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Biomass and Waste Pyrolysis: A Critical Review of Reaction Pathways, Reactor Engineering, Product Quality, Catalytic Upgrading, and Industrial Scale-Up

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ABSTRACT

Pyrolysis is a thermochemical conversion route in which carbonaceous feedstocks are heated under oxygen-deficient or oxygen-free conditions to form a controllable mixture of solid, liquid, and gaseous products. This review critically synthesizes the engineering principles governing biomass and waste pyrolysis, with emphasis on reaction mechanisms, feedstock properties, operating parameters, reactor configurations, product formation, catalytic upgrading, environmental performance, and scale-up challenges. The literature shows that pyrolysis performance is not determined by temperature alone; heating rate, particle size, vapor residence time, pressure, mineral matter, moisture, reactor hydrodynamics, and secondary reactions jointly control product yield and quality. Slow pyrolysis generally favors carbon-rich solid products, whereas fast and intermediate pyrolysis can increase condensable vapors and bio-oil production when heat and vapor residence time are appropriately controlled. Fluidized-bed, circulating-bed, auger, ablative, and fixed-bed reactors each provide different compromises between heat transfer, solids handling, residence-time control, product recovery, and capital cost. Catalytic pyrolysis can reduce oxygenates and increase hydrocarbons or selected chemicals, but catalyst deactivation, coke deposition, contamination, regeneration, and product selectivity remain major barriers. Particular attention is given to oil-palm residues such as empty fruit bunches, palm kernel shells, mesocarp fiber, fronds, and trunks because they are abundant in Indonesia and provide a strong opportunity for decentralized thermochemical valorization. The review concludes that future development should move from yield maximization toward integrated process design, product quality, heat integration, emissions control, techno-economic assessment, life-cycle assessment, and digital process optimization.

I. Introduction

Biomass and waste pyrolysis has moved from a predominantly laboratory-scale thermochemical conversion concept toward a broader platform for producing carbon materials, condensable chemicals, and process gas. The attraction is not simply that a solid feedstock can be converted into several products, but that the product slate can be deliberately shifted by controlling thermal history, vapor residence, reaction environment, and downstream separation. Recent reviews describe pyrolysis as a family of processes rather than a single technology, including slow, intermediate, fast, flash, microwave-assisted, catalytic, and staged configurations [1]–[4].

Pyrolysis is particularly relevant to regions with concentrated agricultural residues and growing waste-management requirements. Indonesia is a major producer of palm oil, and palm processing generates empty fruit bunches (EFB), palm kernel shells (PKS), fibers, ash, and other residues. The energetic potential of palm solid waste as an alternative fuel has been demonstrated, and the feasibility of industrial-scale pyrolysis of polyethylene and polystyrene waste has also been evaluated

[5], [6]. These findings highlight the importance of considering pyrolysis not only as a laboratory-scale chemical process but also as an integrated engineering system involving feedstock preparation, heat management, reactor operation, product separation, safety, and economic considerations.

A central difficulty is that the apparent effect of a single operating parameter can change when the reactor or feedstock changes. Temperature, for example, is frequently reported as the dominant parameter, but temperature interacts with heating rate, particle size, vapor residence time, moisture, mineral matter, carrier-gas flow, and reactor hydrodynamics. A 2025 systematic review found broad trends toward lower biochar and higher gas production with increasing temperature, while bio-oil exhibited a more complex response and was often favored near 500 °C under appropriate conditions [3].

The second challenge is product quality. A high liquid yield is not equivalent to a high-value bio-oil. Raw bio-oil contains substantial oxygenated compounds and water and may exhibit acidity, high viscosity, corrosiveness, polymerization, and storage instability. These limitations have motivated physical separation, catalytic cracking, hydrogenation, hydrodeoxygenation, and other upgrading strategies [7]–[9]. Biochar likewise must be evaluated according to its intended application because surface area, ash, aromaticity, fixed carbon, stability, and contaminants can be more important than yield alone [10]–[13].

The third challenge is scale-up. Laboratory reactors can achieve rapid and uniform heating because the particles are small, while industrial systems must process variable feedstock with non-uniform moisture and particle size. Industrial vapor paths are also longer, increasing the possibility of secondary cracking, aerosol formation, condensation on walls, and coke deposition. Consequently, scale-up must preserve relevant heat-transfer and residence-time characteristics rather than simply multiplying reactor dimensions [1], [2], [14].

However, existing reviews have often discussed biomass pyrolysis from specific perspectives, such as reaction chemistry, reactor technologies, product formation, catalytic upgrading, or techno-economic assessment. These perspectives provide valuable knowledge, but the interdependence among feedstock characteristics, preprocessing, heat and mass transfer, reactor selection, vapor management, product quality, process integration, and industrial scale-up is not always considered within a single engineering framework. This limitation is particularly important for oil-palm residues, especially empty fruit bunches (EFB) and palm kernel shells (PKS), because their different physical and structural characteristics lead to different requirements for drying, size reduction, feeding, heat transfer, reactor operation, and downstream processing.

Therefore, this review provides an integrated engineering assessment of biomass and waste pyrolysis by connecting feedstock characteristics and preprocessing with reaction pathways, operating conditions, reactor technologies, product quality, catalytic upgrading, process integration, modeling, techno-economic and environmental considerations, and industrial scale-up. The novelty of this review lies not in discussing these topics individually, but in synthesizing their interactions to identify engineering trade-offs and practical requirements for reliable pyrolysis deployment. Particular emphasis is placed on EFB and PKS as representative oil-palm residues, with the aim of moving the evaluation of pyrolysis performance beyond product yield toward product quality, energy efficiency, process integration, operational reliability, and value maximization per unit of feedstock.

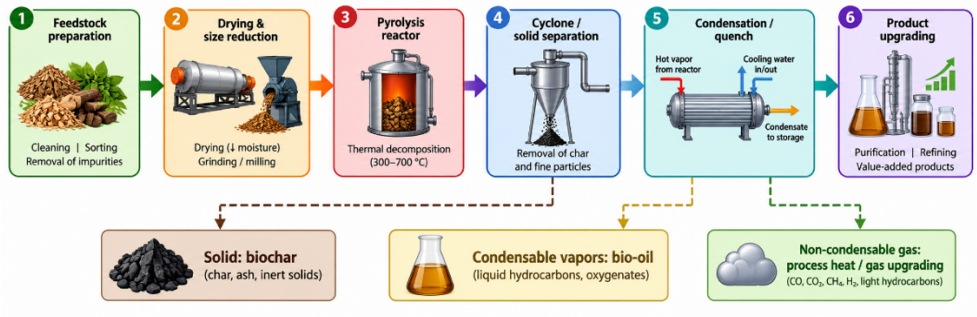

Fig. 1. Generalized pyrolysis process chain from feed preparation to product upgrading. The figure is a conceptual synthesis of the reviewed literature [1]–[4].

