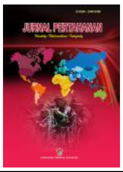

Jurnal Pertahanan: Media Informasi tentang Kajian dan Strategi Pertahanan yang Mengedepankan Identity, Nasionalism dan Integrity
Vol. 12 No. 1 (2026) pp.22-37
https://jurnal.idu.ac.id/index.php/DefenseJournal

Co-hydrothermal Carbonization: An Innovative Solution for Enhancing National Energy Resilience Through the Production of Clean Solid Fuels from Sewage Sludge and Coal Slime

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Article Info

Article history:
Received : July 23, 2025
Revised : March 8, 2026
Accepted : April 29, 2026

Keywords:
Co-HTC,
Co-Hydrothermal,
Carbonization,
Environmental Sustainability,
Solid Fuel,
Waste management.

DOI:
http://dx.doi.org/10.33172/jp.v12i1.20031

Abstract

Indonesia faces dual challenges of waste management and energy security. This study conducts a systematic literature review of co-hydrothermal carbonization (co-HTC) as a waste-to-energy pathway for converting sewage sludge and coal slime into clean solid fuel, synthesizing peer-reviewed evidence from 2019 to 2025 on synergistic effects, environmental benefits, implementation challenges, and policy alignment with Indonesia's energy security framework. Following PRISMA guidelines, searches in Web of Science, Scopus, and Google Scholar identified 487 publications, of which 19 met the inclusion criteria focused on co-HTC process characteristics, synergistic performance, environmental impacts, and commercialization barriers. Synthesized findings show that co-HTC of sewage sludge and coal slime delivers synergistic improvements of 1.87-6.52% in mass yield, 4.04-17.54% in higher heating value, and 35.26-40.08% in energy balance compared to single-feedstock processing. Reported hydrochar heating values of 19-32 MJ/kg (comparable to lignite coal) and soil fertility improvements of up to 34% indicate dual benefits for energy and agriculture. A literature analysis reveals alignment with Law No. 30/2007 on Energy Security and Presidential Regulation No. 109/2025 on Waste-to-Energy (WtE), positioning co-HTC toward Indonesia's 453 MW waste-to-energy target by 2034. Overall, the review confirms co-HTC as a promising technology to address waste management while potentially enhancing energy security, but also identifies critical barriers: capital costs of approximately $120-180 million per 1,000-ton-per-day facility, limited commercial-scale deployment (TRL 4-6), process water treatment challenges, and issues of social acceptance. Evidence from existing studies underscores the

need for pilot-scale demonstration projects in priority regions to validate Indonesian-specific performance and inform evidence-based scaling strategies.

INTRODUCTION

Waste management remains one of the most pressing environmental and energy challenges facing both developed and developing nations, particularly in countries experiencing rapid industrialization and urbanization. Globally, industrial wastewater treatment processes generate approximately 45 million tons of sewage sludge annually (Ischia et al., 2024), while coal mining operations produce an estimated 3 billion tons of coal slime waste (C. Wei et al., 2018). These waste streams pose severe environmental risks due to their high moisture content, typically ranging from 70% to 90%, combined with elevated concentrations of organic pollutants, heavy metals, and pathogenic microorganisms that threaten both environmental integrity and public health.

In Indonesia specifically, the dual challenge of managing sewage sludge, as shown in Figure 1, from expanding wastewater treatment infrastructure, and coal slime, as shown in Figure 2, from extensive mining activities, has intensified as the nation generates over 35 million tons of municipal and industrial waste annually, with approximately 61% being improperly managed (Databoks, 2023; Reuters, 2025).

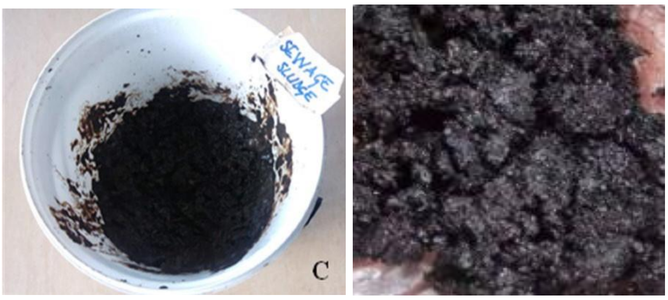

Figure 1. Sewage Sludge (left) and Coal Slime (right) (Jordan, 2025; Kahilu et al., 2022)

This waste crisis directly threatens Indonesia's achievement of its Nationally Determined Contributions (NDCs) under the Paris Agreement and the government's ambitious target of achieving Net Zero Emissions by 2060. Furthermore, Indonesia's heavy dependence on fossil fuels underscores the critical need for innovative waste-to-energy solutions that can simultaneously address waste management challenges and enhance national energy security while contributing to climate change mitigation efforts (Office of Assistant to Deputy Cabinet Secretary for State Documents & Translation, 2025).

