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From Oil Palm Residues to Engineered Carbon: Biochar and Activated Carbon Pathways for Carbon Removal, Environmental Purification, and a Circular Bioeconomy

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ABSTRACT

The rapid expansion of palm-oil processing has created a parallel challenge of managing large volumes of lignocellulosic residues, including empty fruit bunches, palm kernel shells, mesocarp fibre, oil palm fronds, and oil palm trunks. This qualitative literature review examines whether these residues can be repositioned from low-value wastes into feedstocks for biochar and engineered activated carbon. The review synthesizes recent literature published from 2020 onward across biomass conversion, materials engineering, environmental remediation, carbon sequestration, and techno-economic assessment. The evidence indicates that feedstock composition and thermochemical processing conditions jointly determine carbon yield, aromaticity, pore development, surface chemistry, adsorption performance, and long-term carbon stability. Biochar offers comparatively high carbon retention and promising applications in soils, nutrient management, remediation, and carbon sequestration, whereas further physical, chemical, or hybrid activation can produce higher-value porous carbons for wastewater purification, heavy-metal adsorption, organic-pollutant removal, CO₂ capture, gas purification, catalysis, and energy applications. However, maximum surface area is not synonymous with maximum sustainability because severe activation can reduce product yield and increase energy, reagent, washing, and wastewater burdens. The review therefore proposes an integrated oil-palm carbon platform based on feedstock–process–product matching, selective upgrading, coproduct energy recovery, credible life-cycle carbon accounting, and market segmentation. Such a portfolio approach can transform oil-palm residues into complementary agricultural, environmental, industrial, and climate products while strengthening circular-bioeconomy development.

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Introduction

Palm-oil production is generally discussed in terms of crude palm oil, kernel products, edible oils, oleochemicals, biodiesel, and other downstream products. Yet an equally important material flow occurs outside the principal oil stream substantial quantities of empty fruit bunches (EFB), palm kernel shells (PKS), mesocarp fibre (MF), oil palm fronds (OPF), and oil palm trunks (OPT) arise from mills and plantations. These residues differ considerably in moisture, density, ash, lignin, cellulose, hemicellulose, fixed carbon, mineral composition, and logistics, meaning that the term “oil palm biomass” hides a heterogeneous family of feedstocks rather than a single raw material. Contemporary research increasingly treats these residues as renewable carbon resources that can be converted into bioenergy, fuels, chemicals, biochar, activated carbon, and other value-added materials [1-4].

Among the available valorization routes, thermochemical conversion is especially relevant because it can concentrate biogenic carbon into a solid phase while simultaneously producing gaseous or liquid coproducts that may contribute process energy.

Slow pyrolysis and related carbonization processes are particularly attractive when solid-char yield is prioritized, whereas more severe thermal treatment, activation, or functionalization can transform char into highly porous engineered carbon materials. The distinction is crucial biochar is commonly optimized for carbon retention, soil functionality, remediation, and environmental persistence, whereas activated carbon is typically optimized for accessible porosity, surface chemistry, and adsorption performance. Consequently, an oil-palm carbon strategy should not treat biochar and activated carbon as interchangeable materials [5,6].

Commercial development of biochar and activated-carbon technologies illustrates two ends of the carbon-material spectrum. Biochar systems are often evaluated in terms of biomass-processing capacity and durable carbon storage, whereas activated carbon is supplied in pellet, granular, powder, and impregnated forms for water treatment, gas purification, solvent recovery, VOC control, and other industrial applications. These commercial performance claims require scientific qualification because a plant that processes a given mass of biomass annually does not sequester the same mass of carbon, and the amount of CO₂-equivalent removal cannot be inferred directly from feedstock throughput. Biochar yield, carbon concentration, stable-carbon fraction, feedstock baseline, pyrolysis emissions, transport, energy demand, coproduct substitution, application pathway, and expected permanence all influence the net result [7-10].

This distinction has direct relevance for oil-palm-producing countries. EFB is bulky and often comparatively moist, creating different preprocessing and transportation requirements from denser PKS. Mesocarp fibre is already frequently valued as mill fuel, creating an opportunity cost if diverted to other uses. Fronds are geographically dispersed throughout plantations, while trunks become abundant particularly during replanting cycles. Feedstock selection must therefore consider not only laboratory carbon properties but also existing uses, collection radius, seasonal and spatial supply, processing cost, competing energy demand, and potential end-market value [11,12].

Oil-palm-derived biochar has demonstrated functionality far beyond simple charcoal. EFB, MF, OPF, PKS and related materials have been investigated for adsorption, soil improvement, controlled nutrient release, catalytic supports, and carbon-storage applications. Studies have shown, for example, that OPF subjected to steam-assisted pyrolysis can develop substantial mesoporosity and adsorb phenolic compounds, while EFB biochars can be engineered for removal of dissolved metals and can undergo major structural transformation as pyrolysis severity increases [13,14,15].

Activated carbon represents a further degree of material engineering. Carbonization is followed or integrated with physical activation using gases such as steam or CO₂, chemical activation using acids, alkalis, or salts, or combined activation and surface modification. Such processing can substantially increase microporosity, mesoporosity, surface functionality, and adsorption selectivity. PKS is especially attractive because its lignocellulosic structure and relatively high carbon density can support strong activated-carbon performance. Recent oil-palm studies encompass CO₂ capture, methane adsorption, heavy-metal removal, POME treatment, tannin adsorption, controlled-release fertilizers, and energy-storage electrodes [16-19].

Yet the transition from biomass to increasingly engineered carbon also introduces trade-offs. Severe pyrolysis can increase aromaticity and create thermally stable carbon but reduce solid yield. Activation may produce exceptional pore development but consumes part of the carbon matrix. Chemical activation introduces reagent recovery, washing, corrosion, and wastewater issues. Surface functionalization can improve affinity for particular molecules but may reduce available surface area or complicate regeneration. Thus, maximizing BET surface area or adsorption capacity alone does not necessarily maximize environmental or economic performance. The core research problem is therefore not simply whether palm residues can produce biochar or activated carbon. The more useful question is: **which oil-palm residue should be converted by which process into which carbon product for which end use, and under what environmental and economic conditions?** Answering that question requires integration across biomass science, pyrolysis engineering, carbon-material characterization, adsorption chemistry, agriculture, climate mitigation, life-cycle assessment, and commercialization. This article responds through a qualitative literature review rather than a systematic literature review. It synthesizes recent evidence around five interconnected propositions: first, oil-palm residues possess feedstock-specific characteristics that should determine processing decisions; second, conversion conditions control the structure and functionality of resulting carbon materials; third, biochar and activated carbon occupy different but complementary positions in a value hierarchy; fourth, credible climate benefits require life-cycle carbon accounting rather than gross production

claims; and fifth, commercialization may be strengthened by a portfolio model that integrates bulk biochar, premium activated carbon, coproduct energy, remediation services, and potentially verified carbon-removal value[20-22].