II. Basic Theory

A. Lignocellulosic structure and primary decomposition

Lignocellulosic biomass is dominated by cellulose, hemicellulose, and lignin, together with extractives, proteins, minerals, and moisture. These fractions decompose over partially overlapping temperature ranges and generate different families of products. Hemicellulose tends to decompose over a relatively broad low-to-intermediate temperature range; cellulose can undergo rapid depolymerization and formation of anhydro sugars and light oxygenates; lignin decomposes over a wider interval and contributes strongly to phenolic compounds and solid carbon [2], [14].

The simplified reaction sequence can be represented as drying → primary devolatilization → vapor transport → secondary vapor reactions → condensation. Primary reactions release volatile fragments, but the final product is determined by what happens to those fragments after leaving the particle. If hot vapors are removed rapidly, more primary condensable compounds can be recovered. If vapors remain at high temperature, cracking, dehydration, decarbonization, decarboxylation, repolymerization, aromatization, and coke formation become more important [2], [14], [15].

Inorganic minerals add another layer of complexity. Alkali and alkaline-earth metals can catalyse dehydration and char-forming reactions, while ash can alter heat transfer and increase the risk of fouling. Therefore, two feedstocks with similar proximate analysis can still generate different products because of differences in mineral composition and structural chemistry.

B. Moisture, particle size, and feed preparation

Moisture consumes heat during evaporation and can reduce reactor thermal efficiency. High moisture also changes the vapor composition and increases condenser loading. Drying is therefore not merely a preprocessing step; it is part of the energy balance of the complete pyrolysis system.

Particle size controls the characteristic time required for heat to penetrate the feed. Smaller particles generally reduce internal temperature gradients and are advantageous for fast pyrolysis. However, grinding consumes electricity and can create dust-management problems. The optimum size must therefore balance heat-transfer requirements against preparation energy and feeder reliability [3], [14].

Feed preparation also includes removal of metals, stones, and undesirable plastics or halogen-containing materials when mixed waste is processed. For oil-palm residues, size reduction and moisture equalization can be particularly important because EFB is fibrous while PKS is dense and hard. A robust industrial feeder must tolerate this heterogeneity without creating unstable mass flow.

C. Primary and secondary reaction competition

The key engineering distinction between fast and slow pyrolysis is not only temperature but the relative rates of heat transfer, devolatilization, vapor removal, and secondary reaction. Slow pyrolysis uses comparatively low heating rates and longer solids residence and is commonly selected when char is the main product. Fast pyrolysis uses rapid heating and short vapor residence to favor condensable products. Flash configurations push heating and vapor residence toward even more extreme conditions [1], [4].

Secondary vapor reactions explain why a reactor can produce less oil even when the feedstock conversion is high. Once primary vapors crack into permanent gases, they cannot be recovered as liquid. Likewise, repolymerization of heavy vapors can form aerosols and coke. The design objective for liquid-oriented pyrolysis is therefore to maximize the fraction of carbon entering the desired vapor pathway and then remove those vapors before extensive secondary chemistry occurs.

D. Operating Parameters and Product Distribution

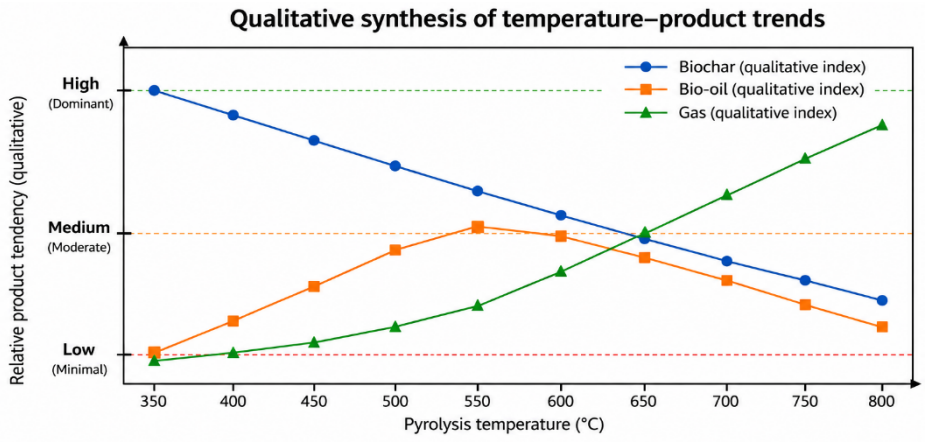

Fig. 2. Qualitative trend of pyrolysis products as function of temperature. Biochar tendency decreases with increasing temperature due to enhanced devolatilization and secondary cracking. Bio-oil tendency increases up to a moderate temperature (around 550-600 ^{0}C) an then decreases at higher temperatures because further cracking converts liquid into gas. Gas tendency increases continuously at higher temperatures due to intensified cracking reaction. (Adapted from general trend reported in the literature [3], [4]; not from any single experimental dataset.)

E. Temperature

Temperature is the most frequently evaluated pyrolysis parameter. Across the literature synthesized by Tamagno Junior et al. [3], experiments covered approximately 300–900 °C. Increasing temperature generally decreases biochar yield because more solid carbon is converted to volatile products. Gas formation tends to increase as secondary cracking becomes more important. Bio-oil often reaches a maximum within an intermediate temperature range, with around 500 °C frequently reported as favorable for lignocellulosic fast pyrolysis, but the exact optimum is feedstock- and reactor-dependent [3].

Temperature also changes product quality. Higher temperature can increase the fixed-carbon content and aromaticity of biochar and can increase gas heating value depending on gas composition. For bio-oil, greater severity can reduce oxygenated compounds but may also reduce liquid yield through cracking. Thus, the temperature that maximizes liquid mass is not necessarily the temperature that maximizes liquid value [7]–[9].

F. Heating rate

Heating rate determines how rapidly the particle passes through the temperature range in which its polymers decompose. High heating rates favor rapid devolatilization and, when combined with short vapor residence, can improve condensable recovery. Low heating rates permit more solid-phase rearrangement and generally increase char formation. The systematic review by Tamagno Junior et al. [3] confirms the importance of heating rate while also emphasizing that its effect cannot be separated from particle size and reactor configuration.

G. Vapor residence time

Vapor residence time is particularly important in fast pyrolysis. Prolonged residence at high temperature increases cracking and secondary condensation. Reactor outlets, cyclones, transfer lines, and condensers must therefore be designed as part of one vapor-management system. A nominal reactor residence time can be misleading if the hot vapor path downstream of the reactor is long.

