks, reflecting their availability and compatibility with circular economy approaches in tropical regions. At the same time, the substantial contribution of urban and industrial waste indicates a growing interest in the use of biochar as a tool for waste management and remediation in non-agricultural environments, particularly in densely populated tropical areas.

From the point of view of modification strategies, mineral- and metal-based approaches are the most frequently reported, followed by chemical activation and surface oxidation. This distribution suggests that researchers tend to prioritize strategies that offer tangible performance improvements while remaining technically feasible and economically accessible (Murtaza et al., 2024). An example of this is composting, to which biochar is added, as it is a simple, low-cost technique accessible to developing countries in tropical regions (Figure 5). More specialized approaches, such as biological modification, are still relatively rare, which points to potential opportunities for innovation, especially in low-cost or nature-based remediation frameworks.

The application categories further highlight the multifunctional nature of MB (Figure 9). Although soil fertility and conditioning remain prominent, accounting for nearly half of the reported applications (~ 48 %, n = 172), a substantial proportion of studies also address environmental remediation and contaminant immobilization, including water and wastewater treatment (~ 26.2 %), as well as other remediation-oriented uses. Carbon sequestration and climate-related applications represent an additional ~ 10 % of the records, while smaller yet relevant fractions are associated with catalysis, composting, and emerging multifunctional uses (together ~ 15-20 %).

The fact that the cumulative number of entries per category (n = 173) exceeds the number of individual studies reflects the frequent overlap of feedstocks, modification strategies, and applications within the same investigation. This quantitative overlap confirms that a single study often targets more than one application pathway, reinforcing the multifunctional design of MB.

Taken together, the patterns revealed indicate that the alignment between biochar modification strategies and intended applications in tropical regions is shaped by an interaction between production constraints, functional demands, feedstock availability, and regional priorities. Instead of converging on a single ideal design, the bibliographic references reflect a diverse landscape in which biochars are adapted to specific environmental challenges and use scenarios. This diversity underscores the need to move beyond generic formulations and toward design frameworks

that explicitly take local conditions, including climate, contamination profiles, and resource availability into account. At the same time, the synthesis highlights persistent gaps in current research.

Despite the growing number of studies on MB, relatively few address long-term stability, scalability, or performance under field conditions in tropical environments. In particular, the durability of modification-induced functionalities and their effectiveness in multiple ecosystem services remain insufficiently explored. Addressing these issues will be crucial to translating laboratory-scale advances into practical and sustainable biochar-based solutions.

Overall, the evidence synthesized in this review demonstrates that MB are increasingly being designed with clear functional objectives in mind, reflecting a maturation of the field in tropical regions. However, future progress will depend on closer integration between material design, specific application requirements, and long-term environmental performance which will ensure that biochar modification strategies are not only technically effective but also environmentally and socioeconomically viable (Alcocer-García et al., 2025; Panić et al., 2025).

Comparative performance of modified and non-modified biochar under tropical conditions

Across the entire dataset, a clear distinction emerges between applications requiring high chemical reactivity and selectivity and those focused on soil conditioning and nutrient cycling (Table 1, Figures 8-9). Approximately 52-55 % of the records are associated with water remediation applications and advanced oxidation processes, while about 30-35 % focus on soil fertility and agricultural productivity, highlighting two well-defined functional domains (Figure 9).

It is important to note that direct comparisons between modified and unmodified biochars are strongly dependent on the experimental context. Biochar performance is influenced not only by the modification strategy but also by feedstock characteristics, pyrolysis temperature, modifier chemistry, soil or aqueous matrix properties, target contaminant, climatic conditions, and experimental or incubation period. These factors can interact and substantially affect sorption, contaminant removal, nutrient availability, and agronomic responses (Beesley et al., 2011). For instance, feedstock and pyrolysis temperature influence the initial surface chemistry, porosity, mineral composition, and stability of biochar, whereas soil properties and contaminant characteristics control the mechanisms and strength of biochar-soil-contaminant interactions. Climate and incubation time may further modify these properties through aging, wetting-drying cycles,

leaching, and changes in surface reactivity (Shaaban et al., 2018). Therefore, the comparisons presented in this section should be interpreted as study-specific evidence rather than as a generalized ranking of modified versus unmodified biochars across tropical environments.

In several studies involving aquatic systems and advanced remediation processes, MB presented higher performance than their respective unmodified materials under the specific experimental conditions evaluated (Table 1). Studies employing heteroatom doping [e.g., nitrogen (N), phosphorous (P), sulfur (S)] or metal/metal oxide loading demonstrated increases in surface reactivity, electron transfer capacity, and catalytic behavior when compared to unmodified biochars (Shi et al., 2025a, b; Zhao et al., 2025).

