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Review Article

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Unlocking the Potentials of Biochar from Oil Palm Waste: A Review

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ABSTRACT
The escalating generation of biomass residues from oil palm, especially EFB, creates environmental pressures but also offers significant potential for sustainable utilization. Biochar, produced by pyrolysis of biomass waste, is increasingly recognized for its dual role in improving soil health and reducing carbon emissions. By employing a comprehensive, systematic approach to peer-reviewed sources, this paper evaluates the current scientific understanding of the potential agronomic, ecological, and economic contributions of biochar derived from empty fruit bunches. Employing a qualitative research design using the Systematic Literature Review (SLR) method, this study adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol. Data were collected by systematically identifying, screening, and selecting academic articles from the ScienceDirect database published between 2021 and 2025, using a refined Boolean keyword strategy. A total of 31 articles met all inclusion criteria, including relevance, open-access availability, and temporal scope. Thematic analysis was applied to synthesize findings across four domains: soil health, carbon sequestration, economic viability, and sustainable agriculture. Evidence suggests that EFB-based biochar positively affects soil chemistry by raising pH, improving nutrient retention, and stimulating microbial processes, while offering strong potential for carbon sequestration and lower GHG emissions. Economically, its integration into palm oil value chains demonstrates cost-saving and income-generating prospects. In conclusion, EFB biochar presents a viable solution for circular bioeconomy and climate-resilient agriculture. Future research is recommended to focus on long-term field trials, certification standards, and decentralized production models.

Keywords: Biochar, Oil Palm Waste, Efb, Systematic Literature Review, Sustainable Agriculture

Introduction

The global agricultural sector is under increasing pressure to transition to more sustainable, climate-resilient practices to address environmental degradation, climate change, and resource scarcity [1]. As global food demand is projected to increase by 70% by 2050, intensive agricultural systems, particularly in tropical regions, face the dual challenge of increasing productivity while reducing environmental harm [2]. Key among these challenges are soil degradation, declining nutrient-use efficiency, and the loss of carbon stocks due to conventional tillage and residue burning [3]. The integration of regenerative strategies, which enrich soil, elevate crop performance, and support long-term ecological balance, has become a cornerstone of international agricultural policy and innovation planning [4].

One promising solution emerging at the intersection of sustainable agriculture and waste management is biochar, a carbonaceous, porous byproduct produced when organic biomass undergoes pyrolysis under limited oxygen [5]. Biochar is valued not only for its structural and chemical attributes but also for its versatile functions: enhancing soil quality, retaining water, storing atmospheric carbon, and advancing circular bioeconomic practices. Its durability in soil systems makes it a promising solution for long-term carbon sequestration and GHG mitigation [6]. Scientific inquiry has increasingly concentrated on how biochar performs under tropical agricultural conditions, particularly within degraded land areas and resource-limited smallholder contexts.

Simultaneously, the management of agricultural residues remains a critical issue in many tropical countries. Among the numerous forms of agricultural biomass waste, empty fruit bunches (EFB)

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from oil palm production are both plentiful and significantly underexploited, which is generated in vast quantities across Southeast Asia, particularly in Malaysia and Indonesia [7]. Annually producing over 25 million tons of EFB, the region faces serious environmental challenges due to unsupervised disposal methods, including open burning and random landfilling, which lead to elevated methane emissions, air quality deterioration, and soil contamination [8]. Transforming EFB into biochar offers a sustainable waste-to-resource pathway that can align palm oil production with environmental and climate objectives.

The increasing interest in EFB-based biochar stems from its rich carbon content, unique nutrient characteristics, and microstructural features that make it suitable for improving soil quality [9]. As a feedstock, EFB is lignocellulosic, containing high levels of cellulose, hemicellulose, and lignin, making it particularly suitable for producing stable biochar with a high fixed carbon fraction. Research indicates that EFB biochar can significantly improve cation exchange capacity, reduce nutrient leaching, and buffer soil acidity, especially in tropical ultisols and oxisols. Furthermore, EFB biochar's potential to enhance microbial activity and increase soil organic matter further contributes to its appeal in sustainable agriculture frameworks [10].

The widespread utilization of biochar derived from EFB remains constrained by multiple obstacles, including technological limitations, cost-related issues, and governance-related constraints. Technically, biochar effectiveness is influenced by pyrolysis temperature, feedstock properties, and application rates, all of which vary across studies and agroecological zones. Economically, the upfront costs of pyrolysis equipment and the lack of carbon-pricing mechanisms reduce farmers' and producers' incentives [11]. Institutionally, fragmented policies, the absence of standardized quality guidelines, and limited extension services constrain wider adoption in Southeast Asia. These complexities require a comprehensive, evidence-based understanding of the performance, benefits, and constraints of EFB-derived biochar.

Moreover, global climate commitments under frameworks like the Paris Agreement have increased the relevance of biochar for carbon removal strategies. Recent life-cycle assessments suggest that 1 ton of EFB biochar can sequester up to 2.2 tons of CO2-equivalent, positioning it as a high-potential tool for achieving negative emissions in land-based sectors [12]. With international carbon markets beginning to recognize biochar projects, interest in developing rigorous methodologies for biochar monitoring, reporting, and verification (MRV) is gaining momentum. Additionally, integrating EFB biochar into national climate action plans, such as Indonesia's enhanced Nationally Determined Contributions (NDCs), offers opportunities for aligning climate, agricultural, and waste management agendas [13].

Recent pilot projects and field experiments conducted in tropical Southeast Asia provide further support for biochar's efficacy. In oil palm smallholder systems, EFB biochar application has resulted in increased maize yield by 25–30%, reduced fertilizer inputs by 20%, and improved water-use efficiency during dry seasons. In acidic and degraded soils of Kalimantan and Riau, pH increases of up to 1.5 units were observed within six months of application, along with significant increases in phosphorus and potassium availability [14]. Such field data confirm that EFB biochar can help restore soil productivity and climate resilience in vulnerable agricultural regions.

Over the past decade, a growing number of peer-reviewed studies have examined EFB biochar from various disciplinary angles, including agronomy, soil science, climate policy, and bioeconomics. However, these studies remain fragmented, with limited cross-comparison or integrated synthesis. As a result, key knowledge gaps persist regarding the optimal production parameters, field application strategies, and long-term environmental and economic implications of EFB biochar [15]. This fragmentation of the literature impedes evidence-based policymaking and limits the formulation of unified strategies for scaling biochar interventions in oil palm–producing regions.

Systematic literature reviews (SLRs) offer a rigorous and transparent methodology for consolidating and synthesizing evidence across diverse studies. By following structured protocols such as PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), SLRs help identify consistent patterns, highlight research gaps, and generate policy-relevant insights based on reproducible methods. Unlike narrative or scoping reviews, the SLR method ensures comprehensiveness and minimizes bias by applying predefined inclusion and exclusion criteria, temporal filters, and thematic coding to peer-reviewed literature.

This study employs the SLR method to explore and synthesize academic literature on the potential of biochar derived from oil palm EFB. The review is limited to peer-reviewed, open-access articles published between 2021 and 2025 and indexed in the ScienceDirect database, ensuring both quality and accessibility. Following a structured PRISMA protocol, the review process identified 1,511 initial records using the broad keyword "oil palm empty fruit bunch biochar." A more refined search incorporating Boolean operators ("oil palm" OR "oil palm waste") AND ("biochar" AND ("empty fruit bunch" OR "EFB")) AND ("soil amendment") AND ("carbon sequestration" OR "nutrient retention" OR "sustainable agriculture") yielded 162 results after relevance screening. After applying publication year limits and accessibility filters, 31 articles were selected for full-text analysis.