Hydrothermal carbonization (HTC) has emerged as a pivotal thermochemical conversion technology that operates at moderate temperatures ranging from 180°C to 250°C under autogenous pressure, using water as both reaction medium and catalyst (Ischia et al., 2024).Unlike pyrolysis or gasification, HTC processes high-moisture feedstocks (>70%) directly, eliminating the need for energy-intensive pre-drying (Dang et al., 2024; Petrović et al., 2024). Building on these advantages, co-hydrothermal carbonization (co-HTC) extends this approach to simultaneous multi-feedstock processing, yielding synergistic improvements in product quality beyond single-feedstock HTC (Song et al., 2019; Yang et al., 2024).

Despite growing research interest, critical knowledge gaps limit the evidence base for co-HTC deployment. Comprehensive systematic reviews focusing on sewage sludge and coal slime combinations remain scarce; furthermore, most existing literature prioritizes technical optimization without integrating environmental, economic, and policy dimensions within national contexts (Farru et al., 2024). Critically, no systematic academic evaluation of co-HTC's role within Indonesia's energy security framework exists, despite ambitious national waste-to-energy initiatives targeting 33 cities and an investment of Rp 91 trillion (approximately $6 billion USD).

This systematic literature review addresses these gaps through five objectives: (1) synthesizing co-HTC process characteristics and synergistic effects for sewage sludge and coal slime (2019–2025); (2) evaluating environmental benefits, including GHG mitigation and circular economy contributions; (3) analyzing implementation challenges, encompassing technology readiness, economic barriers, and commercialization constraints; (4) assessing co-HTC alignment with Indonesia's energy security framework (Law No. 30/2007; Presidential Regulation No. 109/2025); and (5) identifying research gaps and proposing deployment pathways for Indonesian contexts.

The significance of this review lies in informing strategic decisions at a critical juncture in Indonesia's waste-to-energy development. The country targets 453 MW of waste-to-energy capacity by 2034 (PLN, 2025) and requires an estimated USD 2.7 billion in investment (ESG News, 2025). In this context, a systematic synthesis of co-HTC viability, documented performance characteristics, and identified implementation barriers is essential for evidence-based policymaking and investment prioritization. This review ultimately contributes to broader sustainable development objectives by advancing knowledge on dual-benefit technologies that simultaneously address waste management imperatives and energy security challenges across resource-constrained developing economies.

METHODS

This study employs a systematic literature review methodology following the PRISMA 2020 guidelines (Page et al., 2021) to synthesize evidence on co-HTC technology, including its technical characteristics, environmental benefits, implementation challenges, and potential applications within Indonesia's energy security framework. This approach ensures a transparent and replicable synthesis while minimizing subjective bias through predefined search strategies, explicit inclusion criteria, and structured analytical frameworks (Farru et al., 2024).

Literature searches were conducted across Web of Science, Scopus, and Google Scholar for the period from January 2019 to December 2025, capturing recent co-HTC advances directly relevant to current technology readiness and near-term deployment potential.

The primary search string applied across Web of Science and Scopus utilized key Boolean operators as follows: ("co-hydrothermal carbonization" OR "co-HTC" OR "hydrothermal co-carbonization") AND ("sewage sludge" OR "coal slime" OR "municipal solid waste") AND ("synergistic effect" OR "hydrochar" OR "energy recovery" OR "process optimization"). Secondary supplementary searches targeted specific geographic and policy contexts using the strings: ("hydrothermal carbonization" AND "Indonesia" AND "energy security"), ("waste-to-energy" AND "coal waste" AND "carbonization"), and ("HTC" AND "implementation" AND "commercialization").

For Google Scholar, the same primary and secondary search strings were applied using the Advanced Search function with the date range filter set to 2019–2025. Given Google Scholar's limit of 1,000 results per query (Bramer et al., 2016; Gusenbauer & Haddaway, 2020; Page et al., 2021), searches were iteratively refined, and the first 200 results per string were screened. Grey literature, theses, conference abstracts without full texts, and non-peer-reviewed sources were excluded during the title/abstract phase.