Example of this are of this are N/P-doped biochars produced at 700-900 °C that reached specific surface areas greater than 1,100 m² g⁻¹ (up to 1,179 m² g⁻¹), associated with a high density of structural defects, which allowed for the highly efficient activation of oxidants such as peroxymonosulfate and peroxydisulfate, resulting in removals in excess of 90 % of organic contaminants in less than 30 min, even under a wide variation in pH and ionic strength (Table 1) (Shi et al., 2025b). Similarly, co-doped systems with N/S or Co-N achieve removals close to 100 % in 20-30 min, operating simultaneously via radical (SO₄⁻, OH⁻) and non-radical (direct electron transfer) pathways (Wang et al., 2025). These study-specific results illustrate how surface chemistry engineering can improve biochar performance for water treatment although the magnitude of the response depends on the properties of the pristine biochar, modifier chemistry, target contaminant, and experimental conditions.

Metal-modified biochars further illustrate the benefits of targeted functionalization. The incorporation of Fe, Al, or Mg phases substantially increases the affinity for metalloids, antibiotics, and nutrients through specific mechanisms of complexation, precipitation, and ligand exchange (Nardis et al., 2021; Soares et al., 2021; Hu et al., 2025). In Table 1, a study with bamboo biochar modified with Al/Fe indicates maximum sorption capacities (q_{max}) up to three times higher than those of biochars containing only Fe, in addition to maintaining high efficiency over a wide pH range (~ 3-9) and halving the dose required (0.5 vs 1.0 g L⁻¹) for norfloxacin removal (Hu et al., 2025). In studies conducted in Brazil, researchers observed that sugarcane straw biochar modified with FeCl₃ showed sorption kinetics 2.5 times faster for arsenic (As) and up to three times faster for lead (Pb) (Soares et al., 2021), when compared to the unmodified material, demonstrating how surface functionalization can overcome kinetic limitations typical of highly weathered tropical matrices (Table 1).

Table 1 – Characteristics and performance of engineered biochars for environmental remediation in tropical countries.

Country	Feedstock	Pyrolysis temperature (°C)	Modifying agent	Applied rate	Performance	References
China	Cellulose acetate	700	NaH ₂ PO ₄ and melamine	75 mg L ⁻¹	Nitrogen (N) and phosphorus (P) co-doping increased the specific surface area, introduced abundant mesoporosity, and generated a high density of active sites (e.g., graphitic N and C-P bonds), synergistically enhancing peroxymonosulfate adsorption and activation.	Shi et al. (2025c)
		800				
		900				
	Bamboo	900	[Al ₂ (OH)nCl _{6-n}] _m + [Fe ₂ (OH)n(Cl _{6-n}) _m]	0.5 g L ⁻¹	- Aluminum/iron-loaded biochar (AFBC) removed much higher norfloxacin than iron-loaded biochar (FBC), maintaining high efficiency across pH and requiring half the dose. - Kinetics indicated dominance of chemisorption and film diffusion, with a much higher k_{LF} for AFBC, while Langmuir isotherms revealed a threefold higher q_{max}. - The process was spontaneous and endothermic, with enhanced OH and SO₄-driven adsorption and degradation in AFBC, yielding low-toxicity byproducts.	Hu et al. (2025)
	Fruit waste	550	Alanine + K	10 and 20 g kg ⁻¹	The combined application of foliar alanine and K-enriched biochar (KBC) to soil mitigated drought stress in fenugreek, increasing plant dry weight, N, P, and K contents in roots and shoots, as well as chlorophyll content and growth under water deficit.	Ma et al. (2025)
	Chestnut shell	445	FeCl ₃	25 g kg ⁻¹	- Phosphorus- and iron-modified biochar (PFBC) had a strong synergy between cadmium (Cd) immobilization and carbon (C) sequestration in soils under flooding-drainage cycles. - PFBC enhanced Cd adsorption and coprecipitation, limited redox-driven remobilization, and suppressed microbial decomposition of organic matter, thereby promoting C retention.	Shi et al. (2025a)
	Corn cob	300	Na ₂ CO ₃ + CO(NH ₂) ₂ C ₃ H ₈ N ₆ C ₂ H ₄ N ₄ or (NH ₂) ₂ CS	0.7 g L ⁻¹	- Biochar modification via N doping and Na carbonate activation enhanced persistent free radical formation, enabling efficient activation of peroxymonosulfate and rapid aniline degradation. - The 500 °C biochar achieved > 90 % removal in 30 min with good reusability.	Zhao et al. (2025)
		400				
		500				
	Waste fir sawdust	1000	Co(NO ₃) ₂ ·6H ₂ O and Zn(NO ₃) ₂ ·6H ₂ O	0.2 g L ⁻¹	- Co-N@BC catalyst, produced by Co and N co-doping, exhibited uniformly dispersed Co nanoparticles, higher surface area, and defect-rich graphitization, increasing the availability of active sites (Co^o, surface defects, graphitic and pyridinic N, and C-N bonds). - These features enabled efficient activation of peroxymonosulfate through both radical (SO₄[•], OH) and non-radical (O₂, direct electron transfer) pathways, leading to rapid pollutant degradation and highlighting metal-heteroatom synergy in biochar-based catalysts for environmental remediation.	Wang et al. (2025)
	Coffee husk		Cu(NO ₃) ₂ ·3H ₂ O and Ce(NO ₃) ₃ ·6H ₂ O	0.2 g L ⁻¹	- The high-performance adsorbent efficiently removed phosphine (PH₃) under anaerobic, low-temperature conditions (60 °C), achieving a breakthrough capacity of 152.62 mg g⁻¹. - After PH₃ capture, it transformed in situ into a phosphorus-rich composite that functioned as a supercapacitor electrode with a specific capacitance about five times higher than the original N-doped biochar, linking gas purification with energy storage.	Liu et al. (2025)
	Bean dregs	600	Co(NO ₃) ₂ ·6H ₂ O + H ₃ BO ₃	10 g kg ⁻¹	- Bean-waste biochar co-doped with cobalt (Co) and boron (B) was highly efficient in immobilizing tetracycline in contaminated soil. - Enhanced surface area, active sites, and conductivity promoted adsorption and degradation, with B doping (Co@B0.5-DB700) driving strong Co-B synergy. - The material was stable over reuse cycles, highlighting a sustainable strategy for antibiotic-contaminated soil remediation.	Shi et al. (2025b)
		700				
		800				
	Pig manure	600	(NH ₂) ₂ CS	0.5 g L ⁻¹	- Swine biogas residues were converted into an N, S co-doped biochar (NSBC) that efficiently activated peroxydisulfate for bisphenol A (BPA) degradation. - NSBC achieved ~100 % BPA removal within 20 min and showed robust performance across a wide pH, complex ions, and real water matrices, driven mainly by electron-transfer pathways with complementary radical contributions, highlighting a sustainable route for green catalysts in wastewater treatment.	Tan et al. (2025)
Brazil	Sugarcane straw	350	FeCl ₃	0.3 g L ⁻¹	- Biochar efficiency for removing arsenic (As) and lead (Pb) from contaminated water strongly depended on pyrolysis temperature and FeCl₃ modification. - The 750 °C biochar had the best performance, with faster sorption kinetics after iron (Fe) functionalization (2.5× for As and 3× for Pb), due to increased reactive surface sites, highlighting high-temperature, Fe-modified biochar as an effective and selective material for toxic metal remediation.	Soares et al. (2021)
		750				