Literature Review

Oil-Palm Biomass as a Heterogeneous Carbon Feedstock

The suitability of a biomass for carbonization begins with its biochemical and proximate composition. Cellulose and hemicellulose contribute strongly to volatile generation during thermal decomposition, whereas lignin decomposes over a broader temperature interval and contributes substantially to residual fixed carbon. Ash composition also matters because alkali and alkaline-earth minerals can influence pore formation, catalytic decomposition, pH, nutrient value, and adsorption chemistry. Consequently, two chars produced at identical nominal temperatures can have different yield, stability, pore distribution, and reactivity when their parent feedstocks differ. EFB is highly relevant because of its abundance at palm-oil mills, but its physical characteristics complicate its direct valorization. It is comparatively fibrous, bulky, and moisture-sensitive, which can increase drying, shredding, storage, and transportation requirements. Nevertheless, EFB has been successfully carbonized and converted into adsorbents, catalysts, activated carbon, and engineered biochars. Its carbon structure evolves strongly with temperature recent work on Indonesian EFB has shown major changes in crystallinity, surface characteristics, and carbon ordering under increasingly severe pyrolysis EFB-derived biochar has also been evaluated for dissolved Mn²⁺ removal, showing that oxygen-containing surface functionalities can remain important for aqueous adsorption even when higher temperatures increase overall carbonization PKS differs substantially from EFB. It is denser, mechanically stronger, relatively easy to transport and store, and frequently possesses characteristics that make it attractive as a precursor for activated carbon. Its existing energy value, however, means that carbon-material production competes with combustion or fuel markets. From a material perspective, PKS has supported activated carbons for CO₂ capture, methane storage, nutrient adsorption, industrial wastewater treatment, and surface-functionalized adsorbents. These applications demonstrate why feedstock allocation should be based on marginal value rather than on the assumption that every residue should enter the same conversion pathway MF is similarly embedded in mill energy systems because fibre is commonly used as boiler fuel. Its opportunity cost can therefore be significant, but selective diversion may be justified where high-value carbon markets exist or where energy can be supplied by pyrolysis gases. Microwave-assisted pyrolysis of oil-palm mesocarp fibre has demonstrated its ability to produce sorptive biochar for dye removal, illustrating how alternative heating approaches can transform residues normally associated with combustion into environmental materials [23,24].

OPF and OPT create a different supply-chain problem because much of this biomass originates in plantations rather than at mills. Fronds are repeatedly generated during harvesting and pruning, while trunks are generated especially during replanting. Their distributed nature favours consideration of mobile, modular, or decentralized carbonization, although transport density, contamination, drying requirements, and the agronomic function of residues left in the field must be considered. OPF steam pyrolysis has produced porous biochar capable of phenol and tannic-acid adsorption, and OPT has been transformed into both activated carbon powders and activated-carbon fibres [25,26].

Figure 1: Summarizes the central proposition of this review: oil-palm residues should enter a **feedstock–conversion–product cascade** rather than a single standardized carbonization pathway. The framework separates bulk biochar production from selective activated-carbon upgrading and links each branch to appropriate market functions.

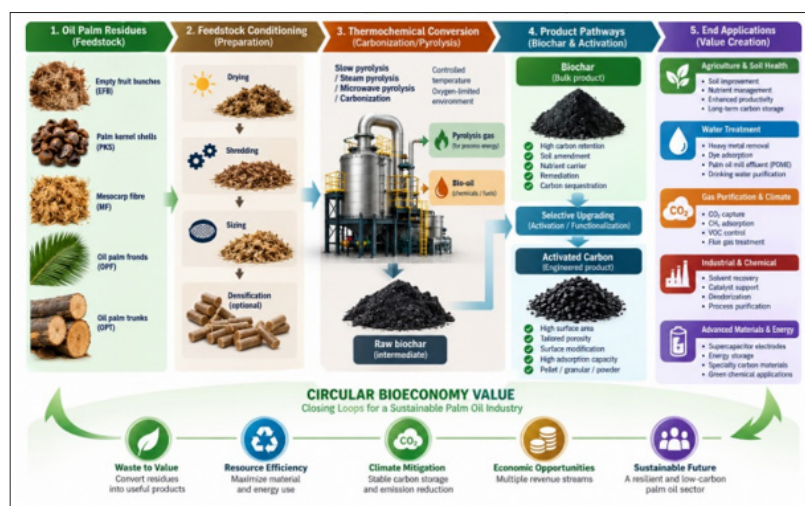


Figure 1: Integrated Oil-Palm Biomass-To-Engineered-Carbon Value Chain

Figure 1 also emphasizes that activation should be selective rather than universal. Converting every tonne of biochar into activated carbon would sacrifice some solid-carbon yield and introduce additional processing requirements, while leaving every tonne as unactivated biochar would forgo higher-value adsorption markets. The optimal architecture therefore separates feedstocks and intermediate chars by quality before assigning them to end uses [27].

Thermochemical Conversion and Carbon Formation

Pyrolysis represents the thermochemical decomposition of organic matter under oxygen-limited conditions. Temperature, heating rate, residence time, feedstock particle size, moisture, ash chemistry, and reactor configuration strongly affect the distribution of char, condensable vapours, and permanent gases. In general, slow heating and conditions designed for prolonged solid conversion tend to favour char production relative to fast-pyrolysis systems optimized for liquids, although feedstock-dependent interactions prevent a universal yield rule. Temperature is one of the most important variables. As temperature rises, dehydration, devolatilization, decarboxylation, dehydrogenation, ring condensation, and aromatization generally progress. The solid material commonly loses hydrogen and oxygen relative to carbon, while its H/C and O/C ratios decline. At the same time, surface functional groups may be removed or transformed, ash can become concentrated, and pore development may increase. These processes can improve stability and surface area but can also reduce char mass yield. Consequently, the temperature that maximizes carbon stability is not necessarily the temperature that maximizes adsorption of a particular aqueous ion, and neither is necessarily the temperature that maximizes financial return. Process emissions deserve equal attention. Carbonization does not automatically represent a clean process merely because biomass is renewable. Incomplete oxidation of pyrolysis gases, volatile organic compounds, particulates, and carbon monoxide can create local environmental burdens if gas treatment and combustion are poorly controlled. For example, directly examined CO emissions from EFB carbonization and demonstrated the importance of downstream gas-management systems. This has practical implications for commercial plants: climate-oriented biochar production should combine stable-carbon production with controlled combustion or beneficial utilization of volatile