The initial database search across Web of Science, Scopus, and Google Scholar yielded 487 potentially relevant publications. Following deduplication, 142 duplicate records were removed, leaving 345 unique records for title and abstract screening. Systematic screening against inclusion and exclusion criteria resulted in the exclusion of 268 records, with 77 articles proceeding to full-text eligibility assessment. After a comprehensive full-text review, an additional 58 articles were excluded due to insufficient quantitative data (n = 19), exclusive focus on single-feedstock HTC (n = 12), lack of systematic methodology (n = 16), and absence of formal peer review (n = 8). This selection process yielded a final corpus of 19 peer-reviewed publications for systematic synthesis.

Inclusion and Exclusion Criteria

Studies were included if they met all of the following criteria: peer-reviewed journal articles, conference proceedings, or technical reports (2019–2025); investigation of HTC or co-HTC regardless of feedstock; examination of sewage sludge, coal slime, or comparable high-moisture waste feedstocks; reporting of quantitative process parameters (temperature, pressure, residence time, mass yield, heating value, or energy recovery); and addressing environmental benefits, implementation challenges, or policy frameworks related to waste-to-energy technologies. Studies were excluded if they were published before 2019, focused exclusively on non-HTC thermochemical processes, examined only conventional biomass without sewage sludge or coal-derived waste, were review articles without primary data, or lacked formal peer review.

Data Extraction

Data extraction from the 19 included studies used a standardized template capturing: study characteristics (author, year, location, and study design); feedstock properties (type, moisture content, and proximate/ultimate analysis); process parameters (temperature, pressure, residence time, mixing ratios); performance metrics (mass yield, Higher Heating Value (HHV), energy recovery, carbon retention, and synergistic effects versus single-feedstock processing); environmental outcomes (waste volume reduction, emission comparisons, and soil amendment potential);

implementation barriers (Technology Readiness Level (TRL), capital costs, and process water challenges); and policy relevance dimensions. This structured dataset enabled a systematic comparison and thematic synthesis across the reviewed literature.

Analytical Framework

Data were synthesized thematically across five analytical dimensions following established systematic review methodologies (Farru et al., 2024):(1) technical performance and synergistic effects inlcuding process parameters, mass yields, HHV, energy recovery, and co-HTC improvements versus single-feedstock processing; (2) hydrochar characteristics and applications encompassing physicochemical properties, combustion behavior, and solid fuel or soil amendment potential; (3) environmental benefits comprising waste volume reduction, GHG emission comparisons, and circular economy contributions; (4) implementation challenges addressing technological constraints, economic feasibility, operational complexities, and social acceptance barriers; and (5) policy alignment focusing on the intersection of co-HTC with Indonesia's energy security frameworks, waste management regulations, and national development priorities.

Findings are systematically contextualized within Indonesia's specific circumstances: 35 million tons of annual waste generation (61% improperly managed); energy security imperatives under Law No. 30/2007 (availability, affordability, accessibility, acceptability); Nationally Determined Contributions (NDC) and Net Zero 2060 climate commitments; and the waste-to-energy policy framework of Presidential Regulation No. 109/2025 targeting 33 cities through the Danantara's program. This contextualization enables an evidence-based assessment of co-HTC relevance for Indonesian deployment, while acknowledging uncertainties that require local pilot validation.

Limitations of the Systematic Review Approach

This review acknowledges four inherent limitations. First, while Web of Science, Scopus, and Google Scholar provide comprehensive coverage, some grey literature or regional publications may have been missed, potentially underrepresenting practical implementation experiences. Second, publication bias toward positive findings may lead to overly optimistic technology assessments if implementation failures are underrepresented in the published literature. Third, the 2019–2025 temporal scope excludes foundational earlier research, though the focus on current Technology Readiness Level (TRL) relevance justifies this selection. Fourth, as a secondary synthesis, this review generates no primary experimental data on Indonesian feedstocks or operating conditions, underscoring the critical need for pilot-scale demonstrations using local materials to validate the synthesized findings.

RESULT AND DISCUSSION

This section presents the synthesized findings from the systematic review of 19 peer-reviewed studies on co-HTC technology, organized thematically across technical performance, environmental benefits, implementation challenges, and policy alignment dimensions.

The reviewed literature consistently demonstrates that the co-hydrothermal carbonization of sewage sludge combined with coal slime achieves significant synergistic improvements compared to single-feedstock HTC processing, as shown in Figure 2, representing one of the most compelling technical advantages of co-processing approaches. Yang et al. (2024) provided one of the most comprehensive quantitative assessments of these synergistic effects across multiple critical performance parameters, reporting improvements in mass yield ranging from 1.87% to 6.52%, Higher Heating Value (HHV) improvements spanning 4.04% to 17.54%, carbon retention gains of 7.52% to 16.80%, energy recovery efficiency improvements from 4.20% to 19.59%, fuel ratio enhancements of 7.58% to 25.45%, and energy balance improvements ranging from 35.26% to 40.08% compared to processing each feedstock independently. These synergistic effects consistently exceed the simple additive performance expected from processing each feedstock separately, indicating fundamental complementary physicochemical interactions during co-HTC that enhance both process efficiency and product quality.