Continue...

Tabel 1 – Continuation.

Brazil	Bamboo Shrimp shell Sunflower straw Chicken manure	300	NH ₄ NO ₃	0.9 g kg ⁻¹	- Combining biochar from organic residues with ammonium nitrate increased soil and soil-solution N availability (NH₄⁺ and NO₃⁻), and enhanced maize growth in Oxisols. - In clayey soils, sunflower cake, and shrimp shell-derived biochars raised biomass compared to mineral N alone, indicating improved N-use efficiency and productivity in tropical conditions.	Paiva et al. (2025)
	Poultry litter				- Magnesium (Mg)-enriched biochars showed high P removal, with swine-manure biochar (PMB-Mg) reaching 68 mg g⁻¹ via P precipitation, secondary mineral formation, and ligand exchange. - Desorption was low, indicating strong binding, though some release occurred under acidic conditions.	Nardis et al. (2021)
	Pig manure	500	MgCl ₂	5 g L ⁻¹	- Langmuir fits suggested high-affinity monolayer adsorption. - In soil, P-loaded Mg-biochars equaled or exceeded triple superphosphate, improving maize growth and nutrient uptake; the addition of poultry-litter biochar (PLB-Mg-P) promoted the highest biomass and P uptake while increasing Mg availability. - Overall, P-saturated Mg-biochars are promising slow-release fertilizers for P-fixing tropical soils.	
	Sewage sludge					
		350			- Adding Mg to poultry manure before pyrolysis increased P availability in the biochars, especially at 300-600 °C.	Leite et al. (2023)
	Poultry manure	500	Mg(OH) ₂	5 g L ⁻¹	- Mg enrichment promoted the formation of more soluble Mg-P minerals while suppressing poorly available Ca-P phases, increasing extractable P.	
		650			- Although water solubility decreased, indicating reduced immediate release, the Mg-enriched biochars enabled more controlled P availability, and improved agronomic efficiency in highly adsorptive tropical soils, highlighting Mg enrichment as a promising strategy for sustainable P fertilizers.	
	Banana peels	600			- Biochars derived from tropical fruit peel wastes, especially those produced at 600 °C (DS600 and BP600), showed very high Cd(II) and Pb(II) adsorption under optimized conditions.	Limmun et al. (2025)
		800			- Metal was extracted mainly via surface complexation, ion exchange, and electrostatic attraction.	
	Monthong durian shells	400	Composting	5 g L ⁻¹	- The combined use of response surface methodology (RSM-BBD) and backpropagation neural network (BPNN) effectively predicted and optimized adsorption performance, highlighting these low-cost, scalable biochars as sustainable materials for heavy-metal remediation within a circular-economy framework.	
Thailand		600				Pearaksa et al. (2025)
	Corn cob	500	Composting	37.5 t ha ⁻¹	- The addition of biochar (CCB) corrected soil acidity, improved soil quality, and enhanced plant growth potential, photosynthetic efficiency, and productivity indices such as Performance Index (PI) and Soil Plant Analysis Development (SPAD). - These results demonstrate that biochar is an economically viable strategy for agriculture and the restoration of degraded acidic soils, while offering promising perspectives for future research on soil acidity management and control.	
	Rice straw	500	Poly(lactic acid (PLA) and poly(vinyl alcohol (PVA)-biodegradable film	1000 g kg ⁻¹	- The material showed adequate mechanical properties, rapid soil degradation, improved soil fertility and microbial activity, increased soil C and N stocks, and enhanced plant growth. - Overall, it offered a scalable, low-C strategy for residue recycling, soil health improvement, and plastic pollution reduction, particularly in rice-growing regions.	Iamsaard et al. (2025)
Nepal	Bracken	400	Composting + slurry + NPK	10 t ha ⁻¹	- Biochar combined with goat manure or enriched with cattle urine, markedly improved soil fertility by increased pH, organic C, total N, and P and potassium (K) availabilities. - Organic amendments outperformed mineral fertilization, with biochar-goat manure showing the strongest improvement in soil chemical properties.	Acharya et al. (2023)
	Eupatorium adenophorum				- The biochar-goat manure treatment produced the highest fruit yield, increasing it by up to 89 % compared with unfertilized control and was 84 % relative to mineral fertilization, while cattle urine-enriched biochar increased yield by approximately 38 %.	
