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Activated carbons from agro-industrial residues in Côte d'Ivoire: Feedstock chemistry, process-structure-property relationships, and pathways to application-specific industrial grades

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Abstract

Côte d'Ivoire generates a diverse range of agricultural and agro-industrial residues that could serve as precursors for activated carbon. This structured critical review maps fourteen experimental studies conducted in Côte

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d'Ivoire or explicitly using Ivorian biomass and integrates them with international evidence on activation mechanisms, process engineering, scale-up, and application-specific qualification. Sources were identified through database and reference-list searches closed on 16 September 2026, and studies were classified with two review-specific scales of technological evidence (D0–D5) and comparability (C1–C3). The analysis focuses on how feedstock characteristics and carbonization/activation conditions control pore architecture, surface chemistry, mechanical behavior, and ultimately service performance. The Ivorian evidence base covers coconut shells, cashew residues, Borassus aethiopum, Acacia species, cocoa residues, rubber-tree biomass, coffee husks, and palm shells. Reported performances include BET specific surface areas above 1,000 $m^2 g^{-1}$, iodine numbers close to or above 900 mg g^{-1}, and high removal efficiencies in water-treatment and biogas-purification tests. However, protocols remain heterogeneous and provide limited information on hardness, attrition, inter-batch reproducibility, dynamic adsorption, regeneration, and closed mass-energy-water balances. Côte d'Ivoire also continues to import activated carbon, while trade statistics alone cannot establish the volume of domestically produced industrial-grade material. The key challenge is therefore no longer to demonstrate conversion feasibility, but to establish reproducible feedstock-process-structure-property-performance relationships through to material qualification. An application-specific grade pathway is proposed for water treatment, gas purification, and gold recovery, linking laboratory evidence to pilot-scale validation and industrial qualification. The pathway is prospective: the Ivorian experimental evidence is limited to laboratory-scale tests (plus one semi-industrial column prototype), no Ivorian carbon has been tested for gold recovery, and reproducible industrial production is not documented.

1. Introduction

Activated carbon is a carbonaceous adsorbent whose technological value arises from the interaction between a developed pore network and tunable surface chemistry. Performance cannot therefore be reduced to a single indicator such as BET specific surface area or iodine number; it depends on pore-size distribution, surface functional groups, ash content, density, mechanical strength, transport phenomena, and the match between these properties and the target adsorbate [1–3]. Recent reviews of biomass-derived activated carbons likewise emphasize the combined effects of precursor type, temperature, residence time, heating rate, activating agent, and impregnation ratio on yield, pore development, and final material performance [1–3].

Côte d'Ivoire provides a particularly relevant setting for this issue. The country has major agricultural value chains - cocoa, cashew, rubber, oil palm, and cassava - that generate lignocellulosic by-products whose availability, spatial concentration, and competing uses vary considerably. A sectoral study prepared for the Netherlands Enterprise Agency (RVO) identified substantial potential for residue valorization across these five value chains, while noting that some streams are already used as feed, fertilizers, or fuels, whereas others, including certain rubber-tree felling residues and processing effluents, remain underutilized [4]. This distinction is essential: high agricultural production does not, by itself, indicate the tonnage that can actually be mobilized for activated-carbon production.

The Ivorian scientific literature is also broader than a focus on recent studies alone would suggest. Coconut-shell activated carbons have been investigated for the removal of diuron, butylparaben, and benzo(a)pyrene [5,19–21]; carbons prepared from Acacia and Borassus have been characterized for aqueous applications [6–8]; and cashew- and shea-shell carbons have been tested for Pb(II) and Cd(II) removal, while Ivorian cashew shells have also been physically activated for water purification [22,23]. More recent work has extended the field to biogas purification using cocoa, cashew-tree, and rubber-tree residues [9–11], activated carbon from coffee husks [12], characterization of cashew-tree-derived carbon [13], and electrochemical storage using a palm-shell activated-carbon/graphene-oxide composite [24]. Conversion feasibility is therefore well established; the more demanding question is whether process conditions, measured material properties, and service requirements are linked coherently enough to support reproducible grade qualification.

The principal scientific gap is therefore not whether an Ivorian residue can be carbonized and activated. It is the absence of an integrated framework that links feedstock chemistry and practical mobilizability to conversion conditions, resulting pore architecture and surface chemistry, and the properties required by a specific industrial service. To the best of our knowledge, the available studies have not previously been synthesized through a feedstock-process-structure-property-grade framework that simultaneously addresses resource availability, process engineering, application-specific qualification, and scale-up. This review addresses that gap by treating feedstocks not as intrinsically "good" or "poor", but as raw materials whose value depends on whether a controlled process can deliver a reproducible grade for water treatment, gas purification, gold recovery, or another defined use.

2. Methodology of the Structured Critical Review

This study adopts a structured critical review with evidence mapping rather than a systematic review in the strict sense. The transparency principles of PRISMA 2020 were used as reporting guidance for information sources, search timing, selection criteria, and data extraction [14,15], without claiming full PRISMA compliance. The literature search was closed on 16 September 2026 and organized into three evidence streams: (i) experimental studies conducted in Côte d'Ivoire or explicitly using Ivorian biomass; (ii) international literature on carbonization and activation mechanisms, process-structure-property relationships, Carbon-in-Pulp (CIP)/Carbon-in-Leach (CIL) systems, and scale-up; and (iii) institutional sources documenting biomass resources, trade flows, and relevant industrial operations.

Information sources and search strategy. Searches for evidence stream (i) were run in Scopus, Web of Science Core Collection, ScienceDirect, and Google Scholar, and complemented by African Journals Online and the websites of regional journals. No lower date limit was applied (the earliest retained study dates from 2009), and the last search was run on 16 September 2026. For streams (ii) and (iii), targeted queries addressed activation mechanisms, scale-up and commercialization, CIP/CIL gold adsorption, and HS 380210 trade statistics; recent reviews, standards, and operator technical reports were preferred.