coproducts. Alternative heating systems can modify both process efficiency and carbon characteristics. Microwave heating can provide volumetric heating and may alter pore formation and thermal gradients compared with conventional external heating. Steam-assisted pyrolysis can simultaneously carbonize and promote pore development. Hydrothermal routes can process wetter biomass without conventional drying, although the resulting hydrochar differs chemically from conventional pyrolysis biochar. Thus, “biochar production technology” should be treated as a design space rather than a single process [28,29].

From Biochar to Activated Carbon

Activated carbon is produced when carbonized material undergoes controlled development of its pore network and, in many cases, modification of its surface chemistry. Physical activation generally uses oxidizing gases such as steam or CO₂ at elevated temperatures. Carbon is selectively gasified, blocked pores open, existing pores enlarge, and new microporous or mesoporous regions emerge. The drawback is burn-off: pore development occurs partly because carbon mass is removed. A high activation degree can therefore generate a premium adsorbent while substantially reducing product yield; the trade-off is visible in PKS Research. Physical activation using CO₂, steam, or combinations of both has generated high-surface-area activated carbon suitable for gas adsorption. Steam-rich conditions can promote strong pore development, while recent pilot- and industrial-scale work on PKS activation demonstrates that physical activation can be modelled and transferred from smaller furnaces toward rotary-kiln production, although scale-up introduces heat- and mass-transfer considerations absent from laboratory systems. Chemical activation can operate through mechanisms that differ from gas activation. KOH can strongly develop microporosity, phosphoric acid can promote dehydration and structural rearrangement, while other acids, salts, and impregnating agents can modify surface chemistry. Chemical activation may achieve high porosity at lower nominal temperatures than some physical routes but creates additional burdens associated with chemical acquisition, corrosion-resistant equipment, product washing, neutralization, salt removal, water demand, and wastewater management. Surface functionalization extends the concept further. Instead of optimizing only total surface area, the material is engineered for affinity toward a particular adsorbate. Nitrogen-containing groups can enhance

interactions with acidic gases metal or metal-oxide sites can introduce stronger chemisorption sulfur-containing groups can affect metal binding and magnetic phases can facilitate adsorbent separation. Concurrent activation and surface modification of PKS-derived carbon has been investigated as a way to reduce the number of unit operations while introducing CO₂-affinity functionality

Figure 2: Conceptualizes The Process–Structure–Property–Performance Nexus.

It illustrates why reporting only pyrolysis temperature or only BET area is insufficient: end-use performance emerges from a chain of interacting decisions beginning with feedstock composition The significance of Figure 2 is that a single “best” biochar does not exist. Lower-temperature carbon may preserve oxygen-containing groups beneficial for certain inorganic contaminants, while higher-temperature treatment can increase aromaticity, hydrophobicity, and pore development. Activation can increase sorption capacity but may reduce retained carbon. Product optimization must therefore begin with an explicit end-use specification rather than maximizing one material parameter in isolation [30-32].

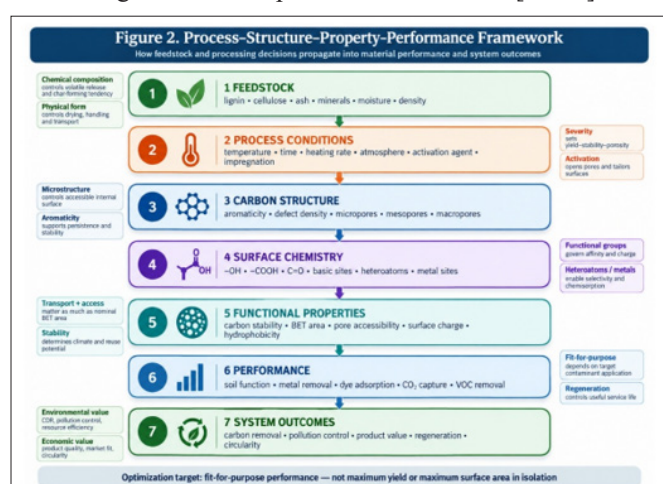


Figure 2: Process–structure–property–performance framework for oil-palm-derived carbon materials

As visualized in Figure 2, optimization is application-specific and requires balancing carbon retention, surface chemistry, pore accessibility, and the intended service environment. This fit-for-purpose framing provides the basis for the adsorption and environmental functions discussed in the following section.

Adsorption and Environmental Functionality

Biochar and activated carbon remove pollutants through combinations of physical adsorption, pore filling, electrostatic attraction, ion exchange, complexation, precipitation, hydrogen bonding, hydrophobic partitioning, and π – π interactions. The relative contribution of these mechanisms depends on the target contaminant, solution pH, ionic strength, competing solutes, carbon surface chemistry, pore size, and degree of the difference between nominal surface area and usable surface area is particularly important. Very high microporosity may be valuable for small gas molecules but less effective for large organic compounds unable to enter the pore network. Mesopores can facilitate transport to smaller pores or provide adsorption space for larger molecules. Illustrated this size-dependent behaviour in OPF-derived porous biochar, where phenol and tannic acid interacted differently with the pore architecture. Such evidence argues for application-specific pore engineering rather than indiscriminate pursuit of the highest BET value.

Oil-palm-derived carbon has demonstrated relevance to water treatment in several forms. OPT-derived activated carbon has been studied for tannin adsorption EFB-derived materials have been developed for metal removal and dyes; functionalized PKS carbon has been tested against heavy metals; and PKS activated carbon has been proposed for lignin removal in palm-oil effluent Broader biochar research also shows expanding interest in engineered carbon composites and biologically enhanced materials for complex water-treatment systems Dyes provide a useful model system because their removal demonstrates interactions between pore accessibility, surface charge, aromatic domains, and solution chemistry. MF-derived biochar has been tested for methylene-blue removal, while activated EFB materials have been investigated for methylene blue, malachite green, and Rhodamine B. Broader syntheses confirm that biochar can remove diverse dyes but that adsorption capacities from simplified laboratory solutions cannot automatically be extrapolated to real industrial wastewater where dissolved salts and competing organics occupy adsorption sites [33-38].