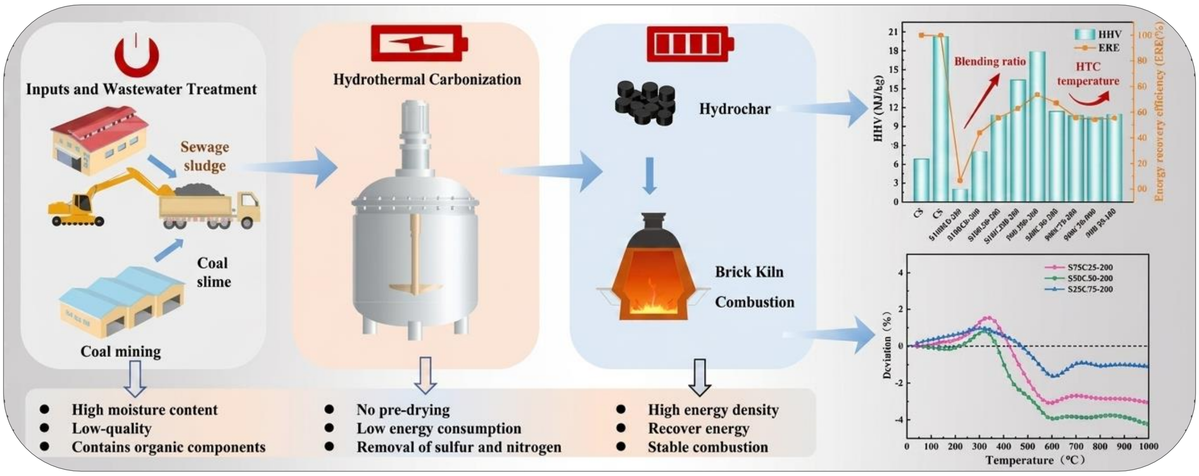

Figure 2. Co-Hydrothermal Carbonization Process (Yang et al., 2024)

The mechanistic basis for these synergistic effects has been explored in multiple studies, with Song et al. (2019) documenting similar synergistic phenomena in sewage sludge-lignite co-HTC and attributing improvements to several interconnected mechanisms. Enhanced dehydration and decarboxylation reactions are facilitated by mineral matter in coal-derived feedstocks, which catalyzes organic matter decomposition and water removal, thereby improving carbonization efficiency. Improved carbon retention occurs through cross-linking and polymerization reactions between organic compounds from different feedstock sources, creating more stable carbon structures in the resulting hydrochar. Additionally, optimized hydrogen-to-carbon ratios in the hydrochar product result from the complementary elemental compositions of sewage sludge and coal slime: sewage sludge typically provides higher hydrogen content. In comparison, coal slime contributes higher fixed carbon content, yielding hydrochar with superior combustion characteristics compared to either feedstock processed individually.

Synthesis of reviewed studies examining optimal operating conditions (Bardhan et al., 2021; Y. Wei et al., 2022; Yang et al., 2024) indicates that co-HTC achieves optimal performance within relatively narrow parameter ranges. Temperature conditions typically range from 200°C to 250°C, representing moderate thermal requirements compared to pyrolysis processes, which require 400°C to 600°C, or gasification, which requires even higher temperatures exceeding 700°C. Operating pressure spans 2 Mpa to 5 MPa, representing autogenous pressure generated by water vapor at elevated temperatures rather than requiring external pressurization. Residence times typically range from 2 to 6 hours, with longer residence times generally associated with higher mass yields and heating values but diminishing marginal returns beyond 6 hours. Critically, co-HTC effectively processes feedstocks with moisture content ranging from 70% to 90% without requiring energy-intensive pre-drying, representing a fundamental advantage over conventional thermochemical processes that necessitate drying to below 15% moisture for efficient operation (Ischia et al., 2024). These moderate operating conditions, particularly the elimination of drying requirements, substantially reduce energy input demands and improve the net energy balance compared to alternative thermochemical conversion pathways.