H. Carrier-gas flow and atmosphere

Carrier-gas flow affects residence time, heat transfer, pressure drop, and condenser loading. Increasing flow can shorten vapor residence but increases gas-handling requirements and dilutes product vapors. Reactive atmospheres such as CO2 can also change chemistry. A recent review of CO2-assisted slow pyrolysis reported that CO2 can increase biochar yield in the 400–600 °C range for several feedstocks, while higher-temperature CO2 interactions can promote gasification and gas formation [16].

III. Method

This study employed a critical narrative review approach to synthesize recent research on biomass and waste pyrolysis, with particular emphasis on reaction pathways, operating parameters, reactor technologies, product quality, catalytic upgrading, oil-palm residues, process integration, and industrial scale-up [1]–[4], [14]. Peer-reviewed journal articles published mainly between 2022 and 2026 were prioritized, while earlier publications were retained when they provided important foundational knowledge relevant to pyrolysis reaction mechanisms, reactor engineering, product formation, and process development. The literature search focused on topics related to biomass pyrolysis, waste pyrolysis, fast and slow pyrolysis, pyrolysis reactors, bio-oil, biochar, pyrolytic gas, catalytic pyrolysis, hydrodeoxygenation, co-pyrolysis, empty fruit bunch (EFB), palm kernel shell (PKS), techno-economic analysis, life-cycle assessment, and process scale-up.

The selected literature was evaluated based on its relevance to the engineering aspects of pyrolysis, including feedstock characteristics, preprocessing, operating conditions, heat and mass transfer, reactor configuration, product distribution, product quality, catalytic upgrading, process integration, modeling, economic feasibility, environmental performance, and industrial deployment [1], [2], [7]–[20]. Particular attention was given to EFB and PKS because these oil-palm residues have different physical characteristics that influence drying, particle-size reduction, feeding behavior, heat transfer, reactor selection, and scale-up requirements [22], [26]–[29]. Experimental studies, review articles, reactor studies, product characterization studies, and engineering assessments were considered to provide a broad basis for comparing the reported findings.

The literature was critically synthesized by considering the interactions among feedstock properties, temperature, heating rate, particle size, vapor residence time, pressure, reaction atmosphere, reactor hydrodynamics, secondary reactions, and product recovery [3], [14]. The analysis did not consider product yield as the sole indicator of pyrolysis performance. Instead, product quality, energy requirements, process stability, catalyst performance, feedstock availability, and potential industrial application were also considered. Differences among reported results were interpreted in relation to variations in feedstock characteristics, reactor configuration, operating conditions, and product recovery systems where sufficient information was available. This approach was used to distinguish general trends from findings that are strongly dependent on specific feedstocks or process configurations.

For the comparison of reactor technologies, fixed-bed, auger/screw, fluidized-bed, rotary-kiln, and ablative configurations were evaluated qualitatively according to heat-transfer performance, scale-up potential, and engineering complexity [1], [4], [14]. The qualitative ratings presented in Fig. 3 represent a synthesis of characteristics reported in the reviewed literature rather than a quantitative ranking of reactor performance. Higher ratings for heat transfer and scale-up potential indicate more favorable characteristics, whereas a higher rating for engineering complexity indicates a greater level of technical complexity. Actual reactor performance may vary depending on feedstock properties, particle size, reactor geometry, operating conditions, heat-transfer mechanisms, and process configuration.

Quantitative values presented in the review were reported only when they were directly associated with an identified study. Figures describing general trends and engineering comparisons were developed as qualitative syntheses of the reviewed literature and were not treated as original

experimental datasets. This distinction is important because pyrolysis product yields and properties can vary considerably with feedstock composition, moisture content, particle size, heating rate, reactor configuration, vapor residence time, and condensation conditions [3], [14]. The overall synthesis was subsequently used to identify the major engineering challenges and research opportunities associated with the development and scale-up of biomass and waste pyrolysis, particularly for oil-palm residues.

A. Reactor Technologies and Heat-Transfer Engineering

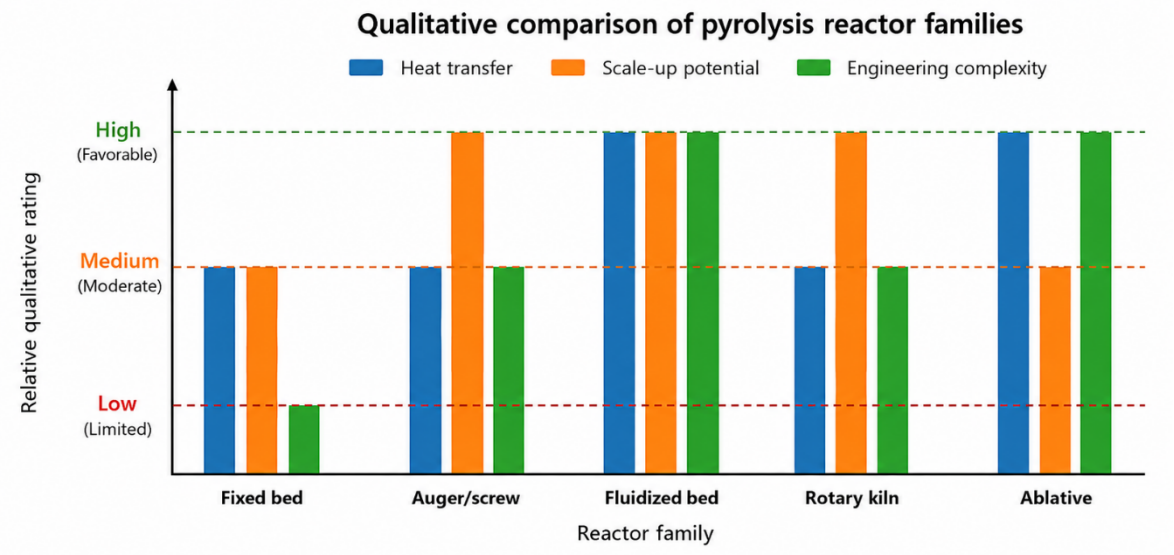

Fig. 3. Qualitative comparison of major pyrolysis reactor families based on heat transfer efficiency, scale-up potential, and engineering complexity. Ratings are expressed qualitatively as Low (Limited), Medium (Moderate), and High (Favorable). Note: Ratings represent general trends reported in the literature and may vary depending on reactor design, operating conditions, and feedstock. [1], [4], [14].

1. Fixed-bed reactors

Fixed beds are simple and useful for laboratory investigations and slow pyrolysis. They offer straightforward solids handling and relatively low mechanical complexity. Their principal limitation is heat-transfer uniformity at larger scales. Temperature gradients can cause different parts of the bed to experience different reaction histories, reducing product consistency.