Agricultural Functions and Controlled Nutrient Release

Biochar can alter soil bulk density, porosity, water retention, nutrient dynamics, cation exchange behaviour, pH, microbial habitat, and organic-carbon stocks. However, the direction and magnitude of these effects depend on both biochar and soil. This is important for oil-palm systems because plantations extend across strongly weathered tropical soils with considerable variability in texture, acidity, nutrient status, hydrology, and management history. A biochar beneficial in one nursery or soil should therefore not be assumed to produce identical response elsewhere Recent oil-palm-specific research provides direct evidence of agronomic possibilities. evaluated biochars produced from MF and EFB as components of oil-palm seedling media and reported improvements in multiple plant and soil indicators under specific biochar treatments. Although nursery evidence cannot establish long-term plantation performance, the work demonstrates the possibility of partially closing a biomass–soil loop within the palm-oil sector. PKS-derived biochar and activated carbon have also been investigated as matrices for controlled-release urea. Activated carbon can adsorb more urea because of its developed porosity, but maximizing nutrient loading is only one design criterion. Fertilizer applications must also consider nutrient-release kinetics, cost per unit nutrient delivered, carbon persistence, potential contaminants, production energy, and whether the additional cost of activation is justified relative to simpler biochar formulations [39-41].

Carbon Sequestration and Permanence

Biochar is attractive for climate mitigation because thermochemical conversion can transform relatively labile biogenic carbon into more condensed forms that may persist substantially longer than the original biomass. Meta-analyses published since 2020 generally support increased soil carbon stocks following biochar application, but they also reveal substantial heterogeneity between feedstocks, soils, experimental designs, application rates, and timescales Carbon persistence should not be conflated with total carbon content. Biochar contains fractions with different susceptibilities to oxidation and biological degradation, while interactions with minerals, aggregates, microorganisms, dissolved organic matter, and native soil carbon can influence system-level outcomes. Therefore emphasize that carbon sequestration involves both intrinsic carbon structure and environmental interactions. This complexity reinforces the need to distinguish stable carbon stored from gross biochar produced.

Life-cycle accounting introduces another layer. Feedstock collection, drying, preprocessing, transport, reactor construction, process energy, methane or CO emissions, activation reagents, water use, product transport, and end-use treatment all contribute environmental burdens. Conversely, recovery and combustion of pyrolysis gases, displacement of fossil heat, avoided waste decomposition, reduced fertilizer requirements, or substitution for fossil-based activated carbon can generate credits. Recent reviews show that feedstock, conversion technology, energy demand, and application scenario can materially change life-cycle performance, reinforcing the need for explicit functional units and system boundaries [42].

Method

This study employs a **qualitative literature review (QLR)**. It is explicitly not designed as a systematic literature review, bibliometric review, or meta-analysis. The objective is interpretive integration of recent scholarship from several disciplines rather than exhaustive enumeration of every publication meeting predetermined screening criterion. This approach is appropriate because the underlying research problem crosses thermochemical engineering, carbon-material science, environmental chemistry, agronomy, life-cycle assessment, industrial economics, and circular-bioeconomy studies. The principal publication window is **2020–2026**, with emphasis on peer-reviewed journal literature concerning oil-palm-derived biochar and activated carbon. Because some critical engineering mechanisms are not oil-palm-specific, the review also includes recent high-quality studies on biomass-derived carbon where their findings are directly transferable to understanding activation, adsorption, carbon sequestration, life-cycle accounting, or commercialization. Literature was prioritized from journals indexed by major scholarly databases and from established publishers in environmental science, chemical engineering, materials science, agriculture, energy, and sustainability. Search concepts were organized around four families. The first addressed **feedstocks**, using combinations of oil palm biomass, empty fruit bunch, palm kernel shell, mesocarp fibre, oil palm frond, and oil palm trunk. The second covered **conversion technologies**, including pyrolysis, carbonization, microwave pyrolysis, steam activation, CO₂ activation, chemical activation, hydrothermal treatment, and surface modification. The third addressed **applications**, including adsorption, wastewater, heavy metals, dyes, CO₂ capture, methane, soil amendment, controlled-release fertilizer, carbon sequestration, catalysis, and energy storage. The fourth addressed **system performance**, incorporating life-cycle assessment, techno-economic analysis, commercialization, circular bioeconomy, regeneration, scale-up, and carbon removal. Rather than applying a PRISMA-style screening architecture, papers were selected purposively according to their ability to inform the thematic framework. Primary experimental research was combined with recent reviews, meta-analyses, and techno-economic studies. Greater interpretive weight was given to oil-palm-specific experiments when assessing feedstock performance, while broader reviews were used to establish adsorption mechanisms, carbon-stability principles, environmental trade-offs, and commercialization considerations.

The analysis proceeded through thematic coding. First-cycle categories comprised feedstock properties, process conditions, carbon yield, porous structure, surface chemistry, adsorption target, agricultural performance, carbon stability, emissions, activation method, regeneration, scale, and economics. Second-cycle synthesis then organized these codes around seven themes: feedstock architecture; conversion technology; material engineering; end-use performance; climate and environmental

performance; economics and commercialization; and circular-bioeconomy integration. Non-peer-reviewed commercial materials were excluded from the evidentiary synthesis. Application categories or performance claims were retained only when they could be independently supported or critically evaluated using peer-reviewed literature, thereby separating market context from scientific evidence.

Results

Feedstock Choice Determines the Starting Opportunity Set

The literature indicates that oil-palm biomass should not enter a uniform processing chain. PKS emerges as a particularly strong activated-carbon precursor because its relatively dense structure and carbon-rich characteristics facilitate storage, transport, carbonization, and subsequent activation. EFB offers much larger mill-linked bulk but requires more attention to drying, handling, and densification. MF is attractive technically but often already carries an internal energy value. OPF and OPT offer large plantation-side resources but impose distributed collection challenges. This has direct economic consequences. A tonne of residue at the reactor gate is not equivalent across feedstocks because delivered cost includes handling, moisture removal, densification, transport distance, storage loss, and the value of displaced alternative use. The economics therefore cannot be generalized by quoting one feedstock price. Techno-economic research on oil-palm-waste pyrolysis confirms that feedstock selection and process configuration can materially alter capital requirements, operating costs, product yields, and investment performance. The evidence also suggests a hierarchy in which carbonization near the biomass source is often preferable to transporting low-density wet material long distances. This is especially relevant to EFB and plantation residues. A decentralized or mill-integrated carbonization stage can reduce mass and volume before downstream transport, while activated-carbon upgrading could be concentrated at regional facilities where chemical recovery, quality control, wastewater treatment, laboratories, and specialized packaging are economically feasible. Such a hub-and-spoke model requires further demonstration but is consistent with broader commercialization arguments for biomass-derived products [45,46].