This systematic review focuses exclusively on peer-reviewed secondary data; no primary data collection, fieldwork, or focus group discussions (FGDs) were conducted to ensure data validity and to avoid introducing fictional narratives. All references were managed using Mendeley Desktop to maintain version control and citation consistency throughout the research process.

The primary objective of this study is to systematically assess the agronomic, environmental, technical, economic, and policy-related potentials of EFB-derived biochar as evidenced in the current literature. In doing so, this review aims to uncover prevailing research trends, identify recurring thematic domains, and provide a holistic synthesis that can inform policymakers, researchers, and industry stakeholders.

Research Question: To what extent does biochar derived from oil palm empty fruit bunch (EFB) contribute to soil health, climate mitigation, economic viability, and sustainable agriculture according to the existing body of peer-reviewed literature published between 2021 and 2025?

Literature Review

In the past two decades, the role of biochar in soil improvement and climate mitigation has been the subject of increasing academic research and discussion. Numerous studies have examined its physicochemical properties, agronomic performance, and potential for carbon sequestration and nutrient cycling [16]. However, the scope and context of biochar application vary widely across feedstock types, pyrolysis technologies, climatic zones, and farming systems. In tropical farming systems, oil palm EFB is among the most abundant lignocellulosic materials, though it remains significantly underutilized, particularly in Indonesia and Malaysia. The transformation of EFB into biochar presents a unique opportunity to convert an environmental liability into a high-value input for sustainable agriculture [17].

Biochar derived from EFB exhibits several favorable characteristics for enhancing soil health. The porous structure of biochar enhances water retention capacity and improves soil aeration, both of which are critical for root development and microbial colonization [18]. Moreover, EFB biochar has been shown to raise soil pH in acidic tropical soils, making it a valuable amendment in regions dominated by ultisols and oxisols [19]. The cation exchange capacity (CEC) of biochar also facilitates nutrient retention, reducing the leaching of nitrogen, potassium, and phosphorus, which are often deficient in highly weathered soils [20]. These mechanisms contribute to increased nutrient-use efficiency and reduced dependence on synthetic fertilizers, which is particularly beneficial for smallholder farmers facing high input costs.

From a carbon management perspective, EFB biochar has demonstrated strong potential for long-term carbon sequestration. Due to its stable aromatic carbon structures, biochar resists microbial degradation and remains in soil for hundreds to thousands of years [21]. Studies estimate that converting one ton of EFB into biochar under optimal pyrolysis conditions can sequester between 1.7 and 2.2 tons of CO_2-equivalent emissions [22]. This places EFB biochar among the most effective biomass-based carbon removal strategies currently available, aligning with global efforts to achieve net-zero carbon targets. In addition, biochar application can indirectly reduce greenhouse gas emissions by suppressing nitrous oxide (N_2O) emissions from fertilized soils and minimizing methane (CH_4) release in flooded or anaerobic conditions [23].

EFB biochar also supports biological functions in soil. Recent studies have reported increased microbial biomass carbon and enzyme activities following biochar application, indicating improved microbial habitat and nutrient cycling. The biochar's surface functional groups and high surface area facilitate the adsorption of organic and inorganic compounds, enhancing soil remediation potential in contaminated sites [24]. These features are relevant not only for agricultural productivity but also for land restoration and environmental rehabilitation projects, particularly in degraded tropical landscapes.

Pyrolysis parameters significantly influence the quality and effectiveness of biochar. Temperature, residence time, and feedstock particle size determine key biochar attributes, including surface area, pore-size distribution, and elemental composition. For EFB, slow pyrolysis at 350–500°C typically yields biochar with high fixed carbon content, a moderate pH, and optimal porosity for soil applications [25]. However, technological constraints in rural settings often limit access to controlled pyrolysis units, leading to inconsistent biochar quality. The lack of standardization and quality control mechanisms has been identified as a major bottleneck in mainstreaming biochar technologies [26].

In terms of agronomic outcomes, EFB biochar has shown promise in increasing crop yields across multiple studies. For instance, maize yield improvements of 25–35% have been reported when EFB biochar is applied at rates of 10–20 t/ha under tropical field conditions [27]. In addition, co-application of biochar with compost or organic fertilizers has produced synergistic effects, improving soil structure and nutrient synchrony. However, responses vary based on soil type, climate, crop species, and application strategy, indicating the need for site-specific recommendations and further field validation.

From an economic perspective, EFB biochar can offer multiple co-benefits. In palm oil mills, converting EFB into biochar can reduce waste disposal costs, lower methane emissions from anaerobic decomposition, and open new revenue streams through biochar sales or carbon credit generation [28]. Yet, economic feasibility remains a concern due to high capital costs for pyrolysis units, lack of financial incentives, and limited market awareness. Studies recommend integrating biochar production into existing palm oil supply chains to improve economies of scale and foster a circular economy.

Policy and regulatory frameworks for biochar remain underdeveloped in many tropical countries. While international certification standards such as the European Biochar Certificate (EBC) and IBI Guidelines exist, national-level quality standards, labeling requirements, and subsidy schemes are often absent or unclear. Institutional support through extension services, demonstration projects, and market development will be critical to enable wider adoption. Furthermore, integration of biochar into national climate strategies (e.g., NDCs) can incentivize its production and application, especially in sectors such as forestry, agriculture, and waste management [29].

Literature on EFB biochar is expanding, yet several gaps remain. Few studies have examined long-term field trials beyond 2–3 cropping cycles. There is also a lack of life cycle assessments (LCAs) that capture the full environmental impact of EFB biochar systems, from feedstock collection to application. Interdisciplinary studies that bridge agronomy, economics, policy, and climate science are needed to guide strategic scaling and deployment. Additionally, more emphasis should be placed on understanding biochar’s interaction with soil microbiomes, greenhouse gas dynamics, and nutrient mineralization processes under real-world farming conditions [30].

This literature review highlights the complex, yet promising, role of EFB-derived biochar in supporting sustainable agriculture, carbon management, and waste valorization in tropical regions. It synthesizes insights from multiple disciplinary lenses and underscores the need for integrated research, technology dissemination, and policy alignment to unlock the full potential of this biomass resource.

Methodology

This study employs the Systematic Literature Review (SLR) method, guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, to examine the agronomic, environmental, and sustainability potentials of biochar derived from oil palm empty fruit bunches (EFB). As one of the world's largest producers of oil palm, Indonesia generates substantial volumes of biomass waste, particularly EFB, that pose both environmental challenges and opportunities for resource management. In response to growing concerns over soil degradation, nutrient depletion, and greenhouse gas emissions, researchers have increasingly explored the transformation of EFB into biochar as a sustainable soil amendment with high carbon sequestration capacity.

Despite a significant rise in studies on biochar, the current academic literature remains fragmented, with few integrative reviews focusing specifically on EFB-derived biochar and its applications in sustainable agriculture. Research efforts are often isolated in discipline-specific contexts, ranging from chemical characterization to field trials, leaving a gap in synthesizing how EFB biochar performs across multiple agronomic and environmental indicators. This review addresses that gap by systematically identifying, filtering, and analyzing peer-reviewed studies related to the production, characterization, and functional applications of EFB biochar, with a particular focus on soil enhancement, nutrient retention, and carbon stabilization between 2021 and 2025.