The review combined targeted literature searches with backward screening of reference lists from selected publications. Search terms covered the principal feedstocks investigated in Côte d'Ivoire, carbonization and activation routes, process-structure-property relationships, scale-up, and applications in water treatment, gas purification, and gold recovery. Institutional evidence was assessed separately from experimental studies so that resource availability, trade statistics, and mining-process information were not conflated with material-performance data.

Studies were retained in the experimental corpus when they clearly identified the feedstock, the main material-preparation conditions, and at least one physicochemical property or application-performance metric. Publications addressing the same feedstock were retained as separate lines of evidence when they provided complementary process, characterization, or application data. Fourteen directly relevant experimental studies were included in the Ivorian evidence map. Extracted variables comprised feedstock origin and type; initial characterization where reported; pretreatment; carbonization conditions; activating agent and impregnation ratio; temperature; residence time; yield; Brunauer-Emmett-Teller (BET) specific surface area; pore-size distribution; iodine number; ash content; moisture; pH/point of zero charge (pH_{PZC}); mechanical properties; application; and test conditions.

Records were screened on title and abstract and then on full text. Inclusion criteria were: (a) activated carbon, or carbon explicitly subjected to activation, prepared from a lignocellulosic or agro-industrial residue

sourced in Côte d'Ivoire, or prepared from Ivorian biomass by Ivorian groups; (b) explicit identification of the feedstock and main preparation conditions; and (c) at least one physicochemical property or application-performance metric. Exclusion criteria were: (a) commercial carbons or non-Ivorian feedstocks (used only as international benchmarks in streams ii and iii); (b) char or biochar without activation, adsorption, or equivalent performance data; (c) records without enough methodological detail to identify the feedstock and preparation route (e.g., abstracts without full text); and (d) duplicate reports of the same dataset, for which the most complete publication was retained. Because this is a structured critical review and not a systematic review, no PRISMA flow diagram and no formal risk-of-bias appraisal were produced. The corpus should therefore be read as a transparent map of the available Ivorian evidence, not as an exhaustive census.

Two independent classifications were used to limit overinterpretation. The D0-D5 technological-evidence scale proposed in this review distinguishes D0 (theoretical potential/resource), D1 (demonstrated carbonization), D2 (activation plus material characterization), D3 (demonstrated application), D4 (pilot- or service-relevant validation), and D5 (documented, reproducible industrial production). The C1-C3 comparability scale distinguishes C1 (direct quantitative comparison possible), C2 (partial or mainly qualitative comparison), and C3 (no defensible quantitative comparison). These are analytical tools developed for this review, not industrial standards or formally standardized technology-readiness scales. BET values, iodine numbers, and removal percentages were compared quantitatively only when methods, units, and experimental conditions were sufficiently compatible.

The operational criteria used to assign the D and C levels are given in Table 1 and were applied in the same way to Tables 2 and 4 and to the text. Each study was assigned the highest D level that is documented in the study itself, and a level was not assigned when the evidence for the preceding level was missing; individual studies therefore receive a single level, whereas ranges in Table 2 (e.g., D0–D3) indicate the spread across the streams or studies available for a residue. The C level was assigned to the principal metrics of each study (BET specific surface area, iodine number, and adsorption or removal performance) by checking three conditions: (i) the measurement method is standardized or fully described; (ii) units and basis are consistent; and (iii) the test conditions (adsorbate, concentration, adsorbent dose, pH, temperature, contact time, or flow regime) are fully reported and shared with at least one other study. C1 requires the three conditions, C2 requires the first two with only partial or non-shared test conditions, and C3 applies when the metrics cannot be compared defensibly. No study in Table 4 meets all three conditions simultaneously, and none is therefore classed C1.

Table 1. Operational criteria for the D0–D5 technological-evidence scale and the C1–C3 comparability scale used in this review.

Level	Definition	Minimum evidence required	Example in this review
D0	Theoretical potential / resource	Residue identified or quantified as a potential feedstock; no carbon produced locally	Palm-kernel shells and cassava peels for activated carbon (Table 2)
D1	Demonstrated carbonization	Char or biochar produced, with at least yield or proximate characterization; no activation	Upper bound for palm-kernel shells locally (Table 2)
D2	Activation plus material characterization	Activated carbon produced with reported conditions and at least one porosity or quality metric (BET, iodine number, pore volume); no adsorption test on a target	Cashew-tree branches [13]

Level	Definition	Minimum evidence required	Example in this review
D3	Demonstrated application (laboratory)	Batch or small-scale laboratory adsorption or electrochemical test with a reported performance metric on a target	Acacia [6]; biogas studies [9–11]
D4	Pilot- or service-relevant validation	Dynamic (column, breakthrough, or fixed-bed) tests, or a pilot unit, under conditions representative of the intended service	Borassus aethiopum prototype [7,8]
D5	Documented, reproducible industrial production	Multiple industrial batches with quality-control data (inter-batch variability, hardness, etc.) and commercial supply	None documented
C1	Direct quantitative comparison possible	Standardized or fully described method, consistent units and basis, and fully reported test conditions shared with at least one other study	None in the corpus
C2	Partial or mainly qualitative comparison	Method and units compatible, but test conditions only partly reported or not shared	Most studies in Table 4
C3	No defensible quantitative comparison	Different adsorbates, methods, or bases, or insufficient information	Acacia [6]; cocoa residues [9]

The scales are analytical tools developed for this review; they are neither industrial standards nor formal technology-readiness levels.

Figure 1 summarizes the analytical framework used in this review, from feedstock characteristics to the targeted application-specific grade through the conversion process and the resulting material properties.