Pakistan	Date palm	300	Filtered slurry	20 g kg ⁻¹	- Biochar, enriched with buffalo slurry (SEB), controlled nutrient losses and enhanced crop performance. - SEB suppressed soil N and C loss pathways, reducing nitrification, ammonification, CO₂ emissions, and nutrient leaching (N, P, and K), while increasing microbial biomass and enzymatic activity associated with nutrient cycling. - These biogeochemical gains translated into superior agronomic efficiency, with higher wheat growth, nutrient uptake, and fertilizer-use efficiency, including apparent N recovery of up to 55 % compared with 20 % in the unfertilized control, highlighting slurry-enriched biochar as an effective strategy for alkaline soils.	Javeed et al. (2021)

Continue...

Tabel 1 – Continuation.

	Banana trunk	500	ZnCl ₂ + HCl	30, 50 and 70 g kg ⁻¹	- A sulfonated biochar catalyst derived from banana pseudo stem [<i>Musa acuminata</i> (L.)] was developed through ZnCl₂ activation, pyrolysis at 500 °C, and subsequent SO₃H functionalization, yielding a thermally stable, amorphous solid acid catalyst (BT-SO₃H). - When applied as a heterogeneous catalyst in the transesterification of lipids extracted from <i>Chlorella vulgaris</i> (L.), BT-SO₃H achieved its highest performance at a 5 % dosage, producing a fatty acid methyl esters (FAME) yield of 58.29 %. - The results highlighted the novel use of agricultural-waste-derived sulfonated biochar as an efficient and sustainable catalyst for biodiesel production, rather than for soil or water applications.	Ao et al. (2024)
India	Maize stalks	470	Phosphate rock and simple superphosphate + <i>Bacillus megaterium</i> (L.)	0.75 t ha ⁻¹	- Biochar formulations enriched with <i>Bacillus megaterium</i> and rock phosphate outperformed conventional fertilizers by increasing P availability in acidic soils. - The combined biochar-farm yard manure (FYM)-rock phosphate-B. megaterium treatment enhanced P availability, stimulated acid phosphatase activity, increased microbial P biomass, and reduced Fe-P and Al-P fractions through organic acid release and improved soil pH and structure. - These biochemical improvements translated into higher P use efficiency, greater plant P uptake, enhanced microbial diversity and nodulation, and increased pigeon pea biomass and grain yield, demonstrating fortified organo-mineral biochar as a sustainable alternative to soluble P fertilizers in acidic soils.	Pandian et al. (2025)
	Maize stalks	450	Phosphate rock and simple superphosphate + <i>Bacillus megaterium</i> (L.)	0.75 t ha ⁻¹	- Organo-mineral formulations combining biochar, manure, and <i>Bacillus megaterium</i> (L.), particularly biochar enriched with superphosphate and bacterial inoculation, proved more effective than mineral fertilizer alone in increasing P availability in acidic soils. - The bioactivated organo-biochar raised soil pH and organic C content, enhanced microbial activity and acid phosphatase, reduced Fe-P and Al-P fractions through organic acid release, and improved fertilizer-use efficiency. - Field application enhanced black gram [<i>Vigna mungo</i> (L.)] growth, nodulation, P uptake, and chlorophyll content, resulting in higher grain yield and greater soil bacterial diversity, demonstrating a synergistic and sustainable strategy for improving fertility and productivity in acidic soils.	Pandian et al. (2024)
Indonesia	Palm kernel shell	300	alginate-producing bacteria	60 g kg ⁻¹	- Combining biochar with alginate-producing plant growth-promoting bacteria (PGPR) enhanced maize growth in degraded soils. - Biochar improved water retention, particularly under low-moisture conditions, leading to greater plant height, leaf area, and root development. - Corn cob biochar had the best performance. - Inoculation with alginate-producing bacteria increased nutrient use efficiency and drought tolerance, especially under water stress, demonstrating the synergistic potential of biochar-PGPR systems to improve maize productivity in dry and nutrient-poor soils.	Sukmawati et al. (2020)
		400				
	Oil palm empty fruit bunches	300				
		400				
	Corn cob	300				
		400				