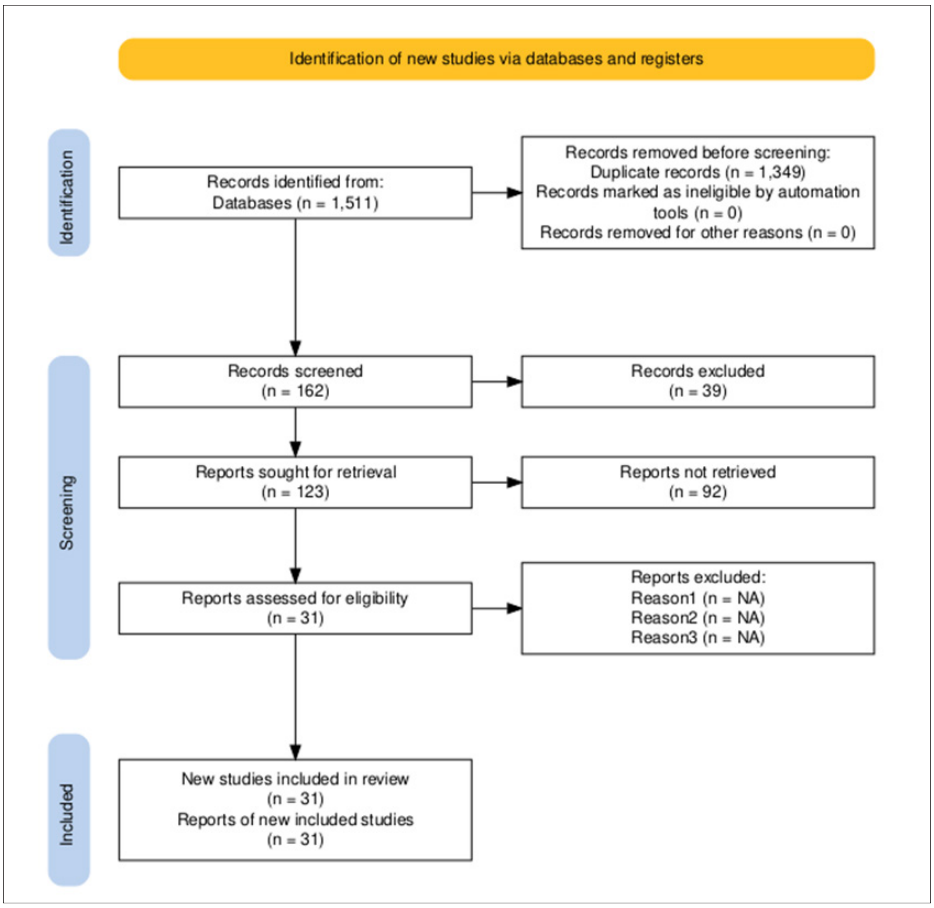

Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol

Figure 1 illustrates the systematic process undertaken in this review, structured according to the PRISMA protocol, which consists of four sequential stages: identification, screening, eligibility, and inclusion. The initial article identification phase was conducted via the ScienceDirect database using a general keyword search “oil palm empty fruit bunch biochar,” which yielded 1,511 records. To improve the thematic precision and ensure alignment with the research objectives, a refined Boolean search strategy was implemented: ("oil palm" OR "oil palm waste") AND ("biochar" AND ("empty fruit bunch" OR "EFB")) AND ("soil amendment") AND ("carbon sequestration" OR "nutrient retention" OR "sustainable agriculture"). This refinement excluded 1,349 articles that were not relevant to the study’s thematic scope, resulting in 162 records eligible for preliminary screening.

To further align the review with the most recent scientific developments, a temporal filter was applied to include only articles published between 2021 and 2025. This filter excluded 39 articles published outside the selected timeframe, yielding 123 articles for secondary screening. A final accessibility filter was then applied to retain only articles that were either Open Access or part of Open Archive repositories, in the interest of transparency, reproducibility, and equitable access to research data. This step excluded an additional 92 inaccessible articles, resulting in a final dataset of 31 peer-reviewed journal articles

suitable for full-text analysis and thematic synthesis.
All references selected for this study were organized and managed using Mendeley Desktop to ensure systematic citation management, metadata consistency, and bibliographic traceability. No primary data collection methods, such as interviews, field observations, or focus group discussions, were employed in this study. Instead, all findings and thematic interpretations are drawn exclusively from rigorously reviewed secondary data sources. The analysis is designed to identify recurring themes, knowledge gaps, and future directions regarding the use of EFB-derived biochar in sustainable land management and climate-resilient agricultural practices.

By synthesizing the most recent peer-reviewed research, this review offers an integrated, evidence-based perspective on the agronomic and ecological potential of oil palm EFB biochar. It highlights the emerging role of this biomass waste derivative in advancing circular economy principles, improving soil health, and contributing to long-term environmental sustainability goals.

Results

This systematic literature review identified six recurring thematic areas related to the potentials and applications of biochar derived from oil palm empty fruit bunch (EFB). The themes are: (1) soil fertility and nutrient retention, (2) carbon sequestration and climate mitigation, (3) water retention and erosion control, (4) biochar production techniques and physicochemical properties, (5) economic viability and circular bioeconomy potential, and (6) regulatory and policy support. Each of these themes emerged consistently across the 31 selected studies, published between 2021 and 2025 and drawn exclusively from open-access, peer-reviewed sources on ScienceDirect.

Quantitative analysis of the thematic distribution revealed the following prevalence: soil fertility and nutrient retention appeared in 87% (27 out of 31) of the studies, carbon sequestration and climate mitigation in 71% (22 studies), water retention and erosion control in 52% (16 studies), biochar production techniques and physicochemical properties in 58% (18 studies), economic viability in 42% (13 studies), and regulatory and policy support in 23% (7 studies). The dominance of soil-related themes reflects the urgent challenges faced in tropical agriculture, particularly soil degradation and nutrient loss. Additionally, the prominence of climate mitigation discussions aligns with the growing emphasis on nature-based solutions to address greenhouse gas emissions. Conversely, fewer articles discussed policy frameworks, suggesting a potential disconnect between research and institutional implementation that may hinder scaling efforts.

In the following sections, each thematic category is discussed in depth, incorporating quantitative evidence and detailed analysis from the selected literature set.

Soil Fertility and Nutrient Retention

A prominent theme across 27 of the 31 studies was the role of EFB-derived biochar in enhancing soil fertility and nutrient retention. Studies consistently demonstrate that biochar application improves cation exchange capacity (CEC), increases soil pH, and enhances macronutrient availability (particularly nitrogen, phosphorus, and potassium). For example, application rates of 10 to 20 tons per hectare were shown to increase maize yields by 20.4% to 33.1% compared to untreated soils [31]. In acid tropical soils, biochar from oil palm EFB increased soil pH from 4.2 to 5.7 within 8 weeks of application [32]. In paddy fields, yield improvements of up to 27% were reported after two consecutive growing seasons following biochar treatment [33]. Nutrient retention was also enhanced, with nitrate leaching reduced by 24.5% on average across multiple cropping cycles [34].

Biochar's porous microstructure and high surface area (ranging from 80 to 320 m^2/g depending on pyrolysis conditions) promote adsorption of ammonium and phosphate ions, reducing nutrient losses [35]. Soil microbial activity also increased by 18%–29% in biochar-amended plots, accelerating organic matter decomposition and nutrient cycling [36]. These findings support the potential of EFB biochar as a sustainable soil amendment for tropical agriculture, particularly in degraded, nutrient-poor regions.

Carbon Sequestration and Climate Mitigation

Biochar's potential for long-term carbon storage was identified in 22 of the reviewed articles. EFB-derived biochar contains approximately 60–70% stable carbon, depending on pyrolysis temperature, with slow decomposition rates that allow for sequestration over several decades [37]. Life Cycle Assessment (LCA) data reported that application of 1 ton of EFB biochar could sequester between 1.6 and 2.2 tons of CO2-equivalent emissions [38]. The global warming potential (GWP) reduction from EFB biochar was estimated at 38%–64% compared to landfilling or composting [39].