2. Auger and screw reactors

Auger reactors are attractive for decentralized biomass conversion because the solids can be conveyed mechanically and the reactor can be relatively compact. They can process a broad range of particle sizes and do not require the high fluidizing-gas demand of a fluidized bed. The major engineering challenges are heat-transfer uniformity, screw wear, sealing, residence-time distribution, and stable feeding of fibrous materials [4].

3. Fluidized-bed reactors

Fluidized beds provide intense gas–solid mixing and high heat-transfer rates and are therefore widely used for fast pyrolysis. Their limitations include more complex solids separation, the need for controlled particle-size distributions, pressure-drop management, and entrainment of fine char. Cyclone design and hot-vapor filtration become important because entrained char can catalyze secondary reactions and contaminate the condensate.

4. Rotary-kiln and ablative configurations

Rotary kilns tolerate heterogeneous feedstocks and can provide long solids residence times, making them attractive for slow and intermediate pyrolysis. Ablative reactors use direct contact between particles and hot surfaces to achieve high heating rates without requiring extremely small particles. These configurations can be useful for specialized applications but require more detailed mechanical and thermal design.

5. Heat-transfer design

Scale-up should preserve the thermal history of the particles rather than only geometric similarity. Important mechanisms include conduction inside particles, convection between gas and solids, radiation, wall heat flux, and circulation of hot sand or other heat carriers. Coupling kinetics with particle heat-transfer models and reactor-scale validation is therefore preferable to using a single global activation energy as a stand-alone design basis [14], [17].

B. Pyrolysis Products and Product-Specification Requirements

1. *Bio-oil*
   Raw biomass pyrolysis oil is a chemically complex mixture of water and oxygenated compounds including acids, aldehydes, ketones, furans, phenolics, sugars, and oligomeric species. These components contribute to acidity, viscosity, low stability, and a relatively low heating value compared with petroleum-derived fuels. Recent reviews consistently identify high oxygen content and instability as major barriers to direct use as transportation fuel [7]–[9].
2. *Biochar*
   Biochar is increasingly treated as an engineered carbon product. Its properties depend on feedstock, temperature, heating rate, residence time, atmosphere, and reactor type. Higher severity commonly increases aromaticity and fixed carbon while reducing volatile matter. Surface area may also increase, making high-temperature biochar attractive for adsorption and catalytic applications. However, high ash or contaminant levels can restrict end uses [10]–[13].
3. *Pyrolytic gas*
   Non-condensable gas normally contains CO2, CO, H2, CH4, and light hydrocarbons. The gas can be used as process fuel, reducing external energy demand. Its value depends on heating value, gas cleaning requirements, and whether the plant can safely burn or reform the gas. A recent review emphasizes that pyrolysis gas can also be upgraded for higher-value applications, including hydrogen-rich streams [18].

Table 1. Product-oriented evaluation criteria for pyrolysis products.

Product	Primary value	Critical quality indicators	Typical bottleneck
Bio-oil	Fuel / chemicals	Water, oxygen, acidity, viscosity, stability	Upgrading and aging
Biochar	Carbon material / soil / adsorbent	Fixed C, ash, surface area, PAHs, stability	Consistent specification
Gas	Process heat / fuel / H2 feed	H2, CO, CH4, CO2, HHV, contaminants	Cleaning and safe combustion

IV. Results and Discussion

A. Catalytic Pyrolysis and Bio-Oil Upgrading

Catalytic pyrolysis introduces active sites that alter the fate of primary vapors. Zeolites, metal oxides, supported metals, and multifunctional catalysts can promote cracking, dehydration, decarbonylation, decarboxylation, demethoxylation, aromatization, and deoxygenation [8], [9]. The benefit is improved product quality or selectivity; the penalty is catalyst cost, coke formation, poisoning, regeneration, and potential loss of liquid yield.

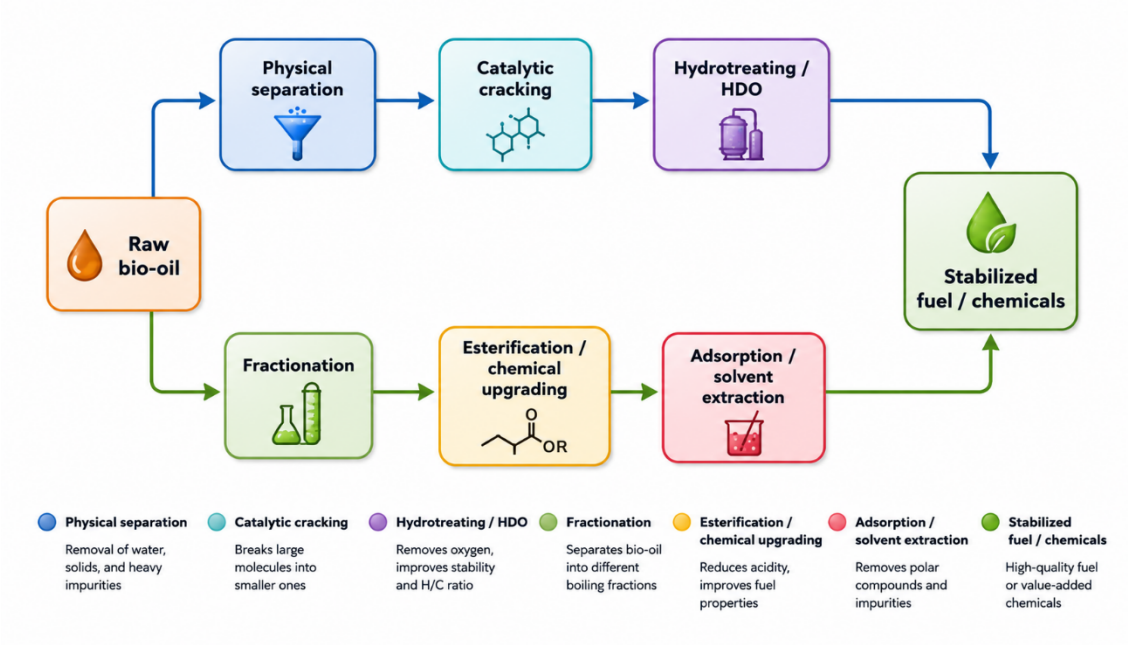

Fig. 4. Main pathways for upgrading raw pyrolysis oil toward stabilized fuels or value-added chemicals [7]–[9].

Recent work on lignocellulosic catalytic fast pyrolysis highlights zeolites as important catalysts for upgrading oxygenated vapors and shows growing interest in combining in-situ and ex-situ configurations [19]. Ex-situ reactors provide better separation between thermal conversion and catalytic upgrading and can make catalyst management easier, whereas in-situ configurations can reduce vapor-transfer losses.