The advantage of chemical modification becomes more context-dependent when the performance approach shifts from contaminant removal to soil fertility and agronomic response (Table 1, Figure 9). Approximately one-third of the studies focus directly on agricultural productivity and soil quality, and within this group, a significant portion employs unmodified or only organically enriched biochars (Figure 9).

These materials can provide substantial benefits in tropical soils, improving pH, water retention, and C stocks, with indirect effects on nutrient availability and plant growth (Acharya et al., 2023; Pandian et al., 2024; Iamsaard et al., 2025). For example, corn cob biochar applied to acidic soils resulted in 19-30 % increases in plant biomass, as well as improvements in physiological indicators such as Soil Plant Analysis Development (SPAD) and performance index, even in the absence of specific chemical doping (Pearaksa et al., 2025). These results reinforce that, for general soil conditioning applications, the structural properties,

alkalinity, and stability of biochar are often sufficient, especially when scalability and low production cost are decisive factors.

Strategic modification becomes essential when the objective is to overcome specific limitations of tropical soils, particularly the strong P fixation and low nutrient use efficiency (Table 1, Figure 8). Mg-enriched biochars, especially those derived from poultry litter and swine manure, exhibit P sorption capacities in the order of 60-70 mg g⁻¹, associated with low water desorption, which makes their application as slow-release P fertilizers viable (Nardis et al., 2021; Leite et al., 2023).

In pot and field trials, Nardis et al. (2021) observed that Mg-saturated biochars can equal or surpass triple superphosphate in terms of biomass production and P absorption, while reducing leaching losses under high rainfall regimes typical of tropical environments (Nardis et al., 2021). Furthermore, Leite et al. (2023) found that pre-pyrolysis enrichment

with $\text{Mg}(\text{OH})_2$ promoted increases of up to 20-46 % in extractable P, favoring the formation of more available Mg-P phases and suppressing poorly soluble Ca-P, which directly addresses the high P fixation capacity of highly weathered soils.

Biological and organo-mineral modifications further expand the functional scope of biochar in soil systems. Biochars combined with compost, slurry, or phosphate-solubilizing microorganisms, such as *Bacillus megaterium* de Bery, resulted in increases of up to 36 % in P availability, associated with increased phosphatase activity, the release of organic acids, and the reduction of Fe-P and Al-P fractions (Pandian et al., 2024, 2025). These biochemical gains translate into increases of up to 89 % in agricultural yield of pigeon pea [*Cajanus cajan* (L.)] compared to the unfertilized control, even surpassing conventional mineral fertilization (Pandian et al., 2025). It is important to emphasize that these approaches maintain low technological complexity, which favors their widespread adoption in tropical agriculture.

The variability among these responses also highlights the difficulty of isolating the effect of biochar modification from other experimental factors. Feedstock composition affects the initial organic and mineral matrix available for modification, while pyrolysis temperature controls aromaticity, porosity, surface functional groups, and mineral transformations (Sousa et al., 2022; Soares et al., 2026b). Modifiers introduce additional reactive sites or phases whose effectiveness depends on the target contaminant or nutrient (Qiu et al., 2022). In soils, these interactions are further influenced by pH, mineralogy, organic matter, and competing ions, meaning that the same MB may perform differently among soil types.

Climatic conditions are also particularly relevant in humid tropical environments, where high temperatures, intense rainfall, and wetting-drying or redox fluctuations can accelerate biochar aging and affect modifier stability (Soares et al., 2023, 2024). Experimental duration should likewise be considered, since short-term sorption or incubation studies may not capture changes in surface reactivity, nutrient release, contaminant retention, or modifier stability that occur over longer periods. Thus, the differences observed among studies reflect the combined influence of material properties, environmental conditions, target application, and experimental duration rather than the modification process alone.