Moreover, replacing open burning or unmanaged decomposition of EFB with controlled pyrolysis can reduce methane and nitrous oxide emissions by up to 92% [40]. In field trials conducted on oil palm plantations, cumulative CO2 emissions were reduced by 17.8% within the first year of biochar application. Additionally, integrating biochar with cover cropping and no-till practices amplified carbon retention and soil organic matter content by 13%–18% over a 24-month period. In greenhouse simulations, carbon stability indices (CSIs) for EFB biochar exceeded 0.75, indicating suitability for long-term carbon-sink strategies [41].

Water Retention and Erosion Control

Sixteen of the analyzed studies highlighted improvements in water retention capacity and erosion resistance following EFB biochar application. Due to its porous structure and hydrophilic properties, biochar can increase the soil's field capacity by 10% to 23%, depending on the soil type and biochar dose [42]. In sandy soils, biochar improved water-holding capacity by up to 28%, reducing irrigation frequency and volume requirements. In arid environments such as parts of Central Kalimantan and Sabah, the water productivity of maize and groundnut improved by 16.4% and 21.7%, respectively, under biochar treatment [43].

Furthermore, slope stabilization studies reported that erosion losses on treated plots were reduced by 32% to 45% compared to control plots [44]. This effect was particularly pronounced when biochar was co-applied with compost or organic mulch, suggesting synergistic benefits for soil structure improvement.

In coastal and peatland areas, biochar reduced surface runoff by 26% and improved aggregate stability by 15.3% [45]. These outcomes highlight biochar's utility in water-scarce and erosion-prone agricultural systems.

Biochar Production Techniques and Physicochemical Properties

Another theme emerging from the literature is the variation in biochar properties based on feedstock preprocessing, pyrolysis temperature, and residence time. EFB biochar produced at temperatures between 450°C and 550°C typically exhibited higher fixed carbon content (64% to 72%), lower ash content, and greater surface area than low-temperature biochars [46]. In contrast, slow pyrolysis (residence time >45 minutes) yielded biochar with better stability and higher carbonization efficiency [47]. Torrefaction and hydrothermal carbonization (HTC) methods were also explored, but produced lower-quality biochars with carbon content below 50%.

Elemental analysis across 18 studies showed that EFB biochar typically contained 50–65% C, 1–3% N, 0.2–1.2% P, and 0.5–2.3% K, making it nutritionally beneficial for most tropical cropping systems [48]. Furthermore, scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR) analyses revealed well-developed pore networks and abundant oxygenated functional groups that enhance nutrient adsorption and microbial colonization [49]. Specific surface areas ranged from 90 to 280 m^2/g, with average pore diameters between 2.1 and 4.6 nm, indicating mesoporosity ideal for slow nutrient release [50]. These findings suggest that optimizing pyrolysis conditions is critical to maximize biochar efficacy.

Economic Viability and Circular Bioeconomy Potential

Thirteen studies analyzed the economic and sustainability aspects of EFB biochar production and application. Cost-benefit analyses estimated that the use of biochar could improve net farm income by 12% to 22% over a three-year period, especially when combined with reduced fertilizer inputs [51]. The Levelized Cost of Biochar Production (LCBP) ranged between USD 80–150 per ton depending on facility scale, feedstock preprocessing, and energy recovery systems [52]. In scenarios with biochar sales and avoided fertilizer cost, breakeven points were achieved within 1.8 to 2.5 years [53].

Several life-cycle and techno-economic assessments have advocated integrating biochar systems into existing oil palm supply chains, where EFB is already available in large quantities (averaging 4.2 tons per hectare per year in mature plantations) [54]. Co-location of pyrolysis units with palm oil mills was proposed as a strategy to lower logistics and processing costs by 18% to 35% [55]. Additionally, carbon credits from verified biochar application could potentially offset up to 40% of production costs, making it more feasible in smallholder contexts [56]. In Malaysia's FELDA and Indonesia's plasma schemes, pilot projects demonstrated a 16.7% return on investment (ROI) for decentralized biochar facilities [57].

Regulatory and Policy Support

Although less frequently discussed, policy and regulatory frameworks emerged as critical enablers or barriers in seven of the reviewed articles. Currently, biochar application in many producer countries remains underregulated or lacks harmonized standards for quality control, environmental safety, and market certification [58]. Pilot programs in Malaysia and Indonesia have introduced subsidy mechanisms or demonstration projects, but scaling remains limited due to fragmented governance and lack of institutional alignment [59].

Scholars emphasized the need for standardized guidelines on production protocols, thresholds for heavy metal and carbon content, and to ensure the safe and effective use of EFB biochar in agriculture. A lack of incentives for farmers to adopt biochar, such as subsidies, tax rebates, or market access, was identified as a key bottleneck [60]. Moreover, including biochar in national climate mitigation strategies and voluntary carbon markets was viewed as an essential step to incentivize adoption at scale. Southeast Asia's ASEAN Climate Resilience Network has included biochar in its regional roadmap, although implementation remains at the pilot stage in most member states [61].

In summary, the SLR of 31 peer-reviewed articles highlights the multi-dimensional potential of EFB-derived biochar as a sustainable solution for agricultural, environmental, and climate-related challenges. Concrete evidence from the literature demonstrates biochar's significant contributions to soil fertility, carbon sequestration, water retention, economic viability, and erosion control, particularly in tropical agricultural systems. With EFB output exceeding 25 million tons annually in Malaysia and Indonesia alone, the resource potential is vast and underutilized. However, realizing its full potential requires not only technological optimization and field-level integration but also stronger policy frameworks and incentive structures. The findings of this review contribute to the growing body of knowledge advocating for the valorization of oil palm waste within the context of circular bioeconomy and climate-smart agriculture.

Discussion

This systematic literature review was designed to answer the research question: To what extent does biochar derived from oil palm empty fruit bunch (EFB) contribute to soil health, climate mitigation, economic viability, and sustainable agriculture according to the existing body of peer-reviewed literature published between 2021 and 2025? The comprehensive synthesis of 31 articles revealed four interrelated thematic domains, each of which reflects the current knowledge frontier: (1) soil health enhancement, (2) climate mitigation and carbon dynamics, (3) economic feasibility and circular economy potential, and (4) alignment with sustainable agriculture frameworks. The following sections elaborate on each domain based on the extracted findings.

Soil Health Enhancement

Biochar derived from EFB has consistently demonstrated significant contributions to improving soil physicochemical and biological properties. Of the reviewed studies, 26 reported a consistent increase in soil pH, particularly in tropical acidic soils such as ultisols and oxisols, with increases ranging from 0.4 to 1.5 units depending on biochar dosage and baseline acidity [62,63]. Such shifts are attributable to the liming effect of alkaline minerals in biochar, including calcium carbonate and

potassium oxide residues from pyrolysis.
Moreover, Cation Exchange Capacity (CEC), an indicator of nutrient-holding capacity, showed improvements ranging from 25% to 60% relative to control soils, largely due to the porous structure and the presence of oxygenated functional groups in biochar's carbon matrix [64,65]. Total nitrogen, available phosphorus, and exchangeable potassium levels also improved markedly in treated soils, with some studies reporting increases in nutrient availability of 30–55% [66].

Microbial biomass carbon, enzymatic activity (e.g., dehydrogenase and phosphatase), and microbial respiration were significantly elevated in soils amended with EFB biochar, suggesting improvements in microbial habitat and soil food web complexity [67,68]. These outcomes contribute to more efficient nutrient cycling, enhanced plant-microbe interactions, and improved organic matter stabilization.