Hydrochar Characteristics and Fuel Quality

Reviewed literature reports that hydrochar produced from sewage sludge-coal slime co-HTC exhibits heating values ranging from 19 to 32 MJ/kg across various studies (Y. Wei et al., 2022; Yang et al., 2024)positioning the product as directly comparable to lignite coal that typically exhibits heating values between 15 and 25 MJ/kg. This energy density makes hydrochar suitable for multiple combustion applications, including direct combustion as a solid fuel in dedicated biomass boilers; co-firing with conventional coal in existing coal-fired power plants to reduce fossil fuel consumption and associated emissions; utilization in industrial process heating where solid fuel is required; and potential upgrading to higher-quality fuels through additional processing steps such as pelletization or briquetting to improve handling characteristics and combustion efficiency.

The thermogravimetric analysis conducted by Yang et al. (2024) provided a detailed characterization of combustion behavior, demonstrating progressive improvements in combustion performance with increasing coal slime ratios in the feedstock mixture. At a 25% coal slime composition, mass loss during combustion reached 38.39%, indicating substantial volatile matter content and relatively rapid combustion kinetics. At a 50% coal slime composition, mass loss increased to 48.14%, indicating greater combustion completeness. At a 75% coal slime composition, mass loss reached 58.08%, indicating optimal combustion performance within the tested range. These combustion characteristics indicate favorable reactivity profiles and energy-release patterns suitable for power generation applications, with higher coal-slime ratios generally associated with improved combustion efficiency and reduced residual ash content; however, optimal mixing ratios must balance combustion performance with other factors, including feedstock availability, preprocessing requirements, and overall process economics.

Beyond direct energy applications, the reviewed literature consistently identifies hydrochar's potential as an organic soil amendment, representing a dual-benefit characteristic that significantly enhances the overall value proposition and supports circular economy principles. Bardhan et al. (2021) and Ong et al. (2024) reported soil fertility improvements of up to 34% when hydrochar is applied as a soil conditioner in agricultural contexts, attributable to several interconnected mechanisms. Enhanced water retention capacity results from hydrochar's porous structure and high surface area that physically retain water in the soil matrix, particularly beneficial in sandy or degraded soils with poor water-holding capacity. Increased cation exchange capacity enhances nutrient retention by providing negatively charged surface sites that bind positively charged nutrient ions, such as ammonium, calcium, and magnesium, reducing nutrient leaching and improving fertilizer efficiency. Reduced nutrient leaching occurs through both physical and chemical mechanisms, decreasing fertilizer requirements and associated costs while minimizing groundwater contamination from agricultural runoff. Additionally, the potential for long-term carbon sequestration in agricultural soils represents a climate-mitigation benefit when hydrochar is applied to land rather than combusted, with stable carbon fractions in hydrochar persisting in soils for decades to centuries, depending on environmental conditions and soil characteristics.

This dual-application potential, serving both as an energy source and an agricultural soil amendment, positions co-HTC within circular economy frameworks by generating multiple value streams from waste materials. Strategic decisions regarding hydrochar utilization pathways can be optimized based on local conditions, including energy demand, agricultural land availability, soil quality constraints, and the relative economic values of energy versus agricultural applications in specific contexts.

Environmental Benefits and Climate Mitigation Potential

Reviewed studies consistently document substantial reductions in waste volume through co-HTC processing compared to raw waste handling and disposal. Fakudze & Chen (2023) and Huang et al. (2019) report that HTC conversion produces dense, stable hydrochar requiring significantly less landfill space than raw sewage sludge or coal slime due to both mass reduction through volatile matter removal and volume reduction through densification. For Indonesia's context, where 35 million tons of waste are generated annually with 61% being improperly managed through open dumping, uncontrolled landfilling, or direct discharge to water bodies, this volume reduction capability has immediate practical significance for alleviating landfill capacity constraints, reducing land area requirements for waste disposal facilities, minimizing transportation costs and associated emissions for waste logistics, and decreasing environmental contamination from inadequately managed waste sites.

Reviewed literature indicates substantially lower GHG emissions compared to direct waste combustion or landfill disposal (Yang et al., 2024). Key mechanisms include: avoided landfill methane emissions (since CH_4 has 28–36 times the global warming potential of CO_2 over 100 years), which are eliminated by diverting waste through co-HTC; fossil fuel displacement benefits when hydrochar replaces coal, since biogenic carbon in sewage sludge does not constitute net fossil emissions; and carbon sequestration potential when hydrochar is applied as a soil amendment, with stable aromatic carbon structures persisting in agricultural soils for decades (Bardhan et al., 2021).

These environmental benefits align directly with Indonesia's climate commitments under the Nationally Determined Contributions (NDC) framework, targeting a 29% reduction in emissions by 2030 (41% with international support) and the Net Zero Emissions target by 2060. Co-HTC technology offers a concrete pathway to advance waste management objectives simultaneously, enhance energy security through domestic renewable energy resources, and contribute to emission-reduction targets across the waste, energy, and, potentially, agricultural sectors through integrated deployment strategies.