In general, the comparative analysis demonstrates that the performance of biochar in tropical environments cannot be evaluated solely under the modified versus unmodified dichotomy. The compiled data indicate that effectiveness is directly linked to the alignment between modification strategy, target function, and environmental context. Modified biochars offer clear advantages to chemically demanding applications, such as contaminant

degradation, selective sorption, and controlled nutrient release, while unmodified or biologically enhanced biochars remain highly effective for overall soil improvement, particularly when economic and scale criteria are prioritized (Kabir et al., 2023; Souza and Ferreira, 2024).

Economic accessibility of modified biochar in tropical contexts: a relative perspective

From an economic standpoint, biochar has emerged as a competitive alternative to conventional sorbents for environmental remediation. However, economic comparisons should be interpreted cautiously because production costs vary substantially among countries, feedstocks, pyrolysis technologies, production scales, energy prices, transportation logistics, labor costs, and regulatory frameworks. Consequently, there is no universal production cost for either pristine or MB, and values reported in the literature should be regarded as context-specific rather than broadly representative.

Nevertheless, biochar can often be produced at substantially lower costs than conventional sorbents. In 2020, biochar produced from woody biomass for wastewater treatment was estimated to cost between US\$ 91 and 319 t^{-1} , whereas activated C and synthetic zeolites were estimated at approximately US\$ 1,500 t^{-1} and US\$ 6,000 t^{-1} , respectively (Sun et al., 2022; Borges et al., 2025). Although these values should not be generalized across production systems, they illustrate the potential economic advantage of biochar under favorable production conditions.

Feedstock selection represents one of the major determinants of production cost. Agricultural residues, forestry by-products, sewage sludge, livestock manure, and agro-industrial wastes are often inexpensive or even associated with disposal costs, creating opportunities for simultaneous waste management and biochar production. Sewage sludge, for example, is marketed at relatively low prices in some countries; in Germany, reported values ranged from US\$ 21 to 43 t^{-1} , with the material primarily destined for the cement industry or agricultural applications (Geller et al., 2009; Dart, 2019). Converting these residues into biochar can increase their value by stabilizing contaminants, improving sorption properties, and reducing disposal requirements. However, feedstock price alone rarely indicates economic feasibility. Drying, grinding, transportation, pyrolysis efficiency, storage, and field application frequently account for a substantial proportion of total production costs, particularly where biomass sources and treatment facilities are geographically dispersed.

In tropical regions, biomass availability generally favors biochar production, but economic feasibility remains highly dependent on local infrastructure, energy availability, transportation networks, and market development. In Brazil, for

example, reported production costs range from US\$ 133 to 297 t⁻¹ depending on biomass type, reactor design, production scale, and pyrolysis conditions (Investalk, 2024; Sylvera, 2026). These estimates provide useful regional benchmarks but should not be extrapolated to other tropical countries, where socioeconomic conditions and production systems differ considerably. Consequently, economic assessments should preferably be conducted at regional rather than global scales.

Additional uncertainty arises when chemical modification or nanostructuring is incorporated. Although these approaches frequently improve adsorption capacity, catalytic activity, or selectivity toward target contaminants, they also introduce additional costs associated with reagent acquisition, grinding, washing, solvent consumption, energy demand, process control, waste management, and quality assurance. Moreover, the magnitude of these costs varies widely according to the modification strategy, modifier loading, recovery and recycling of reagents, and process integration. Considering the average production cost of biochar in Brazil, together with milling (~ US\$ 58 t⁻¹) (SOBRATEMA, 2024) and the use of 3-mercaptopropyltrimethoxysilane (~ US\$ 730 t⁻¹), the estimated total production cost reaches US\$ 921-1,085 t⁻¹, corresponding to an increase of approximately 265-597 % relative to unmodified biochar. These estimates illustrate the potential economic impact of high-value chemical modifiers rather than representing a universal cost for MB.

Importantly, higher production costs do not necessarily imply lower economic competitiveness. Modification may substantially increase adsorption capacity, contaminant selectivity, catalytic efficiency, or material longevity, potentially reducing the amount of sorbent required or extending operational lifetime. Therefore, the economic performance of MB should not be evaluated solely on the basis of production cost, but rather through integrated metrics such as treatment efficiency per unit cost, regeneration potential, operational lifetime, and cost per unit of contaminant removed. Unfortunately, such analyses remain scarce in the current literature, particularly under tropical conditions.