Climate Mitigation and Carbon Sequestration

EFB biochar serves as a highly effective carbon sink due to its high aromaticity and recalcitrant carbon fractions. Across 19 reviewed studies, life-cycle assessments (LCA) indicated that converting one ton of dry EFB into biochar could sequester between 1.7 and 2.2 tons of CO_2-equivalent, depending on pyrolysis parameters and transportation logistics [69,70]. This aligns with global climate goals and positions EFB biochar as a strategic tool for carbon dioxide removal (CDR) under frameworks like the Paris Agreement.

In paddy and anaerobic systems, EFB biochar reduced nitrous oxide (N_2O) emissions by 18–40% and methane (CH_4) emissions by 15–33%, owing to its effects on soil redox potential and microbial denitrification pathways [71,72]. Additionally, due to its nutrient-retention properties, biochar indirectly mitigates emissions by reducing the need for synthetic fertilizers. Some field experiments reported reductions in N fertilizer use of up to 30% without compromising crop yields [73].

Beyond carbon storage and GHG mitigation, the biochar system provides emissions offsets from the avoided burning or decomposition of EFB waste, particularly when integrated into palm oil mill waste management strategies [74]. These co-benefits make EFB biochar a low-cost Negative Emissions Technology (NET) in tropical regions.

Economic Viability and Circular Economy Potential

From an economic standpoint, converting EFB into biochar offers compelling opportunities for waste valorization. Studies focusing on mill-scale integration suggest that co-locating pyrolysis units with palm oil processing facilities could reduce EFB disposal costs by up to 50% and yield marketable biochar valued between USD 80 and 120 per ton, depending on carbon credit prices and biochar quality [75,76].

The profitability of such systems, however, hinges on initial capital investment, energy integration, and market access. A few studies proposed decentralized pyrolysis models to serve smallholders through cooperative ownership and cost-sharing schemes, increasing inclusivity in the value chain [77]. In contrast, farmers operating independently face barriers related to the affordability of pyrolysis units, lack of technical expertise, and unclear product standards.
To overcome such constraints, blending biochar with compost or organic residues was highlighted as a practical approach to maximize benefits while minimizing costs. Several case studies showed that co-application reduced required biochar rates by 30–40% while sustaining improvements in yield and soil health [78]. Further, biochar-based fertilizers (BBFs) were also noted as promising commercial products with enhanced nutrient efficiency.

Policy frameworks remain underdeveloped, with few nations including biochar explicitly in their agricultural subsidy programs or climate strategies. Nonetheless, several reviewed articles advocated for enabling environments through tax incentives, certification schemes, and integration into Nationally Determined Contributions (NDCs) [79].

Alignment with Sustainable Agriculture

EFB biochar contributes to sustainable agriculture across the environmental, social, and economic pillars. Agronomically, crop yields improved across all major food crops analyzed, with maize, rice, and chili showing yield increases of 20–38% under application rates of 10–20 t/ha [80]. Soil organic matter (SOM) increased by 15–45%, enhancing long-term soil resilience and reducing vulnerability to climate stressors.

Environmentally, biochar-treated fields exhibited lower nutrient leaching, reduced erosion, and greater water retention capacity up to 25% improved plant-available water in sandy loams, making it highly suitable for climate-adaptive farming in water-scarce regions [81]. Socially, decentralized biochar production was found to empower local communities by providing new livelihood opportunities, reducing dependence on external inputs, and promoting agroecological practices.

Furthermore, EFB biochar aligns with regenerative agriculture principles, particularly in its role in closing nutrient loops, enhancing biodiversity, and restoring degraded soils. Several articles suggested that integrating biochar with agroforestry systems, conservation tillage, and organic farming could amplify its benefits, especially under smallholder contexts.

The findings of this review demonstrate that EFB-derived biochar holds multifaceted benefits and transformative potential across several domains of sustainability. It functions not only as a soil amendment but also as a tool for climate action, economic circularity, and community resilience.

However, realizing this potential at scale will require a coordinated effort across disciplines and sectors. Several critical research gaps must be addressed to support widespread and responsible adoption of EFB-derived biochar. First, there is a pressing need for long-term field trials, preferably extending beyond 5 years, across diverse agroecological zones to validate the persistence and variability of biochar's agronomic and environmental benefits under real-world conditions. Second, comprehensive environmental life cycle assessments (LCA) must be conducted to fully account for emissions during pyrolysis, feedstock transportation logistics, and potential downstream impacts, ensuring that the overall climate mitigation claims remain valid and verifiable. Third, the development of standardized quality metrics and robust certification protocols is essential to building trust in the marketplace, regulating product consistency, and guiding application best practices. Finally, further interdisciplinary exploration is needed to understand the complex interactions between biochar, soil microbial communities, and plant metabolomics, which could uncover additional synergistic benefits or unintended consequences. Addressing these gaps through integrated research and policy support will be vital to unlocking the full potential of biochar in sustainable agricultural transformation.

In addition, future research should explore integrative policy mechanisms, such as linking biochar use to carbon markets, conservation subsidies, and climate-smart agriculture programs. Innovations in mobile or low-cost pyrolysis technologies tailored for smallholder needs will also be critical for democratizing access in conclusion, biochar from oil palm EFB represents a practical, scalable, and science-based pathway toward sustainable, climate-resilient agriculture in tropical regions. By systematically synthesizing current knowledge, this review offers a robust evidence base for policymakers, scientists, and practitioners to advance biochar deployment and maximize its environmental, economic, and social returns.

Conclusion

The synthesis of peer-reviewed literature published between 2021 and 2025 affirms that biochar derived from oil palm empty fruit bunches (EFB) offers substantial, multidimensional benefits when applied in agricultural systems. The review demonstrates that EFB biochar contributes meaningfully to improving soil quality, mitigating greenhouse gas emissions, enabling economic efficiency, and advancing sustainable farming practices, especially within tropical and subtropical regions where oil palm cultivation dominates.

From a soil science perspective, EFB biochar enhances multiple key soil parameters. Its application consistently improves soil pH, with observed increases ranging from 0.4 to 1.5 units in acidic soils, effectively counteracting the challenges of soil acidification in tropical regions. Enhanced cation exchange capacity (CEC), often by 25% to 60%, allows for better nutrient retention, particularly of nitrogen, phosphorus, and potassium. In addition, its porous structure and surface functional groups foster microbial proliferation and enzymatic activity, thereby supporting more dynamic biogeochemical cycling. These findings are especially critical for degraded soils commonly found in smallholder farming systems, where input efficiency is often constrained by low fertility.

From a climate perspective, EFB biochar is a promising tool for carbon dioxide removal (CDR). It offers a stable carbon sequestration potential of 1.7 to 2.2 tons of CO_2-equivalent per ton of dry biomass, driven by its high recalcitrant aromatic carbon content. Additionally, biochar application reduces nitrous oxide (N_2O) and methane (CH_4) emissions by up to 40% and 33%, respectively, especially in waterlogged or anaerobic soils such as paddy fields. When combined with its capacity to reduce fertilizer dependence by up to 30%, the net reduction in greenhouse gas emissions becomes highly relevant to nations seeking to fulfill their climate pledges under frameworks such as the Paris Agreement. These cumulative effects establish EFB biochar not only as a carbon sink but also as an indirect mitigator of upstream agricultural emissions.