Processing Severity Creates a Yield–Quality Frontier

A consistent pattern across studies is that thermochemical severity generates a trade-off. Increasing temperature and activation can improve some functional properties while reducing solid yield. For biochar-oriented systems, losing too much solid carbon undermines the objective of retaining biogenic carbon. For activated-carbon systems, some burn-off is necessary to develop accessible pore volume. The relevant optimization variable is therefore not maximum yield or maximum surface area independently, but **value and environmental benefit per unit feedstock carbon**. This distinction can be framed as a carbon-allocation problem. Suppose a residue contains a defined mass of biogenic carbon. One fraction can remain in char, another leaves as condensable vapours, and another is converted to gases. Further activation intentionally oxidizes part of the solid matrix to create pore space. If those gases provide process energy and displace fossil fuel, the apparent “loss” may have system value; if they are flared inefficiently or released incompletely combusted, the same carbon transfer can create an environmental burden. The quality of process integration therefore determines whether lower solid yield represents waste or purposeful coproduct generation, an issue also highlighted by recent EFB carbon-conversion Research. The same trade-off appears in chemical activation. Strong KOH activation may create exceptional microporous carbon, but reagent-to-char

ratios, chemical recovery, washing water, drying energy, and neutralization influence the actual environmental footprint. Phosphoric-acid activation can create highly porous carbons under different conditions, while surface modification can increase selectivity at the expense of additional reagents and unit operations. Consequently, material studies should increasingly report mass yield, energy input, reagent recovery, and wastewater burden alongside adsorption capacity [47].

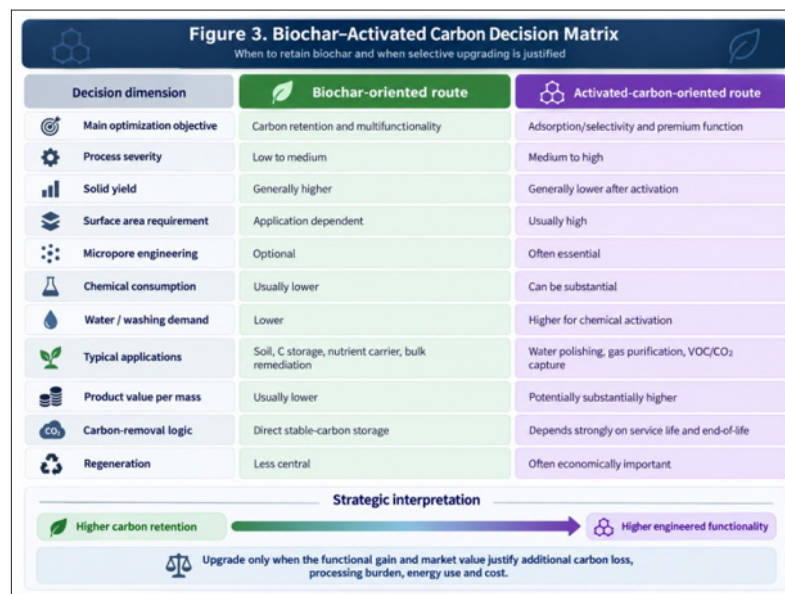


Figure 3: Presents the Resulting Biochar–Activated Carbon Decision Matrix.

Rather than assuming that activated carbon is simply a “better” biochar, it shows that each occupies a different position on a carbon-retention versus material-functionality frontier.

Figure 3. Conceptual decision matrix for retaining biochar or upgrading to activated carbon

Figure 3 highlights why the appropriate question is not “biochar or activated carbon?” in the abstract. A carbon product should be upgraded only when the functional gain and market value justify the additional carbon loss, processing burden, and cost. PKS may justify aggressive activation for gas or high-value liquid adsorption, whereas some EFB or MF streams may generate greater system value as agricultural biochar or moderately engineered sorbents.

Biochar Offers Multiple Pathways Beyond Soil Amendment

The review finds that describing biochar solely as a soil amendment understates its technological breadth. Oil-palm biochars have been investigated for aqueous adsorption, catalyst production, controlled nutrient systems, and energy-related applications in addition to agronomy. For example, EFB-derived biochar has been sulfonated into a heterogeneous acid catalyst for esterification, demonstrating that carbonized residues can function as renewable catalyst supports rather than merely inert soil additives Engineered biochar is especially important because a binary distinction between “raw biochar” and “activated carbon” can be misleading. Steam treatment, oxidation, mineral loading, magnetic modification, ball milling, or formation of composites can substantially enhance biochar without applying the full processing sequence associated with commercial activated carbon. Contemporary reviews therefore describe a continuum from pristine biochar through engineered biochar to highly activated or functionalized carbon materials This continuum can be strategically valuable for the palm-oil sector. A producer may use a relatively simple EFB biochar for soil carbon and physical improvement; a modified version for metal removal; PKS activated carbon for industrial adsorption; and a specialized impregnated grade for gas treatment. Such product differentiation spreads market risk and enables biomass fractions of different quality to be allocated to different

revenue streams [48].

Activated Carbon Creates Higher-Value Environmental Markets
Activated carbon is already associated commercially with drinking-water treatment, wastewater polishing, gas purification, solvent recovery, odour control, and industrial adsorption. Biomass-derived activated carbons are increasingly being investigated as substitutes for fossil precursors because their pore architecture and surface chemistry can be tailored while utilising renewable residues. Recent syntheses also emphasise regeneration, reuse, and process integration as essential criteria for sustainable large-scale deployment [49].