Hydrodeoxygenation (HDO) is a major downstream route for converting oxygen-rich pyrolysis oil toward more petroleum-like products. Recent reviews emphasize that HDO can improve heating value and reduce acidity and viscosity but requires hydrogen, high-pressure equipment, and catalysts that resist deactivation [8], [20]. Online upgrading approaches are also being explored to minimize the handling of unstable raw bio-oil [9].

Product selectivity should be defined before catalyst selection. If the target is aromatic hydrocarbons, an acidic zeolite may be appropriate. If the target is deoxygenated fuel, bifunctional hydrogenation–hydrodeoxygenation catalysts may be more relevant. If the target is phenolic chemicals, conditions that maximize phenol concentration can be preferable even when total liquid yield decreases.

B. Oil-Palm Biomass as a Strategic Feedstock

Oil-palm residues are especially attractive for pyrolysis in Indonesia because feedstock generation is geographically concentrated around mills. EFB is abundant and fibrous, PKS is dense and energy-rich, and mesocarp fiber is already widely used as boiler fuel. This existing energy market is important: pyrolysis must create sufficient additional value to justify diverting residues from direct combustion [5], [6].

Recent studies demonstrate the diversity of possible products. A 2025 study on EFB investigated temperature-dependent pyrolysis for biochar synthesis and emphasized the relationship between pyrolysis temperature and material properties [21]. PKS has been investigated in continuous two-stage reactors, where an auger reactor was combined with a fluidized bed to produce phenol-rich bio-oil. In that study, increasing the fluidized-bed temperature from 550 to 650 °C increased phenol concentration in the fluidized-bed bio-oil, with a reported maximum phenol yield of 3.3 g per 100 g PKS at 600 °C under the selected conditions [22].

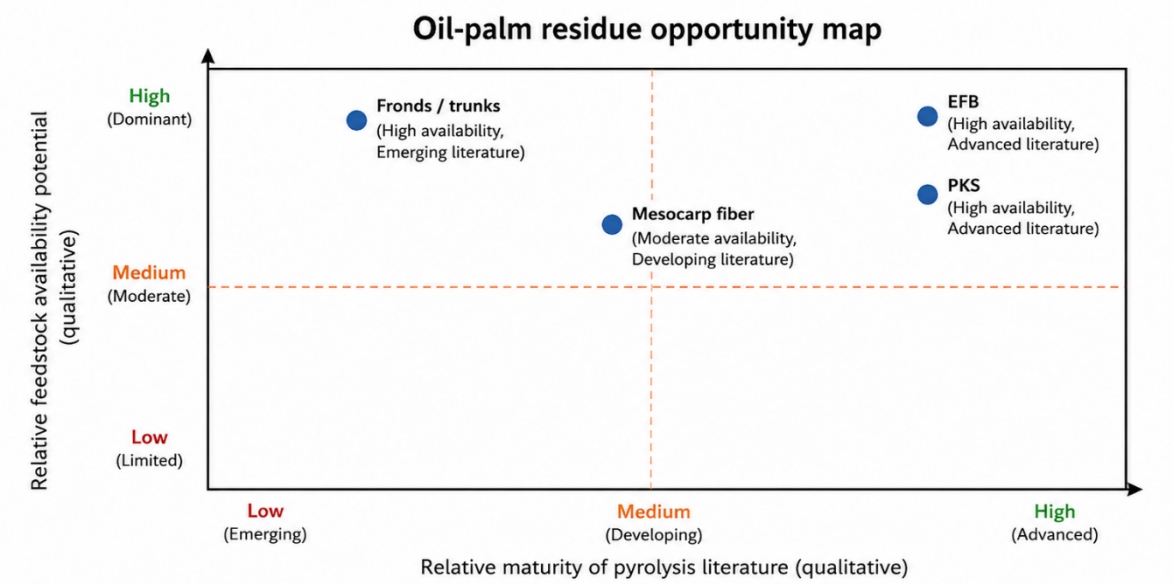

Fig. 5. Qualitative opportunity map for major oil-palm residues in terms of feedstock availability potential and maturity of pyrolysis research. EFB = empty fruit bunch; PKS = palm kernel shell. The map indicates that EFB and PKS combine high availability with relatively advanced pyrolysis literature, while mesocarp fiber has moderate availability and developing literature. Fronds and trunks have high availability potential but remain comparatively underexplored for pyrolysis applications. The positioning represents general trends reported in the literature and may vary depending on region, supply chain, feedstock characteristics, and technological focus.

PKS has also been investigated under CO2-assisted catalytic fast pyrolysis. A Ni–Ce/CN catalyst system improved oxygen-removal behaviour, while Ce addition reduced coke formation and promoted pathways associated with alkylphenols and acetic acid [23]. This illustrates how the atmosphere and catalyst can be deliberately combined to move beyond conventional inert-atmosphere pyrolysis.

EFB has been combined with high-density polyethylene (HDPE) in catalytic co-pyrolysis. A 2024 study using waste-derived CaO catalysts reported a maximum oil yield of 26.07 wt% with an eggshell-derived catalyst, while pure CaO produced the highest reported hydrocarbon composition among the tested catalysts [24]. The study is significant because it connects waste-derived catalyst production with simultaneous biomass–plastic valorisation.

The local engineering literature also supports the wider energy context. INOTERA reported that palm solid waste processed as refuse-derived fuel reached an average calorific value of 4,216.75 cal/g, with moisture of 10.76% and ash of 4.37%, demonstrating the importance of comparing pyrolysis with alternative energy-recovery pathways [5]. INOTERA also published an industrial-scale assessment of PE and PS pyrolysis at 200 kg/day, showing that high oil yield does not automatically guarantee energy self-sufficiency or economic feasibility [6]. These findings reinforce the central conclusion of this review: pyrolysis should be selected because of its complete value proposition, not because it produces a high laboratory liquid yield.

From an engineering perspective, EFB may be particularly suited to decentralized or mill-integrated pyrolysis when drying and feed handling can use existing mill heat. PKS, in contrast, has a high direct-fuel value and may be more attractive for catalytic or staged pyrolysis when high-value phenolic products, hydrogen-rich gas, or carbon products can compensate for the opportunity cost.

- EFB Feed Preparation and Feeding Behaviour

From an engineering perspective, the physical form of empty fruit bunches (EFB) is a major scale-up constraint. Fresh EFB is bulky, fibrous, and highly moist; reported moisture contents are commonly above 50 wt.% on a wet basis, with some studies reporting values approaching 60 wt.% [26], [27]. The elastic fiber network also gives EFB poor flowability compared with granular fuels. Consequently, whole EFB normally requires chopping, shredding, drying, and size reduction before controlled metering into a pyrolysis reactor.