Scalability represents an additional challenge. Many modification strategies have been demonstrated only at laboratory scale using gram-scale synthesis under highly controlled conditions. Their transition to industrial production may be constrained by reagent consumption, water demand, energy requirements, corrosion of processing equipment, generation of secondary waste streams, and the need for consistent quality control. In contrast, relatively simple approaches based on mineral impregnation, steam or CO₂ activation, or the incorporation of locally available agricultural and industrial residues may offer greater scalability because they require

fewer processing steps and lower chemical inputs. Future studies should therefore evaluate modification strategies not only according to their laboratory performance but also according to their technological readiness, operational complexity, and compatibility with existing biomass processing infrastructure.

Overall, the economic accessibility of MB in humid tropical regions will depend on balancing performance gains with production costs and implementation feasibility. Highly engineered materials may be justified for applications requiring exceptional adsorption capacity or contaminant selectivity, whereas conventional or minimally MB produced from locally available waste streams are likely to remain the most realistic option for large-scale environmental remediation and soil management.

Future researches should prioritize low-cost modification strategies, integration of biochar production into existing waste management systems, standardized techno-economic assessments, life-cycle analysis, and region-specific cost-benefit evaluations. Such an approach will help identify modification pathways that are not only technically effective but also economically competitive and scalable under the diverse environmental and socioeconomic conditions found across tropical regions.

Environmental risks associated with modified biochar

Although modification can substantially improve biochar performance, it may also introduce environmental risks that remain poorly understood, particularly under tropical conditions. High rainfall, intense weathering, fluctuating redox conditions, and rapid organic matter turnover may accelerate the transformation of both the biochar matrix and incorporated modifiers. Therefore, environmental safety should be evaluated not only by initial performance but also by the long-term stability, mobility, and biological effects of engineered functional phases.

A major concern is the stability of mineral modifiers after soil application. The persistence of Fe-, Mn-, Al-, Ca-, or Mg-based phases depends on pH, redox potential, dissolved organic matter, and competing ligands (Xu and Tsang, 2024). Their dissolution, recrystallization, or surface passivation may alter sorption capacity and release previously immobilized contaminants or modifier-derived elements (Yang et al., 2018). Because these processes are closely linked to Fe, Mn, P, S, and C biogeochemical cycles, contaminant immobilization observed in short-term studies may not be maintained under field conditions.

The potential release of nanoparticles also deserves attention. Mechanical disturbance, weathering, and microbial activity may detach

engineered nanoparticles from the biochar surface, increasing their mobility and interactions with soil colloids and biota (Chausali et al., 2021). Similarly, the ecotoxicological effects of modifiers, residual reagents, and fine C particles remain poorly characterized and may influence microbial activity, nutrient cycling, and soil ecological functions.

Long-term aging further complicates these processes by altering surface functional groups, promoting organo-mineral associations, and modifying the accessibility of reactive sites (Wang et al., 2020; Soares et al., 2022). Consequently, short-term laboratory experiments cannot fully predict the environmental behavior of MB under tropical field conditions.

Regulatory frameworks have not kept pace with the development of engineered biochars. Current quality standards generally address conventional biochar properties but rarely consider modifier stability, nanoparticle release, ecotoxicity, or long-term environmental persistence. Similarly, life-cycle assessment remains scarce, despite being essential to determining whether the environmental benefits of modification outweigh the impacts associated with reagent production, energy consumption, waste generation, and end-of-life management.

Overall, future studies should integrate long-term aging, modifier leaching, nanoparticle release, ecotoxicological assessments, life-cycle analysis, and field validation to ensure that MB remain chemically stable, environmentally safe, and effective under the dynamic biogeochemical conditions of tropical soils.

Knowledge gaps and future research priorities for modified biochar in tropical regions

Despite the rapid expansion of MB research in tropical regions, important knowledge gaps still constrain its transition from experimental studies to field-scale applications. The main priorities identified from the reviewed bibliographic references concern the persistence of modification-induced surface properties under tropical pedoenvironments, the long-term stability of reactive functional groups and mineral modifiers, field validation, economic feasibility, mechanistic understanding, and the assessment of potential unintended biogeochemical impacts associated with MB application.

A major research priority is determining whether the properties introduced by modification persist under tropical environmental conditions. Most available studies focus on short-term responses under controlled conditions, providing limited information on how reactive surface sites, functional groups, mineral phases, and incorporated modifiers evolve after prolonged exposure to high temperatures, intense rainfall, wetting-drying cycles, flooding-

draining events, and intense microbial activity. These conditions promote continuous oxidation-reduction reactions, mineral weathering, organic matter turnover, and fluctuations in ionic strength that may alter surface complexation reactions, destabilize metal-bearing phases, transform oxygen-containing functional groups, and modify the electrochemical properties responsible for contaminant retention and nutrient adsorption.

Similarly, repeated changes in pH and redox potential may affect the stability of Fe-, Mn-, or Ca-based modifiers through dissolution, recrystallization, or secondary mineral formation, progressively changing the abundance and reactivity of sorption sites. Long-term field experiments coupled with accelerated aging studies are therefore required to determine whether the mechanisms responsible for the superior performance of MB remain operative under tropical conditions.