Co-HTC aligns with circular economy principles by transforming waste streams into valuable resources. This approach reduces reliance on virgin materials, creates economic value from previously discarded materials, minimizes environmental pollution from the 61% of Indonesia's waste currently improperly disposed of, and supports Sustainable Development Goals (SDGs) 7, 11, 12, and 13 simultaneously, demonstrating how integrated waste-to-energy systems generate co-benefits across interconnected sustainability challenges.

Implementation Challenges and Commercialization Barriers

Despite documented technical benefits and favorable environmental characteristics, the reviewed literature identifies multiple critical barriers that currently constrain widespread co-HTC deployment and must be systematically addressed to enable technology scale-up from demonstration to commercial deployment. Understanding these barriers is essential for a realistic assessment of deployment prospects and for designing appropriate de-risking strategies, policy support mechanisms, and research priorities to overcome identified constraints.

Ogunleye et al. (2024) and Ischia et al. (2024) confirm that co-HTC technology remains at a pilot-to-demonstration scale globally, typically characterized as Technology Readiness Level (TRL) 4 to 6 on the nine-level scale used by government agencies and technology investors to assess commercialization status. This means that while the technology has been demonstrated in relevant environments at a pilot scale, it has not yet achieved full commercial deployment with multiple independent operators, diverse feedstock conditions, and proven long-term operational reliability. Only a few commercial HTC facilities currently operate worldwide, primarily in Europe, with limited geographic and climatic diversity, creating uncertainty about technology transfer to tropical contexts with different ambient conditions, feedstock characteristics, and infrastructure availability.

This limited commercial track record creates multiple uncertainties that discourage private investment and complicate financing arrangements. Long-term operational reliability under variable feedstock conditions remains unproven, particularly regarding wear patterns, maintenance intervals, and component lifetimes when processing chemically complex and potentially corrosive waste streams over multi-year operating periods. Actual maintenance requirements and associated costs lack comprehensive documentation, and existing pilot facilities are often operated by research institutions or technology developers, with maintenance practices that may not reflect commercial operational realities. Performance consistency across seasonal variations in feedstock composition, ambient temperature-driven heat management, and precipitation patterns that influence waste characteristics requires extended operational periods to characterize fully. Technology scalability from laboratory or pilot scale to full industrial scale introduces engineering challenges regarding heat transfer dynamics in larger reactors, mixing efficiency in scaled-up systems, and the complexity of process control in continuous rather than batch operations, all of which have not been fully demonstrated through commercial deployment experience.

This technology maturity gap represents a classic “valley of death” challenge in clean energy technology deployment, where technologies proven at laboratory or pilot scale struggle to attract investment for first-of-a-kind (FOAK) commercial facilities due to perceived risks and uncertainty that can only be resolved through actual commercial operation, creating a circular problem that impedes technology advancement.

Capital Investment Requirements

The reviewed literature consistently identifies high capital costs as a primary economic barrier (Ogunleye et al., 2024), with requirements of $120–180 million per 1,000-ton-per-day facility. Major cost components include pressure-resistant reactor systems, heat recovery networks, process water treatment infrastructure, solid-liquid separation equipment, and quality control systems. Auxiliary costs for site development, grid connection, and permitting can substantially increase total project costs, particularly in locations lacking existing industrial infrastructure. These capital requirements present classic “valley of death” financing challenges for first-mover projects, requiring innovative mechanisms such as concessional financing, investment guarantees, and results-based payments to attract private investment.

Process Water Management Challenges

Multiple reviewed studies identify process water treatment as a critical challenge (Bardhan et al., 2021; Ipiales et al., 2021). Co-HTC generates high Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) process water (often >10,000 mg/L) containing nutrients (nitrogen and phosphorus) and potentially trace levels of heavy metals or persistent organic compounds, requiring treatment before discharge. Key challenges include eutrophication risk from untreated nutrient loads, monitoring requirements for variable trace contaminants, and integration complexity with existing wastewater treatment systems.

Ipiales et al. (2021) propose integration with anaerobic digestion to recover biogas from dissolved organics while reducing the treatment burden, though commercial demonstration of integrated HTC-anaerobic digestion systems remains limited.

Feedstock Variability and Quality Control

Reviewed literature highlights feedstock variability as a key operational challenge. Sewage sludge characteristics vary substantially with wastewater source composition, treatment technology, seasonal patterns, and demographic factors. Coal slime properties also differ across mining regions, depending on coal rank, ash composition, sulfur content, and processing methods. This variability complicates process optimization and product quality consistency, necessitating flexible operating parameters or robust feedstock blending strategies.