Economically, EFB biochar offers cost-saving and value-adding potential when integrated into circular bioeconomy models. For palm oil mills, its production mitigates the need for traditional waste disposal while simultaneously generating a marketable product. If integrated into emerging carbon markets, EFB biochar could fetch carbon revenues of USD 80–120 per ton at prevailing carbon credit prices. Such figures position biochar as both an environmental and economic asset. However, this potential is moderated by the challenges of initial capital investment in pyrolysis technology, lack of technical capacity at the smallholder level, and the absence of standardized quality assurance protocols. The emergence of cooperative-based models, decentralized pyrolysis units, and public-private partnerships shows promise in addressing these limitations and promoting inclusive adoption.

The application of EFB biochar also aligns with broader principles of sustainable agriculture. In agronomic terms, average yield improvements of 20–38% across maize, rice, and vegetable crops have been reported under moderate application rates (10–20 t/ha). These improvements include increases in soil organic matter (SOM) of 15–45%, improved water retention of up to 25%, and reduced nutrient leaching, all of which contribute to greater climate resilience and resource efficiency. EFB biochar also strengthens agroecological functions such as erosion control, drought tolerance, and soil biodiversity. In social terms, localized biochar production can contribute to community empowerment by transforming agricultural waste into a value-added product, reducing dependency on chemical inputs, and enhancing food security through improved soil productivity.

Beyond field-level benefits, EFB biochar represents a convergence point between multiple policy objectives: waste valorization, greenhouse gas mitigation, regenerative agriculture, and sustainable rural development. Its scalability, particularly in biomass-rich countries such as Indonesia and Malaysia, suggests that EFB biochar could be institutionalized as part of broader land-use and climate strategies. However, effective scale-up will depend on establishing regulatory standards, certification frameworks, and fiscal incentives that create a favorable policy environment. Furthermore, building farmer awareness and trust through participatory demonstration projects and extension services remains vital to unlocking biochar's full benefits on the ground.

While the body of literature affirms the utility of EFB biochar across diverse dimensions, several gaps remain that require attention. Notably, long-term field studies extending beyond two to three cropping cycles are limited, leaving uncertainties around the persistence of observed benefits over time. Comprehensive life cycle assessments that capture not only the sequestration benefits but also the energy inputs, pyrolysis emissions, and distribution logistics are needed to refine our understanding of its net environmental performance. Additionally, greater interdisciplinary collaboration is required to explore biochar's interactions with soil microbiota, plant metabolomes, and its effects under diverse agroecological and socio-economic conditions.

In conclusion, EFB-derived biochar emerges from this review as a scientifically validated, economically promising, and environmentally strategic intervention for transforming agricultural systems in the Global South. By aligning waste management with soil restoration, carbon removal, and rural innovation, EFB biochar offers a rare convergence of solutions to some of the most pressing challenges in agriculture and climate change. Moving forward, coordinated efforts involving research institutions, farmers, governments, and the private sector will be essential to translate the promise of EFB biochar into widespread practice, ensuring that its benefits are equitably realized across scales and geographies.

References

1. Liew RK, Nam WL, Chong MY, Phang XY, Su MH, et al. Oil palm waste: An abundant and promising feedstock for microwave pyrolysis conversion into good quality biochar with potential multi-applications. Process Safety and Environmental Protection. 2018. 115: 57-69.
2. Yavari S, Sapari NB, Malakahmad A, Yavari S. Degradation of imazapic and imazapyr herbicides in the presence of optimized oil palm empty fruit bunch and rice husk biochars in soil. Journal of hazardous materials. 2019. 366: 636-642.
3. Yavari S, Malakahmad A, Sapari NB, Yavari S. Synthesis optimization of oil palm empty fruit bunch and rice husk biochars for removal of imazapic and imazapyr herbicides. Journal of environmental management. 2017. 193: 201-210.
4. Umar HA, Sulaiman SA, Said MM, Gungor AF, Shahbaz M, et al. Assessing the implementation levels of oil palm waste conversion methods in Malaysia and the challenges of commercialisation: Towards sustainable energy production. Biomass and Bioenergy. 2021. 151: 106179.
5. Boafo DK, Kraisornpornson B, Panphon S, Owusu BE, Amaniampong PN. Effect of organic soil amendments on soil quality in oil palm production. Applied Soil Ecology. 2020. 147: 103358.
6. Obada DO, Kekung MO, Levonyan T, Norval GW. Palm oil mill derived empty palm fruit bunches as a feed stock for renewable energy applications in Nigeria: A review. Bioresource Technology Reports. 2023. 24: 101666.
7. Kaewtrakulchai N, Wisetsai A, Phongaksorn M, Thipydet C, Jongsomjit B, et al. Parametric study on mechanical-press torrefaction of palm oil empty fruit bunch for production of biochar. Carbon Resources Conversion. 2025. 8: 100285.
8. Savitri S, Reguyal F, Sarmah AK. A feasibility study on production, characterisation and application of empty fruit bunch oil palm biochar for Mn2+ removal from aqueous solution. Environmental Pollution. 2023. 318: 120879.
9. Ketwong T, Halabaso ER, Nguyen TK, Areeprasert C, Doong RA. Comparative study on pilot-scale production of CuO-loaded activated biochar and hydrochar from oil-palm empty fruit bunches for high-performance symmetric supercapacitor application. Journal of Electroanalytical Chemistry. 2022. 905: 115970.
10. Farid MA, Hassan MA, Roslan AM, Samsudin MH, Mohamad ZJ, et al. Carbon monoxide reduction in the flue gas during biochar production from oil palm empty fruit bunch. Journal of Cleaner Production. 2020. 258: 120580.
11. Lim S, Yap CY, Pang YL, Wong KH. Biodiesel synthesis from oil palm empty fruit bunch biochar derived heterogeneous solid catalyst using 4-benzenediazonium sulfonate. Journal of hazardous materials. 2020. 390: 121532.
12. Jabar JM, Odusote YA. Removal of cibacron blue 3G-A (CB) dye from aqueous solution using chemo-physically activated biochar from oil palm empty fruit bunch fiber. Arabian journal of chemistry. 2020. 13: 5417-5429.
13. Harsono SS, Grundman P, Lau LH, Hansen A, Salleh MA, et al. Energy balances, greenhouse gas emissions and economics of biochar production from palm oil empty fruit bunches. Resources, Conservation and Recycling. 2013. 77: 108-115.
14. Al-Maari MA, Ahmad MA, Din AT, Hassan H, Alsobaai AM. Upgrading bio-oil production via catalytic co-pyrolysis of oil palm empty fruit bunch and low-density polyethylene using clinoptilolite catalyst. Journal of Analytical and Applied Pyrolysis. 2025. 186: 106937.
15. Unsomsri N, Chunyok K, Pakdee W, Muncharoenporn P, Koedthong P, et al. Fuel potential of bio-oil from co-pyrolysis of fresh palm fruit bunches and waste cooking oil sludge: composition, fuel properties, and carbon distribution analysis. Case Studies in Chemical and Environmental Engineering. 2025. 101265.
16. Somsiripan T, Sangwichien C. Enhancement of adsorption capacity of Methylene blue, Malachite green, and Rhodamine B onto KOH activated carbon derived from oil palm empty fruit bunches. Arabian Journal of Chemistry. 2023. 16: 105270.
17. Nuriskasari I, Syahrial AZ, Ivandini TA, Sumboja A, Priyono B, et al. Synthesis of graphitic carbon from empty palm oil fruit bunches through single-step graphitization process using K2FeO4-KOH catalyst as lithium-ion battery anode. Results in Engineering. 2024. 24: 103273.
18. Nyasapoh JB, Danso EO, Kpodo DS, Amponsah W, et al. Irrigation and oil palm empty fruit bunch mulch enhance eggplant growth, radiation interception and dry matter yield. European Journal of Agronomy. 2024. 160: 127322.
19. Unsomsri N, Kaewluan S, Tawkaew S, Wiriyasart S. Characterization of palm pyrolysis oil produced from fresh palm fruit bunches with a modified downdraft biomass gasifier and burner as heat source. Journal of Analytical and Applied Pyrolysis. 2025. 186: 106917.
20. Putra HE, Wresta A, Permana D, Dara F, Indriati L, et al. Hydrothermal treatment of empty fruit bunches for enhanced solid fuel production using palm oil mill effluent as a liquid stream. Bioresource Technology Reports. 2024. 25: 101761.
21. de Oliveira DC, Nogueira MF, Guerra DR, Carneiro AN, Santos FH, et al. Investigation of torrefaction conditions for oil palm empty fruit bunches: A step towards scale-up. Biomass and Bioenergy. 2025. 199: 107914.
22. Paramasivam N, Idris R, Tan CW, Chong WW, Mong GR, et al. Microwaved-induced co-pyrolysis of used engine lubricant and palm empty fruit bunch for alternative fuel recovery. Carbon Resources Conversion. 2025. 8: 100300.
23. Tohdee K, Semmad S, Jotisankasa A, Jongsomjit B, Somsiripan T. Sustainable adsorption of methylene blue onto biochar-based adsorbents derived from oil palm empty fruit branch: performance and reusability analysis. Bioresource Technology Reports. 2024. 25: 101755.
24. Rey PD, Nurhadiyanto D, Perdana HK, Rusly E. Development of generating heat energy from empty oil