Greater emphasis should also be placed on field validation. Contaminant-removal experiments frequently rely on synthetic solutions, whereas agronomic studies are commonly conducted in pots or over short experimental periods. These conditions do not reproduce the spatial and temporal variability of tropical soils, where the composition of the soil solution is continuously regulated by mineral weathering, organic matter decomposition, root activity, and microbial processes.

Field studies should evaluate how dissolved organic matter, competing ligands (e.g., phosphate, silicate and low-molecular-weight organic acids), fluctuating redox conditions, and seasonal changes in microbial activity influence the stability of surface complexes, contaminant speciation, nutrient dynamics, and the persistence of modification-induced functionalities. They should also assess whether modifier dissolution or surface aging alters the mobility of associated elements or affects coupled C, N, P, Fe, Mn, and S biogeochemical cycles over time.

Economic feasibility and scalability represent another major research frontier. Modification procedures involving chemical reagents, metal salts, repeated processing steps, or energy-intensive treatments may produce highly functional materials but can substantially increase production costs. This issue is particularly relevant in tropical regions where access to infrastructure and financial resources may be limited. Researchers should prioritize simpler modification routes based on locally available minerals, agricultural and industrial residues, and low-energy or biological processes. Life-cycle assessment, techno-economic analysis, and region-specific cost-benefit evaluation should become integral components of MB development rather than being considered only after technical performance has been demonstrated.

Further researches are also needed to clarify the mechanisms controlling MB behavior in tropical soils. Particular attention should be given to interactions among MB surfaces, Fe and Al oxyhydroxides, soil organic matter, nutrients, contaminants, and microbial communities. Future studies should integrate molecular-scale spectroscopy with isotope tracers, sequential fractionation, and reactive transport approaches to distinguish adsorption from coprecipitation, surface precipitation, ligand exchange, and redox-driven transformations. Such information is essential to identifying the dominant mechanisms controlling contaminant stabilization, nutrient retention, and the persistence of modification-induced reactive interfaces under tropical weathering conditions.

Finally, future MB development should move from broadly testing modification techniques toward designing materials for specific environmental and agronomic constraints. Application-oriented frameworks integrating locally available feedstocks, soil mineralogy and chemistry, target contaminants or nutrients, climatic conditions, infrastructure, and production costs could guide the selection of appropriate feedstock-pyrolysis-modification combinations.

Such frameworks should also consider the expected geochemical stability of modifiers under different pedoclimatic settings, allowing materials to be designed according to the dominant soil-forming processes and biogeochemical constraints of tropical environments rather than solely on their initial laboratory performance.

Final Remarks

Research into MB in tropical regions has expanded rapidly, particularly since 2022, accompanied by increasing diversification of feedstocks, modification strategies, and agricultural and environmental applications. However, research activity remains geographically uneven, indicating that the current evidence base does not represent the diversity of tropical soils and production systems equally.

Biochar modification consistently emerges as a means of tailoring physicochemical properties, including surface area, surface charge, functional group composition, nutrient content, and affinity for contaminants. These changes have supported applications ranging from soil acidity correction and nutrient management to contaminant immobilization and water treatment. Nevertheless, no single modification strategy was consistently superior, and performance varied according to feedstock, pyrolysis conditions, modification method, target application, and environmental characteristics.

This dependence on environmental context is particularly important in humid tropical soils, where strong weathering, acidity, variable surface charge, and the abundance of Fe and Al oxyhydroxides influence

nutrient retention, P dynamics, and contaminant interactions. Consequently, the effectiveness of MB cannot be attributed solely to the properties of the engineered material but must be understood within the soil-biochar system in which it is applied.

Overall, the available evidence supports MB as a versatile platform for tailoring biochar functionality to specific agricultural and environmental applications in tropical regions. Its broader contribution to sustainable agriculture, waste valorization, and environmental remediation will ultimately depend on matching modification strategies to local soil constraints and target functions while maintaining sufficient technical performance at an economically feasible scale.

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Authors' Contributions

Conceptualization: Soares MB, Oliveira IKR. **Data curation:** Soares MB, Oliveira IKR. **Formal analysis:** Soares MB, Oliveira IKR. **Funding acquisition:** Alleoni LRF. **Investigation:** Soares MB, Oliveira IKR. **Methodology:** Soares MB, Oliveira IKR. **Project administration:** Soares MB, Alleoni LRF. **Resources:** Soares MB, Alleoni LRF. **Supervision:** Alleoni LRF. **Writing-original draft:** Soares MB, Oliveira IKR. **Writing-review & editing:** Soares MB, Alleoni LRF, Oliveira IKR.

Conflict of interest

The authors declare no competing interests.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of use of AI technologies

No AI technologies were used during the writing process.

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