For aqueous metals, adsorption can involve electrostatic interaction, ion exchange, surface complexation, precipitation, and pore-related mechanisms. Functionalized PKS-based carbon has demonstrated removal potential for metals in simulated contaminated water, while broader research confirms that activation parameters and surface functionality strongly determine performance Because real wastewater contains competing species, future research needs to move beyond ideal single-solute tests toward complex matrices, continuous columns, and regeneration cycles. POME represents a particularly compelling circular application because the adsorbent feedstock and wastewater originate within the same industry. demonstrated the use of PKS activated carbon for lignin removal in a model palm-industry effluent system. This supports a broader industrial-symbiosis concept one residue stream can become an environmental material used to treat another waste stream. However, full feasibility requires assessment of adsorbent dosage, hydraulic contact, fouling, regeneration, spent-carbon handling, and whether adsorption should complement rather than replace biological treatment. Gas applications create another value tier. Biomass-derived activated carbon is increasingly studied for CO₂ adsorption because pore size and surface basicity can be engineered toward acidic CO₂ molecules. Micropore development is important, and nitrogen or metal functionalities can enhance affinity under some conditions [52-56].

PKS-specific studies reinforce this potential. investigated PKS-containing activated-carbon systems for CO₂ adsorption, while Lai and Ngu (2024) developed concurrent activation and surface modification to increase CO₂-affinity functionality. PKS-derived activated carbon has also been examined for methane adsorption, broadening potential applications to gas storage and separation. These studies remain primarily material- and process-focused moving toward commercial systems will require dynamic breakthrough tests, humidity tolerance, impurity tolerance, cyclic stability, pressure-drop assessment, and regeneration-energy analysis. Energy-storage applications constitute a further frontier. EFB-derived activated carbons have been investigated as supercapacitor and battery-electrode materials through chemical, physical, and sonication-assisted activation routes. Such applications can potentially command higher product value than bulk environmental adsorbents, but they impose tighter requirements for purity, electrical conductivity, controlled pore-size distribution, electrochemical stability, and reproducibility [50-54-57].

Carbon Removal is Credible Only Under System Boundaries

A central finding is that the phrase “biochar carbon sequestration” requires a clearly stated accounting boundary. The carbon contained in dry biomass is not equal to durable atmospheric carbon removal. First, only a fraction of feedstock mass becomes char. Second, biochar is not pure carbon. Third, not all carbon in the biochar is equally persistent. Fourth, production and logistics generate emissions. Fifth, some climate benefit may come from substituted energy or avoided decomposition rather than from the char itself. A simplified conceptual formulation helps clarify the accounting logic used in this review. It separates durable carbon storage and verified substitution or avoidance credits from supply-chain and process emissions: $CDR_{net} = C_{stable} + C_{credit} - E_{sc}$

– Eprocess (1) Equation (1) is conceptual rather than a universal certification equation. Here, C_{stable} denotes durable biogenic carbon stored, C_{credit} denotes verified substitution or avoidance credits, E_{sc} denotes supply-chain greenhouse-gas emissions, and $E_{process}$ denotes process-related greenhouse-gas emissions. This relation clarifies why a statement such as “6,000 tonnes of biomass processed equals 12,000 tonnes of carbon sequestered” cannot be validated without additional information. Converting stored carbon to CO₂-equivalent uses molecular-mass conversion, but the relevant carbon mass must first be established after yield and stability adjustments, and the baseline fate of biomass must also be specified. Meta-analytic evidence supports the capacity of biochar to increase soil carbon pools. found significant increases in SOC across a large global dataset, and likewise reported increases across several soil-carbon fractions. found a positive overall effect on soil carbon sequestration while showing that other components of the soil-carbon cycle were more variable. These studies support carbon-storage potential but also caution against treating one percentage or permanence assumption as universally applicable. Life-cycle evidence similarly shows that production design matters demonstrated that industrial biochar can deliver negative life-cycle emissions under suitable assumptions and process integration, but carbon-removal cost and performance vary with feedstock, energy, plant operation, and market conditions. Broader reviews stress the importance of harmonised functional units, system boundaries, allocation rules, and permanence assumptions when comparing biochar systems, while recent work places increasing emphasis on measurable durability and project-level verification [51,53].

Figure 4: Translates These Considerations into an Integrated Carbon-Flow Architecture. It separates feedstock carbon from stable stored carbon and explicitly recognizes energy coproducts, activation losses, and life-cycle emissions.

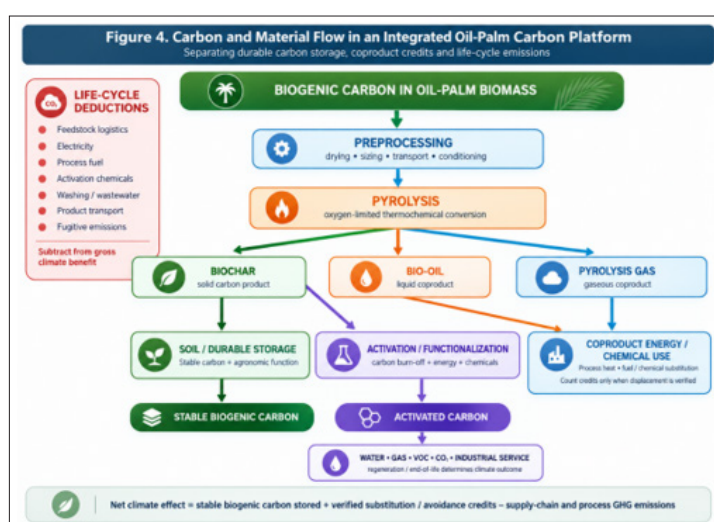


Figure 4: Conceptual Carbon and Material Flow for an Integrated Oil-Palm Carbon Platform

Figure 4 makes clear that a circular carbon plant has at least three possible climate channels: durable carbon storage, displacement of fossil energy by pyrolysis coproducts, and replacement of more emission-intensive materials or treatment processes. Claims should identify which of these channels are included and avoid double counting.

Economics Favour Product Portfolios Rather Than One-Product Plants

The techno-economic literature suggests that biochar economics are highly sensitive to feedstock cost, scale, plant utilization, energy integration, capital cost, product price, and whether carbon value is recognized. although studying orchard biomass rather than oil palm, demonstrate how production-cost uncertainty can span a broad range and how regional economic conditions influence feasibility. Oil-palm-specific pyrolysis analyses likewise find substantial sensitivity to process and feedstock assumptions. Activated carbon potentially improves revenue per tonne but introduces tighter quality control and higher processing cost. Commercial customers often require specifications for particle size, hardness, ash, moisture, iodine number, surface area, pore distribution, adsorption capacity, pressure

drop, and sometimes specific impurity levels. Powdered, granular, pelletized, and impregnated products also serve different markets. This creates an argument for selective fractionation of output rather than a homogeneous bulk commodity. A cascading portfolio could therefore contain several grades. Lower-cost bulk biochar could enter soil, composting, or remediation markets. Higher-quality biochar could serve nutrient carriers or specialized adsorbents. Selected char, particularly from PKS, could be physically or chemically activated for wastewater or gas applications. A smaller fraction might receive expensive functionalization for highly specific contaminants or electrochemical uses. Such a portfolio reduces dependence on a single uncertain market and allows production decisions to reflect feedstock quality. Commercialization remains constrained by market development, product standardization, and scale-up. Note recurring challenges in advancing palm-waste conversion technologies beyond technical feasibility, while emphasize the need for stronger demand-side development for oil-palm biochar and activated carbon. Biomass-derived activated-carbon monolith research similarly identifies scale-up and commercialization as distinct challenges beyond laboratory adsorption performance [55].