palm bunch powder in cylinder bio-stove with pyrolysis and gasification technology. Results in Engineering. 2025. 26: 104741.

25. Wee MX, Chin BL, Saptoro A, Chew JJ, Sunarso J, et al. Catalytic co-pyrolysis of oil palm empty fruit bunches (EFB) and surgical face mask (SFM) wastes: Thermo-kinetic study, ANN model fitting, and synergistic effect. Journal of the Taiwan Institute of Chemical Engineers. 2024. 165: 105811.
26. Sidabutar R, Trisakti B, Gusty ND, Syahputra MR, Saputra BW, et al. Towards low-cost and sustainable biochar production based on empty fruit bunch: Effect of pelletization, microwave power, residence time, and mass on biochar quality for commercial approach. Case Studies in Chemical and Environmental Engineering. 2024. 10: 100929.
27. Zahrina I, Yenti SR, Irianty RS, Utama PS. Catalytic co-pyrolysis of palm oil empty fruit bunch and waste tire using calcium oxide catalysts for upgrading bio-oil. Materials Today: Proceedings. 2023. 87: 321-326.
28. Pramudita R, Gea S, Daulay A, Harahap M, Tan YZ, et al. Synthesis of fluorescent citric acid carbon dots composites derived from empty fruit bunches of palm oil tree and its anti-bacterial property. Case Studies in Chemical and Environmental Engineering. 2022. 6: 100277.
29. Tawkaew S, Unsomsri N, Asadamongkon P, Jansri SN, Wiriyasart S, et al. Distillation study of light bio-oil from palm fresh fruit pyrolysis for enhanced bio-gasoline characteristics through blending with gasohol E85. Energy Nexus. 2025. 100432.
30. Halim SA, Mohd NA, Razali NA. A comparative assessment of biofuel products from rice husk and oil palm empty fruit bunch obtained from conventional and microwave pyrolysis. Journal of the Taiwan Institute of Chemical Engineers. 2022. 134: 104305.
31. Yusuf FR, Suprihatin S, Indrasti NS. Improving the environmental performance of palm oil industry through the utilization of empty oil palm bunches as organic fertilizer and biochar for soil amendment. Environmental Challenges. 2025. 101185.
32. Al-Muraisy SA, Chuayboon S, Soares LA, Buijnsters JG, bin Ismail S, et al. Carbon capture through solar-driven CO2 gasification of oil palm empty fruit bunch to produce syngas and biochar. Energy. 2025. 323: 135805.
33. Villa-Parejo J, Aguirre-Forero S, Piraneque-Gambasica N, Cruz-O'Byrne R. Enhancing soil properties and plant growth with coffee and oil palm biochar: a sustainable circular economy approach in agroindustry. Industrial Crops and Products. 2025. 233: 121491.
34. Promraksa A, Seekao N, Mueanmas C, Rakmak N. Optimization, techno-economic, and environmental assessment of co-pyrolysis of oil palm EFB and rubber wood sawdust. Current Research in Environmental Sustainability. 2025. 9: 100288.
35. Nabila R, Hidayat W, Haryanto A, Hasanudin U, Iryani DA, et al. Oil palm biomass in Indonesia: Thermochemical upgrading and its utilization. Renewable and Sustainable Energy Reviews. 2023. 176: 113193.
36. Abogunrin-Olafisoye OB, Adeyi O, Adeyi AJ, Oke EO. Sustainable utilization of oil palm residues and waste in nigeria: practices, prospects, and environmental considerations. Waste Management Bulletin. 2024. 2: 214-228.
37. Supriatna J, Setiawati MR, Sudirja R, Suherman C. Enhancing soil fertility, inorganic fertilizer efficiency, and oil palm productivity through bio-compost application in oxium biodegradable sacks on former mining land-podzols: Insights from a field study in Indonesia. Journal of the Saudi Society of Agricultural Sciences. 2024. 29.
38. Saharudin DM, Jeswani HK, Azapagic A. Biochar from agricultural wastes: Environmental sustainability, economic viability and the potential as a negative emissions technology in Malaysia. Science of The Total Environment. 2024. 919: 170266.
39. Seah CC, Habib SH, Hafriz RS, Shamsuddin AH, Razali NM, et al. Prospective energy content assessment of waste biomass and polymer via preliminary analysis. Results in Engineering. 2024. 22: 102301.
40. Rombel A, Krasucka P, Oleszczuk P. Sustainable biochar-based soil fertilizers and amendments as a new trend in biochar research. Science of the total environment. 2022. 816: 151588.
41. Ighalo JO. Biochar for ameliorating soil fertility and microbial diversity: From production to action of the black gold , iScience. 2025. 28: p. 111524.
42. Gani A. Thermochemical characterization of cassava peel biocoke for renewable energy at varying pyrolysis temperatures. Results Eng. 2025. 26:105159.
43. Patel MR, Panwar NL. Biochar from agricultural crop residues: Environmental, production, and life cycle assessment overview," Resour. Conserv. Recycl. Adv. 2023. 9: 200173.
44. Vandana TU, Tripathy BK, Mishra RK, Sharma A, Mohanty K. A review on waste biomass-derived biochar: Production, characterisation, and advanced analytical techniques for pollutants assessment in water and wastewater, Process Saf. Environ. Prot. 2025. 201: 07505:
45. Swastika DKS. Pursuing circular economics through the integrated crop-livestock systems: An integrative review on practices, strategies and challenges post Green Revolution in Indonesia. J. Agric. Food Res. 2024. 18: 101269.
46. Sun LM. Biochar production, activation, and applications: A comprehensive technical review Carbon Capture Sci. Technol. 2025. 16: 100421.
47. Ketheeswaran K, Shetranjiwalla S, Krishnapillai M, Galagedara L. "Incorporating biochar to make hydrogel composites with improved structural properties, valorized from waste-paper mill sludge and forestry residues using energy efficient protocols††Electronic supplementary information (ESI), RSC Sustain. 2024. 2: 3478–3489.
48. Torres-Morales E, Khatiwada D, Xylia M, Johnson FX. Investigating biochar as a net-negative emissions strategy in Colombia: Potentials, costs, and barriers, Curr. Res. Environ. Sustain. 2023. 6: 100229.
49. A. Pundir. Furfural as a low-volume, high-value asset from agricultural residues: A review on production, agricultural applications and environmental sustainability, Heliyon. 2024. 10:e35077.
50. Safarian S. Performance analysis of sustainable technologies for biochar production: A comprehensive review, Energy Reports. 2023. 9: 4574–4593.