Such variability creates operational challenges, including inconsistent process optimization requirements, product quality fluctuations in co-firing applications, and more complex regulatory compliance monitoring. Mitigation requires comprehensive feedstock characterization during project development, careful supply contracting with composition specifications, and feedstock blending programs, which are particularly important where feedstock availability is limited or composition is highly variable.

Social Acceptance and Community Engagement

Social acceptance challenges, while less quantified than engineering barriers, can decisively determine project implementation outcomes. Community opposition, including “not-in-my-backyard” (NIMBY) dynamics, often persists despite regulatory compliance assurances, driven by concerns over emissions, truck traffic, noise, odors, property values, and historical experiences with poorly managed waste facilities. Benefit-sharing demands are common, including local employment priority, subsidized energy for nearby households, and community development investments. Sustained transparent communication, participatory planning, and meaningful benefit-sharing arrangements are essential to overcoming these challenges, though they require resources that are often underestimated in project planning.

Policy Alignment and Strategic Integration with Indonesia’s Energy Security Framework

Law No. 30/2007 on Energy Security establishes Indonesia’s framework around four dimensions: availability (adequate supply and source diversification), affordability (accessible pricing across income levels), accessibility (equitable geographic access), and acceptability (social and environmental acceptability of energy sources) (Istiqamah et al., 2024; Pahlevi et al., 2024). Co-HTC demonstrates alignment with all four dimensions: it enhances availability by valorizing domestic waste resources into distributed renewable energy; improves affordability through negative-cost feedstock acquisition and stable waste-derived supply; increases accessibility via decentralized deployment near urban wastewater plants and mining regions; and supports acceptability by addressing pollution concerns while reducing fossil fuel dependence.

Presidential Regulation No. 109/2025 on Waste-to-Energy (WtE), issued on October 10, 2025, establishes a comprehensive regulatory framework for waste-to-energy technologies in Indonesia and explicitly designates them as a government policy priority. This regulation provides a legal foundation for waste-to-energy project development, establishing performance standards, environmental requirements, and institutional responsibilities across government levels and agencies. The Danantara waste-to-energy program operationalizes this regulatory framework through concrete investment commitments and capacity targets, specifically targeting 33 cities with an investment of Rp 91 trillion (approximately $6 billion) and establishing an aggregate capacity target of 453 MW by 2034 across multiple waste-to-energy facilities.

The positioning of co-HTC technology within this policy framework remains to be fully defined, as the current program's emphasis appears to be on conventional waste-to-energy incineration technologies based on European and Japanese precedents. However, the literature suggests that co-HTC offers several complementary benefits that warrant consideration in integrated waste management strategies. The ability to process high-moisture waste streams that are unsuitable for direct incineration without energy-intensive pre-drying expands the range of waste materials amenable to energy recovery, particularly for sewage sludge and industrial sludges that are challenging for conventional incineration. Lower operational temperatures compared to incineration reduce the formation of nitrogen oxides (NO_x) and dioxins, which represent major environmental and health concerns with combustion technologies, potentially simplifying emissions control requirements and regulatory compliance. The production of solid fuel, enabling staged utilization and storage flexibility, provides operational advantages over immediate electricity generation required in incineration facilities, allowing hydrochar stockpiling during low electricity-demand periods and utilization when market conditions are favorable. The dual-benefit potential from energy and soil amendment applications supports circular economy objectives embedded in sustainable development planning, creating multiple value streams that enhance project economics and social benefits.

Several evidence-based policy recommendations emerge for integrating co-HTC into Indonesia's energy security strategy: (1) commission pilot-scale demonstration projects (100–500 t/day) in 2–3 priority regions, Jakarta (sewage sludge from urban WWTPs), South Kalimantan (coal slime from mining operations), and Surabaya (urban-industrial stream integration) operating 18–24 months to validate Indonesian–specific performance; (2) establish technology de-risking mechanisms including blended finance structures, investment guarantees for technology performance risks, and results-based payments tied to verified waste processing volumes; (3) develop regulatory frameworks specifying hydrochar quality standards (minimum HHV, moisture, ash, and contaminant limits), co-firing technical specifications, and environmental performance criteria; and (4) coordinate integrated waste management planning among municipal governments, mining companies, utilities, and investors to optimize feedstock logistics and infrastructure synergies.