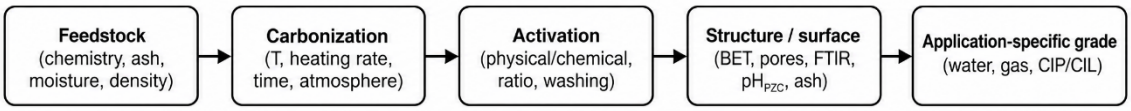


Figure 1. Proposed analytical framework linking feedstock, process, structure, and application-specific grade.

3. Ivorian Biomass Resources: Availability Does Not Equal Mobilizable Supply

Resource assessment should distinguish at least three levels. The theoretical resource is the maximum quantity of residue associated with a given agricultural output; the technically recoverable potential excludes fractions that cannot be collected or are incompatible with the logistics chain; and the practically mobilizable potential additionally accounts for competing uses, moisture, losses, seasonality, transport distances, and economic constraints. In practice, the expected relationship is M_mobilizable < M_technical < M_theoretical, but no generic coefficient should be applied in the absence of local data.

The RVO/Partners for Innovation study shows that the cashew, cassava, cocoa, oil-palm, and rubber value chains all generate potentially recoverable streams, although their characteristics differ markedly [4]. Cashew shells are concentrated at processing plants and their availability should increase with local processing, but they face competing uses related to cashew nut shell liquid (CNSL), energy, and briquetting. Cassava peels and starch-processing effluents are abundant but contain high moisture levels. Cocoa pod husks are largely dispersed in the field, whereas shells from industrial processing are more concentrated. Palm-kernel shells and oil-palm fibers are spatially concentrated at mills but are often already used as boiler fuel. Finally, rubber-tree felling residues and some rubber seeds are lignocellulosic streams that remain only partly valorized [4].

For activated-carbon production, the geography of the resource is as important as feedstock chemistry. A dense, dry residue concentrated at an industrial site may be more attractive than a theoretically abundant but wet and dispersed residue. Industrial feedstock selection should therefore complement chemical characterization with a minimum logistics assessment covering collection radius, inlet moisture content, bulk density, seasonality, and competing uses.

Table 2 summarizes the practical mobilizability of major Ivorian residues considered as candidate feedstocks for activated-carbon production.

Table 2. Practical mobilizability of major Ivorian residues considered as candidate feedstocks for activated-carbon production.

Value chain / residue	Documented resource potential	Spatial concentration	Competing uses / constraints	Process relevance for activated carbon	Resource evidence level
Cashew - shells / branches	High, but dependent on the local processing rate	High for shells at processing plants	CNSL, energy, briquettes; residual oil	Dense feedstock; activation route must be documented for the target use	D0-D3 depending on stream
Rubber - branches / renewal wood	Substantial potential of woody residues	Rubber-growing areas; collection logistics required	Wood/energy uses; moisture and piece size	Woody feedstock favorable for granular carbons	D3 for studied branches
Cocoa - pod husks / processing shells	High, but with markedly different spatial distribution among streams	Pod husks dispersed in the field; factory shells concentrated	Compost, bioenergy; ash/moisture	Biochar/activated carbon already tested for gas treatment; stream selection is critical	D3 for some applications
Oil palm - palm-kernel shells / fibers	High technical potential at mills	Very high at oil mills	Already used as boiler fuel	Dense shells potentially suitable for granular activated carbon (GAC)	D0-D1 locally for activated carbon
Cassava - peels / fibrous residues	High, but with very high moisture	Variable; artisanal and industrial units	Feed, biogas, energy-intensive drying	Requires an energy balance for drying	D0 locally for activated carbon
Coconut - shells	Local availability requires better quantification	Variable across the value chain	Fuel / craft uses	International benchmark feedstock for GAC; historical Ivorian study available	D3

Evidence levels follow the D0–D5 scale defined in Table 1. Ranges (e.g., D0–D3) indicate the spread across the streams or studies available for the residue, not uncertainty about a single study.

4. Feedstock Chemistry and Formation of the Carbon Matrix

Lignocellulosic biomass feedstocks are dominated by cellulose, hemicellulose, and lignin, together with extractives and mineral matter. Their relative proportions influence thermochemical conversion. Hemicellulose generally decomposes at lower temperatures, cellulose over an intermediate range, whereas lignin degrades across a broader interval and contributes substantially to the carbonaceous residue. Mineral matter is partly retained in the solid phase; depending on composition, it can catalyze reactions while also reducing the useful carbon fraction [1,2].

The anatomical structure and initial density of the feedstock also influence particle strength after carbonization. Coconut shells and other dense shells are therefore widely used for granular activated carbon (GAC), whereas wet peels or fibrous biomasses may require more intensive drying, agglomeration, or shaping. A recurring limitation of studies on Ivorian feedstocks is the lack of complete raw-material characterization before activation. A future qualification workflow should report, at minimum, moisture, ash, volatile matter, fixed carbon, and density, and, where possible, lignocellulosic and mineral composition.

This requirement is methodologically important. The composition reported for a given species in another country cannot simply be assigned to an Ivorian biomass without local analysis because pedoclimatic conditions, age, anatomical fraction, and prior treatment can alter composition. International values may serve as benchmarks, but they should be explicitly identified as such.

5. Carbonization and Activation: A Process Engineering Perspective

5.1. Carbonization

Carbonization removes moisture and part of the volatile matter while concentrating carbon and establishing an initial pore network. Final temperature, heating rate, atmosphere, and residence time determine the trade-off between solid yield, structural ordering, and pore development [1–3]. Insufficient thermal treatment can leave volatile material that blocks pores, whereas excessive burn-off reduces yield and can over-widen or partially collapse the pore network. Industrial design should therefore be based on coupled mass and energy balances rather than on target temperature alone.