The size-reduction requirement is not only an energy issue but also a feeder-reliability issue. In a bench-scale fast-pyrolysis study, EFB was manually chopped and shredded, then ground through a 500 μm screen. Feeding trials showed that only a relatively narrow particle-size fraction, approximately 250–355 μm, could be fed reliably, whereas finer and coarser fractions frequently caused feeder blockage [26]. This observation is important for scale-up: excessive fines can increase dust generation and cohesion, while long flexible fibers can bridge, wrap around screws, or form unstable plugs. For an auger reactor, the feeder should therefore include controlled fiber length, sufficient screw torque, anti-bridging geometry, and, where necessary, an agitator or live-bottom device. For a fluidized-bed reactor, the feed must additionally have a particle-size and density distribution compatible with stable entrainment and fluidization [28].

- PKS Feed Preparation and Heat Transfer

Palm kernel shell (PKS) presents a different engineering problem. It is a hard, dense, granular material that behaves more like a natural lignocellulosic pellet. Reported loose and compacted bulk densities are approximately 500–600 and 600–740 kg m−3, respectively, while particle density can exceed 1,100 kg m−3 [27]. Its high density is advantageous for storage and metering, but its hardness increases the mechanical duty of crushers and mills. For fast pyrolysis in a fluidized bed, published experiments have used sub-millimeter to approximately 1–2 mm particles, and smaller particles generally favor faster heat penetration and higher liquid yields [27], [29]. Thus, if a process specification requires particles below 1 mm, the grinding-energy penalty can become a significant part of operating cost.

PKS also creates an intraparticle heat-transfer limitation. Although its bulk density is high, its thermal conductivity is relatively low, so a large shell particle can develop a temperature gradient between its surface and core. This is particularly important when high heating rates and short vapor residence times are required. The practical consequence is a trade-off between grinding energy and heat-transfer performance: larger particles reduce milling demand but increase internal heat-transfer limitations, whereas very fine particles improve thermal response but increase milling power, dust-control requirements, and feeding complexity. Continuous fluidized-bed studies have therefore treated feed size and feed rate as key operating variables [29].

- Thermal Integration at Palm Oil Mills

A palm-oil-mill pyrolysis system should not be designed as an isolated reactor. The high moisture content of fresh EFB makes drying a major pre-processing energy demand, while the mill already contains potentially useful heat sources. Flue gas from the mill boiler can be routed through a controlled drying system, subject to particulate, corrosion, and contamination constraints. The objective is to reduce EFB moisture before milling and pyrolysis without consuming high-value auxiliary fuel. Experimental work on EFB thermal pretreatment confirms that reducing feed moisture can substantially improve energy yield and fuel quality [30].

The pyrolysis unit can provide a second internal heat source. Non-condensable gas (NCG) containing combustible species can be cleaned and combusted to supply reactor heat. In an integrated configuration, the heat hierarchy can prioritize: (1) combustion of suitable pyrolysis gas for reactor duty, (2) recovery of condenser and hot-gas sensible heat for EFB drying or process-water preheating, and (3) supplementary boiler/flue-gas heat when the internal heat supply is insufficient. Such integration can reduce external energy demand, but gas cleaning, combustion control, tar management, and oxygen-leak prevention are essential for safe operation.

- Engineering Implication for Reactor Selection

These feedstock differences imply that reactor selection should follow feed-preparation capability rather than product yield alone. EFB is more naturally suited to mechanically robust systems such as auger or rotary-kiln reactors when the process accepts relatively coarse, dried particles and can tolerate longer solids residence times. Fluidized beds provide excellent heat transfer but impose tighter requirements on particle size, density, and flowability. PKS is well suited to fluidized-bed or auger configurations, but fast-pyrolysis applications may require intensive grinding. For PKS, fluidized-bed operation has demonstrated phenol-rich bio-oil production [22], whereas EFB fast-pyrolysis studies have shown strong sensitivity to ash content and feed preparation [26].

Table 2. Engineering comparison of EFB and PKS as pyrolysis feedstocks.

Parameter	EFB (Empty Fruit Bunch)	PKS (Palm Kernel Shell)	Engineering implication	Literature basis
Physical characteristics	Fibrous, elastic, bulky; high moisture when fresh	Hard, granular, dense; loose bulk density about 500–600 kg m−3	EFB needs drying and flow conditioning; PKS is easier to meter but harder to mill	[26], [27]
Main processing challenge	Drying, shredding/milling, fiber bridging and feeder blockage	High grinding duty for fine particles; intraparticle heat-transfer limitation	EFB emphasizes feedability; PKS emphasizes milling power and heat-transfer control	[26], [27], [29]
Feeding concern	Long fibers and fines can bridge, wrap, or plug feeders; fluidization is sensitive to particle properties	Granular particles are more predictable, but feed size still controls fluidization and conversion	Use anti-bridging screw/agitator for EFB; controlled particle-size distribution for PKS	[26], [28], [29]
Recommended reactor family	Auger / rotary kiln for robust coarse-feed operation; fluidized bed after rigorous size conditioning	Fluidized bed / auger; fluidized bed is attractive when fine particles can be produced economically	Select reactor jointly with preprocessing and feed-system design	[1]–[3], [22], [26], [29]
Product tendency	Bio-oil / volatile-rich products; strongly affected by moisture and ash	Biochar potential and phenolic-rich bio-oil	Target product should be selected together with feed preparation and reactor severity	[22], [26], [27]

C. Co-Pyrolysis of Biomass and Plastics

Co-pyrolysis attempts to exploit interactions between oxygen-rich biomass and hydrogen-rich plastics. Polyolefins such as HDPE and polypropylene can donate hydrocarbon fragments during thermal cracking, potentially reducing oxygenated products and increasing hydrocarbon selectivity. The effect is highly dependent on blend ratio, temperature, catalyst, vapor residence, and plastic type. The EFB–HDPE study by Hakim et al. [24] illustrates the potential of waste-derived CaO catalysts. The authors reported that the eggshell-derived catalyst produced the highest oil yield among the tested catalysts, while pure CaO generated the highest hydrocarbon composition. The result indicates that catalyst choice can change the trade-off between liquid yield and liquid quality.

Mixed-waste systems introduce additional safety and environmental constraints. Chlorine-containing plastics can generate HCl and chlorinated compounds, while additives and metals may transfer into char or condensate. Industrial co-pyrolysis therefore requires feed sorting, contaminant control, corrosion management, gas cleaning, and product testing before commercial operation.