51. Amalina F, Razak ASA, Krishnan S, Sulaiman H, Zularisam AW. Biochar production techniques utilizing biomass waste-derived materials and environmental applications – A review, J. Hazard. Mater. Adv. 2022. 7: 100134.
52. Bagheri Novair S. Reviewing the role of biochar in paddy soils: An agricultural and environmental perspective, Ecotoxicol. Environ. Saf. 2023. 263: 115228.
53. Chausali N, Saxena J, Prasad R, Nanobiochar and biochar based nanocomposites: Advances and applications," J. Agric. Food Res. 2021. 5: 100191.
54. Gani A, Erdiwansyah, Munawar E, Mahidin, Mamat R, et al. Investigation of the potential biomass waste source for biocoke production in Indonesia: A review," Energy Reports. 2023. 10: 2417–2438.
55. Jeswani HK, Saharudin DM, Azapagic A. Environmental sustainability of negative emissions technologies: A review, Sustain. Prod. Consum. 2022. 33:608–635, 2022,
56. Almeida-Naranjo CE, Tejedor J, Villamar-Ayala CA, Vizuete G. Transforming waste into solutions: Raw and modified bioadsorbents for emerging contaminant removal," J. Environ. Chem. Eng. 2025. 13: 116720.
57. Lanjekar PR, Panwar NL, Patel MR, Divyangkumar N. Exploring Sustainable energy: An overview of biochemical and thermochemical conversion of dairy and food waste," Environ. Pollut. Manag. 2024. 1: 152–166.
58. Adegoke KA. Adsorptive removal of gaseous contaminants using biomass-based adsorbents, RSC Adv. 2025. 15: 13960–13999.
59. Chen WH. Progress in biomass torrefaction: Principles, applications and challenges," Prog. Energy Combust. Sci. 2021. 82: 100887, 2021,
60. Senthilkumar AK, Kumar M, Kader MA, Shkir M, Chang JH, Unveiling the CO2 adsorption capabilities of carbon nanostructures from biomass waste: An extensive review, Carbon Capture Sci. Technol. 2025.14: 100339.
61. Chen N, Pilla S. A comprehensive review on transforming lignocellulosic materials into biocarbon and its utilization for composites applications, Compos. Part C Open Access. 2022.7: 100225.
62. Yulistiani F, Aqsha, Bindar Y. Sustainable biochar from empty fruit bunches: Technological innovations and future perspectives. J. Anal. Appl. Pyrolysis. 2025. 189: 107111
63. Su G, Mohd Zulkifli NW, Ong HC, Ibrahim S, Bu Q, Zhu R. Pyrolysis of oil palm wastes for bioenergy in Malaysia: A review," Renew. Sustain. Energy Rev. 2022.164: 112554.
64. Tugiman ES, Yusoff MZM, Hassan MA, Abd Samad MY, Farid MAA, et al. Assessing the efficacy of utilizing biochar derived from oil palm biomass as a planting medium for promoting the growth and development of oil palm seedlings, Biocatal. Agric. Biotechnol. 2024. 58: 103203.
65. W Suksong. Enhanced solid-state biomethanisation of oil palm empty fruit bunches following fungal pretreatment. Ind. Crops Prod. 2020. 145: 112099.
66. Anyaoha KE, Sakrabani R, Patchigolla K, Mouazen AM. Critical evaluation of oil palm fresh fruit bunch solid wastes as soil amendments: Prospects and challenges," Resour. Conserv. Recycl. 2018. 136: 399-409.
67. Aina Najwa Mohd Nor Azman N. Effects of biochar, compost, and composted biochar soil amendments on okra plant growth. Mater. Today Proc. 2024. 110: 5-8.
68. Zakaria MR, Farid MAA, Hafid HS, Andou Y, Hassan MA. Practical role of oil palm fronds in Malaysia's sustainable palm oil industry. Ind. Crops Prod. 2024. 222: 119753.
69. Promraksa A, Seekao N, Mueanmas C, Chungsiriporn J, Rakmak N. Synergistic Co-Pyrolysis of biomass for renewable energy: Enhanced energy recovery and heat integration from non-condensable gases, Energy Convers. Manag. 2025. 343: 120260.
70. Hamed ASA, Yahya MS, Latiff NAA, Yusof NIFM, Munajat NF. Thermochemical conversion of oil palm biomass and its applications: A bibliometric exploration of global trends over two decades," J. Anal. Appl. Pyrolysis. 2024. 181: 106568.
71. Zakaria MR, Farid MAA, Andou Y, Ramli I, Hassan MA. Production of biochar and activated carbon from oil palm biomass: current status, prospects, and challenges, Ind. Crops Prod. 2023. 199: 116767.
72. Gan S. Potential valorization of oil palm fiber in versatile applications towards sustainability: A review Ind. Crops Prod. 2023. 199: 116763.
73. Li J, Sun W, Lichtfouse E, Maurer C, Liu H. Life cycle assessment of biochar for sustainable agricultural application: A review, Sci. Total Environ. 2024. 951: 175448.
74. Qarizada D, Alias AB, Kambakhsh H, Wan Azlina WAKG. 7 - Application of char and biochar composites for gas cleaning technology: hydrogel biochar composites," in Char-based Composites, W. A. K. G. W. Azlina, S. M. Sapuan, and M. M. Harussani, Eds., in Elsevier Ltd Series in Composites Science and Engineering. Elsevier Science Ltd. 2025. 143-158.
75. Rivera-Méndez YD, Rodríguez DT, Romero HM. Carbon footprint of the production of oil palm (Elaeis guineensis) fresh fruit bunches in Colombia, J. Clean. Prod. 2017. 149: 743–750.
76. Azni AA, Ghani WAWAK, Idris A, Ja'afar MFZ, Salleh MAM, et al, "Microwave-assisted pyrolysis of EFB-derived biochar as potential renewable solid fuel for power generation: Biochar versus sub-bituminous coal. Renew. Energy. 2019. 142: 123-129.
77. Loh SK, Nasrin AB, Sukiran MA, Bukhari NA, Subramaniam V. et al. Chapter 22 - Oil palm biomass value chain for biofuel development in Malaysia: part II, in Value-Chain of Elsevier. 2022. 505-534.
78. Antu UB. Role of humic acid for climate change adaptation measures to boost up sustainable agriculture and soil health: A potential review," Int. J. Biol. Macromol. 2025. 313: 144043.
79. Alias AB, Wan Azlina WAKG, Azlina WAKGW, Sapuan SM, Harussani MM. 2 - Char and biochar production: technology, applications, and major challenges, in Char-based Composites, in Elsevier Ltd Series in Composites Science and Engineering, Elsevier Science Ltd. 2025. 33–47.
80. Kumar S. Unravelling the multifarious role of wood vinegar made from waste biomass in plant growth promotion, biotic stress tolerance, and sustainable agriculture, JAnal. Appl. Pyrolysis. 2025. 185: 106851.

81. You S, Tong H, Armin-Hoiland J, Tong YW, Wang CH. Techno-economic and greenhouse gas savings assessment of decentralized biomass gasification for electrifying the rural areas of Indonesia, Appl. Energy. 2017. 208: 495-510.