Ivorian studies cover markedly different operating windows. The rubber-tree branch study combined chemical impregnation with treatment at 450 °C for three hours [11]. Cashew-tree branches used for biogas desulfurization were activated after carbonization within the 500-550 °C range [10], whereas Gbangbo et al. [13] used 20% H_3PO_4, 24 h impregnation, and carbonization at 550 °C for 3 h 47 min. Acacia-derived carbons were evaluated at temperatures up to 800 °C [6]. This dispersion prevents direct ranking of feedstocks; more importantly, it highlights the lack of a common protocol capable of separating feedstock effects from process effects.

Within the Ivorian corpus, process variables are largely confounded with feedstock. Only the comparative coconut-shell studies [5,20], the cashew-branch study comparing H_3PO_4, NaOH, and KOH [10], and the rubber-branch study comparing NaOH and K_2CO_3 [11] vary the activating route or agent on a single feedstock; in the other studies, feedstock, temperature, impregnation, and hold time change simultaneously. Their results are therefore treated here as evidence of what each protocol achieved on a given feedstock, not as evidence that a feedstock or an activating agent is intrinsically superior.

5.2. Physical and Chemical Activation

Physical activation generally involves carbonization followed by controlled gasification with CO_2 or steam. It avoids large-scale use of chemical reagents but often requires high temperatures and precise burn-off control. At larger scale, heat-transfer quality, activating-gas distribution, and bed homogeneity become critical. The historical Ivorian study on coconut shells showed that both physical and chemical routes could develop combined micro- and mesoporosity, with performance depending on the preparation protocol and target contaminant [5].

Chemical activation commonly uses H_3PO_4, KOH, NaOH, K_2CO_3, or $ZnCl_2$. H_3PO_4 promotes dehydration and matrix rearrangement at relatively moderate temperature; KOH and NaOH can generate highly developed microporosity; and K_2CO_3 offers an alkaline alternative whose effectiveness depends strongly on feedstock and temperature [1–3]. Ivorian studies illustrate this diversity: H_3PO_4 has been used for cashew-tree and coffee-derived carbons [12,13], KOH produced the highest iodine number in the cashew-branch desulfurization study [10], and K_2CO_3 was selected with the GT1 rubber clone for CO removal [11].

A critical comparison of these routes requires the controlling variables to be made explicit (Table 3). In physical activation, temperature, activating gas, and hold time set the degree of burn-off: moderate burn-off opens and widens micropores, whereas excessive burn-off widens them into mesopores and macropores and lowers yield and mechanical strength [1–3]. In H_3PO_4 activation, the impregnation ratio and a comparatively moderate temperature control the balance between micro- and mesoporosity, and part of the phosphorus is retained as surface groups, which also modifies surface chemistry [1–3]. In KOH and NaOH activation, the alkali-to-carbon ratio and temperature mainly govern microporosity, at the cost of higher reagent consumption, corrosivity, and washing demand [1–3]. K_2CO_3 is a milder alkaline route whose outcome depends strongly on feedstock and temperature [1–3].

The Ivorian data show why ranking by activating agent alone is not justified. For the same type of feedstock, coconut-shell carbons prepared in different studies span BET specific surface areas from ≈443 $m^2\ g^{-1}$ (physical activation at 800 °C [19]) and ≈725 $m^2\ g^{-1}$ (NaOH, 500 °C [21]) to 1,310.13 $m^2\ g^{-1}$ (physical activation [5]), an almost threefold range. This indicates that the protocol (activating gas, hold time, burn-off, reagent ratio) and the characterization procedure can matter as much as the feedstock, and the reported information does not allow these contributions to be separated. Likewise, KOH-activated [10] and H_3PO_4-activated [13] cashew-branch carbons gave iodine numbers within about 1% of each other (923 and 913.68 mg g^{-1}), although the agents, impregnation protocols, and temperature windows differed. Conversely, the GT1/K_2CO_3 rubber-branch carbon, with a lower iodine number, reached ≈90% CO removal [11]. Taken together, these observations suggest that (i) similar micropore development can be reached through different chemical routes, so that the choice between them should rest on yield, effluent load, and downstream requirements as much as on porosity; and (ii) application performance depends on the match between pore-size window, surface chemistry, and adsorbate rather than on a single activation-quality index.

Table 3. Comparison of activation routes: controlling variables, expected effects, process constraints, and Ivorian studies in this review.

Activation route	Main controlling variables	Typical effect on pore structure and surface chemistry [1–3]	Main process constraints	Ivorian studies
Physical (CO_2 or steam)	Temperature; activating gas; hold time and burn-off; heating rate	Moderate burn-off develops micropores; excessive burn-off widens pores and lowers yield and hardness	High temperature; precise burn-off control; heat transfer and gas distribution at scale	[5,19,23]; [5,20] also compare chemical routes
H_3PO_4	Impregnation ratio and time; temperature (moderate)	Micro- and mesoporosity; phosphorus-containing surface groups	Acidic effluents; corrosion; washing and neutralization; reagent recovery	[6,12,13]; [10] (comparison with NaOH and KOH)
KOH / NaOH	Alkali-to-carbon ratio; temperature	Highly developed microporosity (notably KOH)	Corrosive reagents; high wash-water demand; saline effluents	[10] (KOH); [11,21] (NaOH)
K_2CO_3	Salt-to-carbon ratio; temperature	Intermediate and strongly feedstock- and temperature-dependent	Milder than KOH; washing still required	[11]
$ZnCl_2$	Impregnation ratio; temperature	Micro- and mesoporosity	Zinc-bearing effluents and toxicity concerns	None in the corpus

Effects are general trends from international reviews [1–3]. The Ivorian studies listed used different values of these variables and are therefore not directly comparable (see Table 5).

Scale-up, however, requires the complete process chain to be considered. Chemical activation introduces washing and neutralization steps that consume water and generate saline or acidic effluents. At tonne scale, these operations, together with reagent recovery, corrosion control, final drying, and management or recovery of pyrolysis gases, may be as important to process viability as the BET surface area achieved. Activating-agent selection should therefore be based on material performance and process-wide resource and environmental requirements.