Discussion and Analysis

From Waste Management to Carbon Manufacturing

The principal conceptual shift emerging from the literature is that oil-palm residues should be treated as renewable carbon feedstocks rather than undifferentiated wastes. Waste-management thinking asks how residues can be disposed of or consumed. Carbon-manufacturing thinking asks what molecular and structural characteristics the biomass possesses, what carbon product can be produced, what specification that product must achieve, and which market values those properties. This distinction is important because high-value carbon manufacturing can change the economics of biomass logistics. A low-value feedstock does not justify expensive preprocessing or long-distance transport, but a specialty carbon product may. Conversely, a technically excellent activated carbon may still be commercially unattractive if chemical consumption, washing, product loss, or regeneration costs are too high. Feedstock value and product value must therefore be assessed simultaneously. PKS provides the clearest example. Its high utility as a fuel can make the raw material more expensive than a residue with limited alternative use, but the same properties that make it an effective fuel also make it an attractive carbon precursor. The correct economic comparison is not “free waste versus activated carbon revenue”; it is the incremental value of carbon material relative to the best alternative use of PKS EFB presents almost the opposite profile. It is generally more difficult to transport and dry, but large volumes arise at mill sites. Its conversion is therefore strengthened by integrated mill systems where drying can exploit residual heat, pyrolysis gas can supply thermal energy, and char can be processed without transporting the original wet biomass. Such process integration is consistent with broader palm-oil biorefinery and circular nutrient-management concepts

A Cascading Carbon Hierarchy

A rational processing hierarchy begins with the least severe process capable of delivering the required product function. This principle can be called minimum sufficient engineering. If a moderately carbonized EFB biochar meets agronomic specifications, chemical activation is unnecessary; if an engineered biochar removes a target contaminant at the required rate and can be regenerated, upgrading it to ultra-high-surface-area activated carbon may add cost without proportionate benefit. Conversely, gas purification

may require precisely engineered microporosity or surface basicity that ordinary biochar cannot. Minimum sufficient engineering has environmental advantages. Every additional unit operation introduces energy, materials, equipment, labour, potential emissions, and yield loss. It also has economic advantages because product value can be matched to production cost. This idea aligns with emerging biochar literature emphasizing fit-for-purpose engineering rather than single-property maximization.

The approach also creates a useful role for quality grading. After carbonization, char could be characterised for fixed carbon, ash, pH, elemental composition, H/C ratio, O/C ratio, surface area, pore distribution, and contaminants. High-quality fractions would be upgraded or directed to sensitive markets, while lower grades could enter bulk applications compatible with their properties. Such grading can reduce processing of unsuitable material and improve consistency, while parameters such as H/C provide useful information about carbonisation severity and durability [58]

Activated Carbon Should Be Evaluated by Functional Productivity Research papers frequently compare adsorbents using maximum adsorption capacity, but industrial decisions require a wider concept: functional productivity. An activated carbon that exhibits high equilibrium uptake but adsorbs slowly, breaks mechanically, causes excessive pressure drop, loses performance after one regeneration, or requires expensive chemical washing may be inferior in real service. Regeneration and reusability are therefore essential alongside adsorption capacity when assessing large-scale viability. Functional productivity should therefore combine at least adsorption capacity, kinetics, selectivity, mechanical durability, regeneration efficiency, number of cycles, product yield, and process cost. For gas treatment it should also consider humidity, temperature, pressure, breakthrough time, heat of adsorption, and contaminant mixtures; for water treatment, hydraulic behaviour, fines generation, dissolved-carbon release, competing solutes, pH sensitivity, and spent-adsorbent management are important. This broader framing is particularly relevant to industrial activated-carbon markets. Pelletized, granular, powdered, and impregnated carbons are not merely different physical presentations because particle form affects contact configuration, pressure drop, mass transfer, filtration, recovery, and regeneration. A future oil-palm activated-carbon industry would therefore need product engineering, regeneration protocols, and application testing comparable with incumbent activated-carbon suppliers rather than relying solely on laboratory BET values

Integrating The Carbon-Removal and Adsorption Business Cases Biochar and activated carbon are often discussed in separate markets: one as a climate and agricultural material, the other as an industrial adsorbent. An integrated oil-palm platform can bridge them, but carbon accounting must remain product-specific. Biochar incorporated into soil or another durable matrix can potentially support long-duration carbon storage, whereas activated carbon used for wastewater treatment has a different lifecycle. It may be regenerated thermally, destroyed, combusted, landfilled, incorporated into another material, or otherwise managed after use. Carbon originally present in the adsorbent therefore cannot automatically be counted as permanent removal. The climate benefit of activated carbon may instead arise partly from renewable substitution for fossil-derived carbon, improved pollution control, or energy-efficient purification. This difference suggests that a carbon platform should maintain distinct carbon-accounting ledgers. The first tracks durable carbon-removal products. The second tracks industrial carbon materials whose

primary value is adsorption. The third tracks pyrolysis-derived energy and associated fossil substitution. Combining all three into one headline “sequestration” number would obscure the underlying mechanisms.

Credible measurement, reporting, and verification requires conservative assumptions. Stable-carbon fractions should be based on accepted analytical indicators rather than total carbon, emissions from transport and processing should be measured or modelled, and energy coproduct credits should reflect actual displacement. Feedstock baselines should also avoid crediting avoided emissions that would not realistically have occurred, particularly when biochar carbon credits become a material component of project revenue.