D. Kinetics, Modeling, and Process Control

Thermogravimetric analysis is widely used to estimate apparent kinetic parameters, but the resulting activation energy depends on heating rate, conversion range, sample size, atmosphere, and kinetic model. Recent reviews emphasize that biomass pyrolysis cannot be represented reliably by a single global reaction because cellulose, hemicellulose, lignin, minerals, and extractives follow different pathways [2], [14].

Multi-component kinetic models can describe primary decomposition more realistically, but reactor design also requires heat and mass transfer. A model calibrated against milligram-scale TGA data may fail when applied to centimeter-scale particles because internal temperature gradients change the actual reaction history. The preferred strategy is therefore hierarchical: kinetic experiments → particle-scale heat transfer → reactor-scale validation → process integration.

Computational fluid dynamics can resolve gas–solid flow, temperature fields, pressure drop, and residence-time distributions. Machine-learning models can accelerate optimization when sufficiently

representative datasets are available. However, data-driven models should not be treated as substitutes for physical understanding when feedstock composition changes significantly.

Online measurement is an important industrial opportunity. Temperature mapping, gas composition, pressure, oxygen leakage, and condensate properties can be used to identify process deviations before product quality deteriorates. Sensor-based monitoring of temperature, pressure, and pyrolysis gas composition has been identified as an important approach for precise process control and optimization of pyrolysis systems [25].

E. Techno-Economic and Environmental Considerations

Pyrolysis economics are governed by the complete process chain. Capital expenditure includes feed preparation, drying, reactor, heat-transfer system, cyclone, condenser, gas treatment, storage, instrumentation, and safety systems. Operating costs include electricity, drying energy, carrier gas, catalyst, maintenance, labor, and residue handling. Revenue depends on product quality and market, not only on product mass.

Recent reviews emphasize that biochar production can offer environmental value through carbon storage and soil applications, but economic performance depends strongly on feedstock logistics, reactor choice, product price, and scale [10]–[13]. A plant that sells only low-value raw bio-oil may struggle to compete with direct combustion, whereas a plant that integrates high-value chemicals, engineered biochar, process heat, and carbon-management revenue can have a stronger business case.

Life-cycle assessment should be performed with explicit system boundaries. Drying and grinding can consume substantial energy, while transportation can dominate emissions for low-density feedstocks. Benefits may arise from avoided waste disposal, displacement of fossil products, internal heat recovery, and stable carbon storage. These benefits must be compared against catalyst production, hydrogen consumption, electricity, and auxiliary fuels.

Industrial feasibility should also include opportunity cost. For a palm oil mill, PKS and fiber already have an established use as boiler fuels. The pyrolysis pathway must therefore provide a higher-value product or a strategic environmental benefit. EFB may have a different economic balance because its handling and transportation can be more difficult. This feedstock-specific comparison should be part of any investment decision.

Table 3. Major industrial scale-up challenges and engineering responses.

Scale-up issue	**Laboratory situation**	**Industrial consequence**	**Recommended engineering response**
Moisture	Controlled and narrow range	Variable heat demand	Drying with recovered process heat
Particle size	Uniform	Feeder blockage / uneven heating	Screening and robust metering
Heat transfer	Small particles	Internal temperature gradients	Particle-scale model + pilot validation
Vapor path	Short	Secondary cracking / aerosol / coke	Compact hot-vapor line + rapid quench
Catalyst	Fresh	Deactivation / poisoning	Regeneration strategy + contaminant control
Gas	Low flow	Flammability / emissions	Gas cleaning + controlled combustion
Product	Single batch	Specification variability	Online monitoring + batch/lot QA

Table 4. Engineering comparison of major pyrolysis routes.

Route	Main product	Key strength	Main limitation	Best-fit application
Slow pyrolysis	Biochar	High carbon yield; simple reactors	Low liquid productivity	Carbon materials / soil products
Intermediate pyrolysis	Char + liquids	Balanced product slate	More complex optimization	Distributed biorefineries
Fast pyrolysis	Bio-oil	High condensable productivity	Oil instability; vapor management	Fuel/chemical production
Catalytic pyrolysis	Upgraded vapors	Improved selectivity and deoxygenation	Coke and catalyst deactivation	Value-added chemicals
Co-pyrolysis	Hydrocarbon-rich liquids	Biomass–plastic synergy	Contaminants and feed sorting	Mixed waste valorization
Two-stage pyrolysis	Separated product families	Independent control of stages	Higher capital and control complexity	Selective chemicals / H2

F. Research Gaps and Future Directions

First, standardized reporting is still needed. Studies should report moisture basis, ash, proximate and ultimate analysis, particle size, reactor configuration, heating rate, solids residence time, vapor residence time, carrier-gas flow, pressure, condensation method, and complete mass closure. Without these data, cross-study comparisons remain weak [3].

Second, more experiments should use realistic industrial feedstocks. EFB, PKS, mixed agricultural residues, and real plastic waste contain minerals, moisture, contaminants, and particle-size distributions that are not represented by pure cellulose or clean laboratory plastics. Real-feed testing should become the default at pilot scale.

Third, product quality should be optimized together with yield. For bio-oil, oxygen content, water, total acid number, viscosity, stability, and chemical families should accompany mass yield. For biochar, fixed carbon, surface area, ash, PAHs, stability, and application-specific performance should be reported. For gas, composition and heating value should accompany volume yield.

Fourth, heat integration deserves greater attention. Pyrolysis gas can supply reactor heat, while condenser heat can dry feedstock or preheat process water. For palm oil mills, existing boilers and biomass-handling infrastructure provide an opportunity for integrated systems that reduce auxiliary fuel demand.

Fifth, catalyst studies should include long-duration operation. Initial conversion and selectivity are insufficient evidence for industrial deployment. Deactivation rate, regeneration, contaminant tolerance, mechanical stability, and catalyst replacement cost should be reported.

Sixth, pilot-scale work should focus on reliability and product consistency rather than only maximum yield. A process that operates continuously at a slightly lower yield but with stable mass balance and predictable product quality can be more valuable than a laboratory process with a higher peak yield.

Finally, process digitalization can connect feedstock variability to reactor control. Online gas analysis, temperature mapping, pressure monitoring, and soft sensors can provide the feedback required for stable operation. The scale-up roadmap should therefore combine chemical kinetics, thermal engineering, process control, safety, TEA, and LCA.