6. Process-Structure-Property Relationships: Qualification Criteria

6.1. Specific Surface Area and Pore-Size Distribution

Several Ivorian feedstocks have yielded high BET specific surface areas. Bamba et al. [5] reported a maximum of 1,310.13 $m^2\ g^{-1}$ for physically activated coconut-shell carbon, while Koné et al. [7] measured 1,431 $m^2\ g^{-1}$ for Borassus aethiopum activated carbon. The recent coffee-husk study reported 762.74 $m^2\ g^{-1}$ [12]. These results demonstrate that high surface areas can be achieved from local feedstocks, but they do not justify ranking materials for industrial service on surface area alone. These values come from studies that differ in feedstock, activation route, and measurement protocol, and they are therefore reported as what each protocol achieved, not ranked (see Table 5).

6.2. Iodine Number: A Useful Indicator, but Not a Substitute for BET

The iodine number remains a useful quality-control test because it is simple and responsive to activation

level. ASTM D4607 nevertheless defines it as a relative indicator of porosity and notes that its relationship with specific surface area cannot be generalized because it depends on feedstock, treatment conditions, and pore-size distribution [16]. This limitation is central to interpreting Ivorian studies. An iodine number of 923 mg g^{-1} for KOH-activated cashew-tree carbon [10], or 913.68 mg g^{-1} reported by Gbangbo et al. [13] for H_3PO_4-activated cashew-tree carbon, indicates substantial micropore development in both cases but does not, by itself, establish superiority across all applications. Conversely, GT1/K_2CO_3 rubber-derived carbon, despite a lower iodine number, achieved approximately 90% CO removal in the system studied [11]. Quality must therefore be defined in relation to the intended use.

6.3. Surface Chemistry, Ash, and Mechanical Properties

Oxygen-containing surface groups - including carboxyl, lactone, phenolic, carbonyl, and hydroxyl functionalities - influence acidity/basicity, polarity, and electrostatic interactions. In aqueous systems, pH_{PZC} is particularly useful for interpreting adsorption of ionic species. Ash reduces the useful carbon fraction and can alter pH or catalyze secondary reactions. For fixed-bed, gas-phase, and CIP/CIL applications, apparent density, hardness, and attrition resistance are also critical. These mechanical properties remain substantially less documented in Ivorian studies than iodine number, ash content, or equilibrium adsorption performance.

Table 4 summarizes the process-characterization-evidence matrix for the main Ivorian studies identified.

Table 4. Process-characterization-evidence matrix for the main Ivorian studies identified.

Feedstock / study	Main process	Reported characterization	Application	D level	Comparability
Coconut shells [5]	Physical/chemical activation	BET, porosity, surface functional groups	Diuron in water	D3	C2
Acacia auriculiformis / mangium [6]	H_3PO_4; T up to 800 °C	Methylene-blue isotherms	Aqueous treatment	D3	C3
Borassus aethiopum [7,8]	Artisanal carbonization/activation	BET, micro/mesopores, Fourier-transform infrared spectroscopy (FTIR); column tests	Nitrate removal; semi-industrial prototype	D4	C2
Cocoa residues [9]	Biochar + chemical activation	Carbon properties; H_2S test	Biogas purification / corrosion	D3	C3
Cashew-tree branches [10]	H_3PO_4 / NaOH / KOH, 500-550 °C	Yield, pH_{PZC}, ash, iodine number	H_2S removal from biogas	D3	C2
Rubber-tree branches [11]	NaOH / K_2CO_3; 450 °C	Yield, ash, moisture, iodine number	CO removal from biogas	D3	C2

Feedstock / study	Main process	Reported characterization	Application	D level	Comparability
Coffee husks [12]	H_3PO_4; Box-Behnken design	Iodine number, scanning electron microscopy-energy-dispersive X-ray spectroscopy (SEM-EDS), mesoporous surface area	Adsorbent material	D2	C2
Cashew-tree branches [13]	20% H_3PO_4, 550 °C	Yield, iodine number	Characterization	D2	C2
Coconut shells - butylparaben [19]	Physical activation; 800 °C	BET ≈443 $m^2\ g^{-1}$; surface chemistry; pH	Butylparaben in water	D3	C2
Coconut shells - comparative study [20]	Physical and chemical activation	Porosity; adsorption/isotherms	Diuron	D3	C2
Coconut shells - benzo(a)pyrene [21]	NaOH; carbonization at 500 °C	BET ≈725 $m^2\ g^{-1}$; pH; ash; surface functional groups	Benzo(a)pyrene	D3	C2
Cashew + shea nut shells [22]	Shell-derived activated carbons	Adsorption kinetics and isotherms	Pb(II) and Cd(II) in natural freshwater	D3	C3
Cashew nut shells [23]	Physical activation	BET and pore structure	Water purification	D2	C2
Palm shells / graphene oxide (GO) [24]	Palm-shell activated carbon + graphene oxide	Voltammetry; galvanostatic charge-discharge (GCD); electrochemical impedance spectroscopy (EIS); cycling stability	Supercapacitor electrode	D3	C3

Evidence levels (D) and comparability levels (C) were assigned with the criteria in Table 1. Coffee husks [12] and cashew nut shells [23] are classed D2 because the characterization in Table 4 does not include an adsorption test on a target.

6.4. Comparing Reported Values: Required Test Conditions

Table 5 places the principal quantitative values quoted in this review next to the information needed to interpret them. Three rules were applied. First, BET specific surface areas and iodine numbers are not ranked across studies unless the measurement method (N_2 adsorption analysis for BET; ASTM D4607 [16] for the iodine number) and the basis are compatible. Second, adsorption capacities and removal efficiencies are compared only for the same adsorbate under comparable initial concentration, adsorbent dose, pH, temperature, and contact time or flow regime; a removal percentage depends on the dose-to-concentration ratio and is not an intrinsic property of the carbon. Third, where a condition is not stated, the value is treated as indicative only.