Circularity Inside the Palm-Oil Complex

One of the strongest opportunities is internal industrial symbiosis. Oil-palm biomass can be carbonized using thermal integration the resulting carbon can treat palm-industry Wastewater pyrolysis gas can supply energy nutrient-rich or suitable biochar can return to plantation soils and premium carbon can be sold externally. This architecture links waste management, energy, water treatment, agricultural inputs, and carbon management and is consistent with recent life-cycle evidence for EFB-based soil-amendment pathways POME treatment is an obvious example. Conventional biological systems address high organic loads effectively but may leave colour, recalcitrant compounds, or polishing requirements. PKS activated carbon or engineered biochar could occupy a tertiary-treatment role rather than attempting to substitute for the entire treatment train. Spent adsorbents could potentially be regenerated or evaluated for other safe end uses, although contamination and regeneration efficiency must be considered Nutrient circulation represents another pathway. Biochar can act as a carrier for fertilizers or interact with composting systems, creating opportunities to recycle nutrients and improve fertilizer-use efficiency demonstrate the possibility of urea incorporation into PKS-derived carbon, while the wider literature documents the multifunctional agricultural role of biochar A third pathway is catalyst production. EFB carbon can be functionalized as a heterogeneous acid catalyst, potentially linking biomass residue with palm-derived fuel or chemical synthesis The significance is broader than one catalyst formulation: carbon materials can become process auxiliaries inside the same industrial ecosystem from which their feedstock originates.

Centralized Versus Decentralized Production

Scale is not a purely engineering question. Large centralized plants can offer better heat integration, pollution control, automation, analytical laboratories, chemical recovery, and consistent product quality. However, moving wet or bulky biomass over long distances can erode those benefits. A hybrid configuration may therefore be preferable. Primary drying and carbonization can occur near mills or major feedstock clusters, after which char - lighter and denser than the original wet biomass - can be transported to regional upgrading facilities. High-specification activated carbon production, surface modification, pelletization, regeneration, and quality assurance can then be concentrated where technical capacity exists PKS may be an exception because it already possesses favourable logistics and can be economically moved further than EFB. OPT and OPF may instead favour decentralized conversion because they arise across plantations. A future techno-economic model should therefore calculate feedstock-specific optimal collection radii rather than applying one radius to the entire oil-palm biomass portfolio.

Environmental Safeguards Beyond Carbon

A circular-bioeconomy narrative should not focus on carbon while ignoring other environmental burdens. Chemical activation can create acidic or alkaline wash water and dissolved salts, while contaminated biomass can transfer impurities into char and high ash can reduce some product qualities. Poorly controlled carbonization can also emit particulates, CO, hydrocarbons, and odorous compounds, and fine activated-carbon powders create dust-control and occupational-exposure requirements These concerns are manageable but require industrial design. Closed-loop or reduced-water washing, chemical recovery, thermal oxidizers, gas recirculation, particulate capture, safe solids handling, wastewater treatment, and occupational controls should therefore be integrated into scale-up studies. The carbon product should not solve one environmental problem by shifting impacts into wastewater or air pollution, and life-cycle assessment should be used to detect such burden shifting LCA is essential for detecting these burden shifts. emphasise that bio-based products do not automatically reduce every environmental impact category. A system may perform well on climate indicators but poorly on water use, eutrophication, toxicity, or energy if reagents and utilities are intensive; recent biochar LCA reviews similarly show strong dependence on feedstock, conversion route, and end-use scenario (Li et al., 2024). Environmental assessment should therefore extend beyond a single carbon metric.

Research and Commercialization Agenda

The first priority is movement from batch laboratory experiments toward **continuous pilot operation**. Many publications characterize carbon produced in gram- or kilogram-scale reactors under tightly controlled feedstocks. Commercial mills handle heterogeneous material with changing moisture, ash, size, and contamination. Continuous reactors must demonstrate stable temperature control, residence time, gas handling, product quality, and maintenance under such variability. Second, adsorption studies need greater emphasis on real matrices and cyclic operation. Single-solute equilibrium tests remain useful for fundamental comparison but are insufficient for industrial design. Future work should report dynamic breakthrough, regeneration, competing contaminants, multiple cycles, mechanical degradation, and adsorbent loss because reusability and regeneration strongly influence both environmental and economic performance. Third, biochar research needs longer field trials. Meta-analyses support increases in soil carbon, but response heterogeneity remains substantial. Plantation-scale oil-palm trials should evaluate several years of soil carbon, nutrient cycling, fertilizer use, water relations, root development, yield, greenhouse-gas fluxes, and environmental safety rather than focusing only on short nursery responses Fourth, carbon removal and activated-carbon economics should be analysed together. A project may have several products with different margins. Process models should allocate common costs among biochar, activated carbon, energy, and other coproducts and examine how profitability changes with carbon prices, electricity, activation chemicals, transport, yield, and market penetration. Fifth, standardization will be critical. Agricultural biochar, water-treatment activated carbon, gas adsorbents, and electrode carbons require different test protocols. Producers need application-specific specifications and consistent quality. Without standardization, the market may discount palm-derived carbon regardless of promising laboratory performance.

Conclusion and Recommendations

Oil-palm residues offer a technically credible basis for developing an integrated renewable-carbon industry. The literature published

since 2020 shows that EFB, PKS, MF, OPF, and OPT can be converted into carbon products ranging from relatively high-yield biochars to strongly activated and functionalized adsorbents. Their most appropriate applications differ because feedstock composition, conversion severity, pore architecture, surface chemistry, carbon stability, and logistics vary substantially. The central implication is that biochar and activated carbon should be treated as complementary products rather than competing alternatives. Biochar is particularly suited to applications where stable-carbon retention, soil function, nutrient management, and bulk environmental remediation dominate. Selective activation is justified when high adsorption capacity, controlled porosity, gas capture, water purification, or specialty performance creates sufficient additional value. An economically and environmentally stronger model is therefore a portfolio-based oil-palm carbon platform. Such a platform would condition biomass according to feedstock, carbonize material near major residue sources, recover energy from pyrolysis coproducts, grade the resulting chars, retain suitable fractions as biochar, selectively upgrade high-quality fractions into activated carbon, and match each product to an application-specific market. Carbon-removal claims must remain separate from gross biomass-processing claims. Net removal depends on stable carbon, counterfactual feedstock fate, process emissions, energy integration, transport, application, and permanence. Likewise, activated-carbon production should be judged by functional productivity and life-cycle performance, not surface area alone. The principal next step for the industry is therefore not merely building larger carbonization equipment. It is designing an integrated feedstock, product, environmental, quality-assurance, and market system in which each tonne of oil-palm biomass is directed toward its highest credible environmental and economic value.

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