Research Gaps Identified Through Systematic Review

Several critical research gaps limit the evidence base for co-HTC deployment decisions in Indonesia. The most fundamental is the lack of Indonesian–specific feedstock characterization: reviewed studies predominantly examine Chinese, European, or North

American feedstocks with characteristics different from those of Indonesian sewage sludge and coal slime. Additionally: (1) no pilot-scale operational data exist from tropical climates matching Indonesia's conditions, with 18–24 months of operation required to characterize seasonal performance; (2) techno-economic analyses use international cost parameters that may differ substantially from Indonesian construction costs, labor rates, equipment pricing, and financing terms; (3) process water treatment integration with Indonesian wastewater infrastructure and regulatory standards remains uninvestigated; (4) social acceptance research in Indonesian cultural contexts, covering community perceptions, preferences, and effective engagement strategies is largely absent; (5) life cycle assessments using Indonesian grid carbon intensity, logistics, and waste composition data are needed for a rigorous comparison with alternative pathways; and (6) policy implementation pathway analysis for interagency coordination within Indonesia's governance structures requires dedicated study.

CONCLUSIONS, RECOMMENDATIONS, AND RESEARCH LIMITATIONS

This review demonstrates that the co-hydrothermal carbonization (co-HTC) of sewage sludge and coal slime constitutes a technically viable and strategically relevant waste-to-energy pathway for Indonesia. The co-HTC process delivers measurable synergistic improvements across mass yield, Higher Heating Value (HHV), and energy balance, surpassing what either feedstock can achieve independently, yielding hydrochar with an energy density comparable to lignite coal. Beyond its fuel value, the resulting hydrochar offers meaningful environmental benefits, including reduced waste volume, avoided greenhouse gas (GHG) emissions, and the potential to enhance soil fertility, which collectively support Indonesia's dual agenda of responsible waste management and climate commitments under the 2060 Net Zero Emissions target. From a policy standpoint, co-HTC aligns naturally with all four dimensions of Indonesia's energy security framework: availability, affordability, accessibility, and acceptability, and presents a complementary fit within the waste-to-energy agenda operationalized through Presidential Regulation No. 109/2025 and the Danantara investment program. Nevertheless, the technology remains constrained by substantial capital requirements, limited commercial-scale deployment experience, complex process water management, and the absence of Indonesian–specific performance data. Bridging these gaps demands coordinated investment in pilot-scale demonstration, enabling regulation, and context-specific research before co-HTC can be credibly integrated into Indonesia's national waste-to-energy roadmap.

For government policymakers: (1) commission 2–3 pilot facilities (100–500 t/day) in priority regions Jakarta (sewage sludge from urban wastewater treatment plants), South Kalimantan (coal slime from mining operations), and Surabaya (mixed urban-industrial streams) with a minimum 18–24 month operation period to generate Indonesian–specific performance data; (2) establish blended finance structures, technology performance guarantees, and results-based financing instruments to reduce early-adopter capital risk and catalyze private investment; and (3) develop hydrochar quality standards covering minimum heating value, moisture, ash, and contaminant thresholds, alongside co-firing technical specifications and process water discharge limits, to provide regulatory certainty for developers and investors.

For research institutions: priority research areas include the characterization of Indonesian sewage sludge and coal slime feedstocks across Java, Sumatra, and Kalimantan; the integration of process water treatment with existing local wastewater infrastructure; comprehensive life cycle assessment (LCA) using Indonesian grid carbon intensity and logistics parameters; and social acceptance studies documenting community perceptions and effective engagement strategies within Indonesian cultural contexts.

For private sector stakeholders: coal mining companies should assess co-HTC as a viable pathway for coal slime valorization and mine closure liability reduction; wastewater utilities should evaluate co-HTC as an alternative to conventional sludge disposal with potential revenue from hydrochar; and waste management operators should explore Build-Own-Operate (BOO) and technology licensing models that leverage existing international operational experience.

This review carries four inherent limitations that readers should consider when interpreting the findings. First, despite comprehensive coverage of Web of Science, Scopus, and Google Scholar, some grey literature and regional publications may have been missed, potentially underrepresenting practical implementation experiences from non-English-language contexts. Second, publication bias toward positive experimental outcomes may render the synthesized technical performance data more optimistic than real-world deployment would suggest, as implementation failures are rarely documented in peer-reviewed literature. Third, the 2019–2025 temporal scope, while appropriate for assessing current technology readiness, excludes foundational earlier research that may contain relevant mechanistic insights. Fourth, as a secondary synthesis of existing studies, this review generates no primary experimental data; all reported performance values are derived from studies conducted predominantly in Chinese, European, and North American contexts with feedstock characteristics that may differ substantially from Indonesian sewage sludge and coal slime, underscoring the critical importance of local pilot-scale validation before extrapolating international findings to Indonesian deployment decisions.

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