Table 5. Principal reported values, with the context needed to compare them.

Study	Feedstock / route	Reported value	Test context	Why direct ranking is not justified
[5]	Coconut shells; physical activation	BET maximum 1,310.13 $m^2 g^{-1}$	Diuron removal from water; comparative preparation study	Same feedstock as [19] and [21] but a different protocol; almost threefold BET range across the three studies
[19]	Coconut shells; physical activation, 800 °C	BET ≈443 $m^2 g^{-1}$	Butylparaben adsorption in water	Different adsorbate and activation conditions from [5]
[21]	Coconut shells; NaOH, carbonization at 500 °C	BET ≈725 $m^2 g^{-1}$	Benzo(a)pyrene adsorption	Chemical route; different adsorbate
[7,8]	Borassus aethiopum; artisanal carbonization/activation	BET 1,431 $m^2 g^{-1}$	Nitrate removal; column tests on a semi-industrial prototype [8]	Highest BET in the corpus, but an inorganic anion and an artisanal protocol; surface area alone does not predict service performance
[12]	Coffee husks; H_3PO_4, Box-Behnken design	Surface area 762.74 $m^2 g^{-1}$	No adsorption test on a target (D2)	The nature of the reported surface area (total BET or mesoporous, Table 4) must be checked before comparison
[10]	Cashew-tree branches; KOH, 500–550 °C	Iodine number 923 mg g^{-1}; 90.9% H_2S removal after 8 h	Biogas desulfurization	Removal depends on gas composition, flow, and bed mass, which differ from [11]
[13]	Cashew-tree branches; 20% H_3PO_4, 24 h impregnation, 550 °C, 3 h 47 min	Iodine number 913.68 mg g^{-1}	Characterization only (D2)	Iodine numbers of [10] and [13] agree within about 1%, but the agents and protocols differ
[11]	Rubber-tree branches (GT1 clone); K_2CO_3, 450 °C	≈90% CO removal; iodine number lower than [10,13]	CO removal from biogas	Different target gas; shows that removal is not ranked by iodine number

Two comparisons are defensible within the corpus. For coconut shells, the three studies [5,19,21] show that the same type of feedstock yields very different BET values depending on the protocol, which is direct evidence of the influence of process conditions. For cashew-tree branches, [10] and [13] show that two different activating agents can give nearly identical iodine numbers. Removal efficiencies for different adsorbates (diuron, butylparaben, benzo(a)pyrene, nitrate, Pb(II), Cd(II), H_2S, and CO) are not ranked.

7. Application-Specific Grade Qualification

7.1. Water Treatment

For water treatment, activated-carbon selection should be governed by contaminant properties and operating conditions rather than by a single material metric. The Ivorian literature covers organic micropollutants (diuron, butylparaben, benzo(a)pyrene), inorganic ions (including nitrate), and metals such as Pb(II) and Cd(II) [5–8,19–23]. This breadth is important because BET surface area, pore-size distribution, pH_{PZC}, and surface functional groups do not contribute equally to the adsorption of every solute. Most studies nevertheless remain centered on equilibrium or laboratory-scale kinetic tests. Industrial-grade qualification

requires extension to fixed-bed or column operation, real water matrices, competitive adsorption, regeneration, and inter-batch reproducibility.

In Côte d'Ivoire, water-treatment performance has been demonstrated at laboratory scale for diuron, butylparaben, benzo(a)pyrene, Pb(II), Cd(II), and nitrate [5–8,19–23]; Pb(II) and Cd(II) removal was also tested in natural freshwater [22], and Borassus carbon was tested in column mode on a semi-industrial prototype [8]. Regeneration, competitive adsorption, long-term column operation, and inter-batch reproducibility are not documented in the evidence reviewed; they are qualification recommendations, not results (Table 7).

7.2. Gas and Biogas Purification

For gas-phase applications, microporosity, surface chemistry, humidity tolerance, density, and mechanical strength become dominant design variables. Ivorian studies on H_2S and CO provide a useful proof of concept: KOH-activated cashew-tree carbon maintained 90.9% desulfurization efficiency after eight hours [10], while GT1/K_2CO_3 rubber-derived carbon achieved approximately 90% CO removal under the reported test conditions [11]. These results should be extended to breakthrough curves, dynamic adsorption capacity, pressure drop, humidity effects, cyclic regeneration, and attrition before the materials can be considered qualified gas-treatment grades.

The H_2S and CO results [10,11] and the copper-corrosion assessment after purification [9] are laboratory-scale proofs of concept. Breakthrough curves, dynamic adsorption capacity, pressure drop, humidity effects, cyclic regeneration, and attrition are not documented in the evidence reviewed. No Ivorian carbon can therefore be regarded as a qualified gas-treatment grade, and the extensions listed above are prospects.

7.3. Gold Recovery by CIP/CIL

In Carbon-in-Pulp (CIP) and Carbon-in-Leach (CIL) circuits, activated carbon cannot be qualified solely on the basis of high BET specific surface area or iodine number. Adsorption of the dicyanoaurate complex $Au(CN)_2^-$ depends on pore structure, carbon defects, surface chemistry, and diffusion phenomena [17]. Industrial circuits also operate far from equilibrium: Fleming et al. showed that loading kinetics can exert a stronger influence on circuit design than equilibrium capacity alone [18]. Qualification should therefore combine gold-loading kinetics and capacity with particle-size distribution, apparent density, ash content, hardness, attrition resistance, and performance after elution and thermal regeneration.

This application is directly relevant to Côte d'Ivoire. The Ity operation uses a gravity circuit followed by a CIL circuit comprising eight adsorption tanks containing activated carbon [25]. The Yaouré processing plant employs gravity recovery followed by hybrid CIL cyanidation, with loaded carbon subsequently eluted and regenerated [26]. A local granular activated carbon for gold recovery could therefore address process configurations already operating in the Ivorian mining sector; this remains a prospect, because [25,26] document the circuits and not the performance of any locally produced carbon. The qualification threshold is correspondingly high because the carbon must tolerate repeated adsorption, transfer, elution, and reactivation while minimizing the generation of gold-bearing fines.

Mechanical integrity therefore becomes as important as porosity. A highly porous but friable carbon can generate gold-bearing fines and contribute to metallurgical losses. ASTM D3802-23 provides a ball-pan hardness test [27], while other standards separately address apparent density, ash content, moisture, pH, and iodine number [16,28–31]. None of these measurements alone defines a mining grade. The Ivorian evidence

reviewed here does not yet support the conclusion that a locally produced carbon has been comprehensively qualified for CIP/CIL service, which remains a clear applied-research and process-development gap. Table 6 summarizes the priority properties for the targeted application-specific grades.

None of the fourteen Ivorian studies reviewed reports $Au(CN)_2^-$ adsorption, gold-loading kinetics, ball-pan hardness, attrition in pulp, or elution and reactivation tests on a locally produced carbon. All statements in this review about the suitability of Ivorian carbons for CIP/CIL are therefore prospective: they rest on the properties identified as critical in the international literature [17,18,27] and not on laboratory or plant evidence from Côte d'Ivoire. The mining-operation information [25,26] documents the process context only and does not validate any carbon. On the scale of Table 1, no Ivorian carbon can currently be placed at D3 or higher for CIP/CIL service. A validation sequence for this application would be: (1) loading kinetics and capacity in synthetic cyanide solution against a commercial reference carbon (the step that would allow D3); (2) ball-pan hardness [27] and attrition tests; (3) tests on real pulp from the target operation, including competition from other species; (4) elution and thermal-regeneration cycles; and (5) a plant-scale trial. Steps 3 and 4 would be the minimum for D4.

Table 6. Priority properties according to targeted application-specific grade.

Grade / application	Priority properties	Minimum characterization	Service-relevant validation
Water - micropollutants	Micro/mesoporosity, surface area, pH_{PZC}, surface functional groups	BET + pore-size distribution, FTIR, pH_{PZC}, ash, isotherms/kinetics	Column, real matrix, regeneration
Gas / biogas	Microporosity, surface chemistry, moisture, mechanical strength	BET, moisture, ash, pH_{PZC}/FTIR, density	Breakthrough curve, humidity, pressure drop, cycles
CIP/CIL - gold recovery	$Au(CN)_2^-$ loading kinetics, particle size, hardness, attrition, density	BET/pore structure, particle size, hardness, attrition, ash, density	Synthetic cyanide solution, then real pulp; elution/regeneration
Specialized applications	Pore architecture and functionalities tailored to the target contaminant	Targeted characterization	Testing in the actual process

Table 6 lists validation requirements (prospective); it does not report results obtained in Côte d'Ivoire.

7.4. Demonstrated Results versus Prospects for Industrial Application

To avoid conflating results with recommendations, Table 7 separates what has been demonstrated experimentally with Ivorian carbons from what remains a prospect. In the rest of this review, statements on future qualification steps, industrial grades, or gold-recovery suitability are recommendations or prospects unless the sentence cites an Ivorian experimental study.

Table 7. Experimental evidence from Côte d'Ivoire versus prospects for industrial application.

Application	Demonstrated experimentally (Côte d'Ivoire)	Not yet demonstrated (prospect / recommendation)	Highest D level documented
Water treatment	Laboratory adsorption of diuron, butylparaben, benzo(a)pyrene, Pb(II), Cd(II), and nitrate [5–8,19–23]; Pb(II)/Cd(II) tests in natural freshwater [22]; column tests on a semi-industrial prototype with Borassus carbon [8]	Regeneration; competitive adsorption; long-term column operation; inter-batch reproducibility; industrial-scale supply	D4 (Borassus [7,8]); D3 for the other studies
Gas / biogas purification	Laboratory removal of H_2S and CO from biogas; copper-corrosion assessment after purification [9–11]	Breakthrough curves and dynamic capacity; pressure drop; humidity effects; cyclic regeneration; attrition	D3
Gold recovery (CIP/CIL)	None: no Ivorian carbon tested for $Au(CN)_2^-$ adsorption; mining circuits documented as context only [25,26]	Gold-loading kinetics and capacity; hardness and attrition; elution and thermal regeneration; real-pulp and plant trials	No D3 or higher
Energy storage (supercapacitor)	Electrochemical characterization of a palm-shell carbon/graphene oxide composite (voltammetry, GCD, EIS, cycling) [24]	Device-level validation and scale-up	D3
Industrial supply	Trade statistics only [34–36]; no documented domestic production of reproducible grades	Reproducible multi-batch production; quality-assurance data; closed mass, energy, and water balances; pilot plant	No D5 documented

8. From Laboratory Material to Industrial Grade: The Scale-Up Gap

International reviews on commercialization and scale-up of biomass-derived activated carbons identify recurrent barriers: feedstock variability, thermal non-uniformity, activation control, shaping, inter-batch quality, effluent treatment, and competition with established commercial carbons [32,33]. In Côte d'Ivoire, these barriers should be treated primarily as process-engineering, quality-assurance, and qualification challenges rather than being reduced to financing constraints.

Scaling up first changes the way the feedstock is handled. The few hundred grams of relatively homogeneous material prepared in the laboratory become batches of tens or hundreds of kilograms with variable moisture, ash content, and particle-size distribution. Drying, cleaning, grinding, sieving, storage, and batch blending are no longer secondary operations: they determine furnace stability and reproducibility of the resulting carbon. Inside the reactor, this variability combines with temperature gradients and activating-gas concentration gradients that are negligible at crucible scale. Operating conditions optimized in a muffle furnace therefore cannot be transferred directly without considering heat and mass transfer.

Downstream operations add another layer of complexity. After chemical activation, washing to an acceptable pH becomes a unit operation in its own right, with consequences for water demand, neutralization, ionic-effluent generation, drying, and potentially reagent recovery. Performance can no longer be judged only from equilibrium tests: it must be verified under the hydrodynamic and mechanical conditions of the intended

service using breakthrough curves, pressure-drop measurements, regeneration cycles, and hardness/attrition testing. In the framework proposed here, D4 corresponds to this pilot- or service-relevant validation, whereas D5 requires documented, reproducible industrial production.

Figure 2 presents the proposed D0-D5 maturity scale, distinguishing resource potential, experimental evidence, pilot-scale validation, and industrial production.

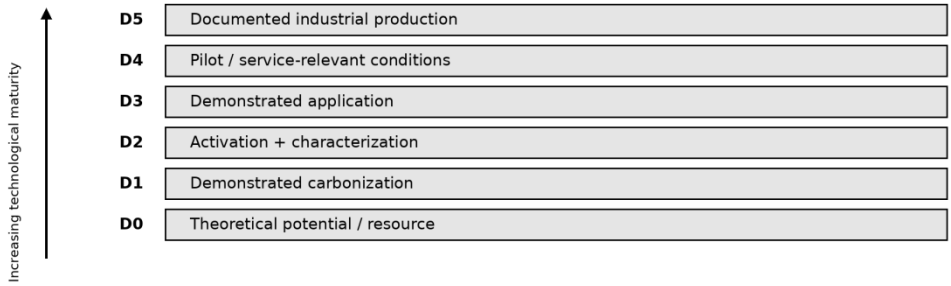


Figure 2. Proposed D0-D5 maturity scale distinguishing resource potential, experimental evidence, pilot-scale validation, and industrial production.

9. Imports, Exports, and Industrial Maturity

Trade statistics provide evidence of market exchange but do not directly measure domestic production. In 2024, Côte d'Ivoire imported 813,479 kg of activated carbon under HS code 380210, valued at approximately US$1.971 million, while 3,143,860 kg were recorded as exports, valued at approximately US$5.747 million [34,35]. These figures should not be interpreted as proof of domestic manufacturing because international merchandise-trade statistics can include re-exports; export tonnage therefore cannot be equated directly with Ivorian industrial production [36].

The persistence of imports, together with the documented operation of activated-carbon circuits at Ity and Yaouré [25,26], raises the more relevant question of whether industrial-grade activated carbons are available locally and reproducibly. For demanding uses such as CIP/CIL, a suitable carbon must combine $Au(CN)_2^-$ adsorption capacity and kinetics with controlled particle size, adequate apparent density and hardness, low attrition, and regenerability. The abundance of Ivorian biomass and the strong laboratory performances reported to date do not yet demonstrate the existence of reproducible local grades available at industrial scale. The principal bottleneck therefore appears to lie less in the theoretical availability of biomass than in controlling the complete feedstock-process-structure-property-performance chain through to qualification.

10. A Feedstock-Process-Structure-Grade Roadmap for Côte d'Ivoire

The roadmap below is a set of recommendations derived from the gaps identified above; it does not describe results already achieved in Côte d'Ivoire.

A credible national strategy should begin with feedstock screening that combines practical mobilizability with local physicochemical characterization. The most abundant biomass will not necessarily be the highest-priority precursor: a dense, dry, concentrated stream with limited competing uses may provide a more robust industrial basis than a larger but wetter or more dispersed resource. Selected feedstocks should then undergo carbonization and activation optimization against a predefined grade specification, while simultaneously tracking yield, pore development, energy demand, activating-agent consumption, wash-water requirements, emissions, and effluent generation.

Qualification should proceed by comparison with a commercial reference intended for the same service and tested using the same methods. For water treatment, this means combining BET/pore analysis and surface chemistry with column tests in representative matrices; for gases, dynamic capacity and breakthrough behavior under relevant humidity and pressure-drop conditions; and for CIP/CIL, gold-loading kinetics, particle-size control, hardness, attrition, elution, and regeneration. Only after these requirements are met should pilot production be used to close mass, energy, and water balances, verify inter-batch reproducibility, quantify emissions and effluents, and determine the yield and cost of marketable activated carbon.

11. Conclusion

The available evidence shows that Côte d'Ivoire combines diverse lignocellulosic resources with a scientific base capable of converting several local residues into functional activated carbons. Experimental work spans water treatment, biogas purification, multiple activation routes, and at least one semi-industrial demonstration. This maturity should not, however, be confused with the existence of a national supply chain for reproducible industrial grades. The principal gaps are systematic precursor characterization, comparability of preparation protocols, measurement of mechanical and dynamic properties, control of washing and regeneration operations, and transfer of laboratory conditions to the heat- and mass-transfer regime of pilot production. The CIP/CIL case illustrates the distinction particularly clearly: a high iodine number is insufficient unless it is accompanied by suitable $Au(CN)_2^-$ loading kinetics, particle-size distribution, density, hardness, attrition resistance, and regenerability. The pathway proposed here therefore centers on the feedstock-process-structure-property-grade chain and links materials chemistry to process engineering, practical resource mobilization, and service-relevant qualification. For Côte d'Ivoire, the decisive next step is not merely to produce activated carbon from agricultural residues, but to produce it reproducibly, qualify it against application-specific specifications and commercial benchmarks, regenerate it reliably, and demonstrate a viable route from pilot manufacture to industrial supply. These recommendations are prospective: the evidence demonstrated in Côte d'Ivoire is limited to laboratory-scale water and biogas tests (plus one semi-industrial column prototype for Borassus carbon), no Ivorian carbon has yet been tested for CIP/CIL service, and reproducible industrial production is not documented.

Conflict of Interest

The authors declare no conflict of interest related to this work.

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