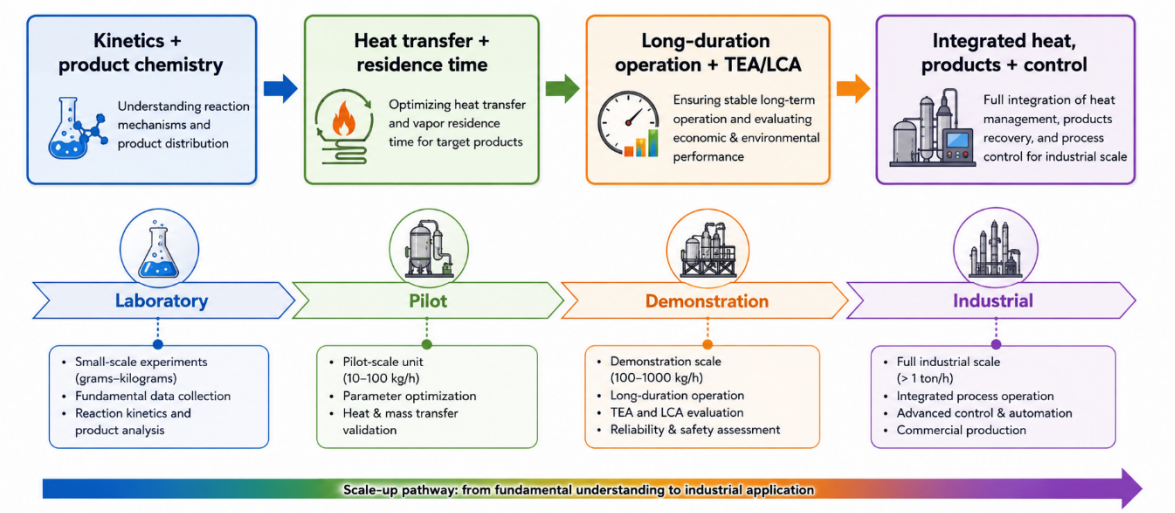

Fig. 6. Recommended scale-up roadmap from laboratory kinetics to integrated industrial pyrolysis. The central requirement is preservation of thermal history, vapor residence, mass balance, and product specification.

V. Conclusion

Pyrolysis is best understood as an integrated thermochemical process rather than a single reactor operation. Feedstock chemistry, moisture, particle size, heating rate, temperature, vapor residence, atmosphere, reactor hydrodynamics, and condensation jointly determine product distribution and quality.

Lower severity and slower heating generally favor biochar, while rapid heating and short vapor residence favor condensable products. Higher severity and secondary vapor reactions increase gas and coke formation. The often-reported optimum near 500 °C for bio-oil should therefore be treated as a literature tendency rather than a universal design value.

Raw biomass pyrolysis oil generally requires upgrading because of high oxygen content, water, acidity, viscosity, and instability. Catalytic cracking, hydrodeoxygenation, fractionation, and online upgrading can improve quality, but catalyst deactivation, hydrogen demand, coke, and process complexity remain major barriers.

Oil-palm residues are strong candidates for integrated pyrolysis in Indonesia. EFB and PKS have demonstrated potential for biochar, phenolic products, bio-oil, and catalytic conversion. However, pyrolysis must be compared with existing uses such as direct boiler combustion and alternative residue-derived fuels.

The most important future research priorities are standardized reporting, realistic industrial feedstocks, product-quality specifications, heat integration, long-duration catalyst testing, pilot-scale reliability, digital control, techno-economic assessment, and life-cycle assessment. Industrial success will depend on maximizing value per unit of feedstock rather than maximizing one laboratory yield.

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References

[1] W. Jerzak, E. Acha, and B. Li, "Comprehensive review of biomass pyrolysis: Conventional and advanced technologies, reactor designs, product compositions and yields, and techno-economic analysis," Energies, vol. 17, no. 20, Art. no. 5082, 2024, doi: 10.3390/en17205082.

[2] A. K. Vuppaladadiyam, S. S. V. Vuppaladadiyam, V. S. Sikarwar, E. Ahmad, K. K. Pant, M. Murugavelh, A. Pandey, S. Bhattacharya, A. Sarmah, and S.-Y. Leu, "A critical review on biomass pyrolysis: Reaction mechanisms, process modeling and potential challenges," *J. Energy Inst.*, vol. 108, Art. no. 101236, 2023, doi: 10.1016/j.joei.2023.101236.

[3] I. J. Tamagno Junior, J. L. F. Alves, C. Z. Brusamarello, and M. Di Domenico, "Impact of operational parameters on the yield of biochar, bio-oil, and pyrolytic gas in lignocellulosic biomass pyrolysis: A systematic review," *Bioresour. Technol. Rep.*, vol. 30, Art. no. 102155, 2025, doi: 10.1016/j.biteb.2025.102155.

[4] A. K. Vuppaladadiyam, S. S. V. Vuppaladadiyam, A. Awasthi, A. Sahoo, S. Rehman, K. K. Pant, S. Murugavelh, Q. Huang, E. Anthony, P. Fennel, S. Bhattacharya, and S.-Y. Leu, "Biomass pyrolysis: A review on recent advancements and green hydrogen production," *Bioresour. Technol.*, vol. 364, Art. no. 128087, 2022, doi: 10.1016/j.biortech.2022.128087.

[5] G. I. Gunadi and D. Dahlan, "Quality test of utilization of palm oil solid waste as a raw material for refuse derived fuel (RDF) for alternative fuels," *J. Inotera*, vol. 9, no. 2, pp. 461–474, 2024, doi: 10.31572/inotera.Vol9.Iss2.2024.ID397.

[6] I. N. D. K. Dewi, A. Muhammad, W. N. Achmadin, Andrie, M. N. Helsinky, and W. Aprillia, "Feasibility analysis of industrial-scale pyrolysis of 200 kg polyethylene and polystyrene plastic waste," *J. Inotera*, vol. 10, no. 1, pp. 181–190, 2025, doi: 10.31572/inotera.Vol10.Iss1.2025.ID461.

[7] D. Lachos-Perez, J. C. Martins-Vieira, J. Missau, K. Anshu, O. K. Siakpebru, S. K. Thengane, A. R. C. Morais, E. H. Tanabe, and D. A. Bertuol, "Review on biomass pyrolysis with a focus on bio-oil upgrading techniques," *Analytica*, vol. 4, no. 2, pp. 182–205, 2023, doi: 10.3390/analytica4020015.

[8] A. Carrasco Díaz, L. Abdelouahoued, N. Brodu, V. Montes-Jiménez, and B. Taouk, "Upgrading of pyrolysis bio-oil by catalytic hydrodeoxygenation, a review focused on catalysts, model molecules, deactivation, and reaction routes," *Molecules*, vol. 29, no. 18, Art. no. 4325, 2024, doi: 10.3390/molecules29184325.

[9] X. Pan, S. Wu, J. Chen, and R. Xiao, "Toward efficient biofuel production: A review of online upgrading methods for biomass pyrolysis," *Energy Fuels*, vol. 38, no. 20, pp. 19414–19441, 2024, doi: 10.1021/acs.energyfuels.4c04131.

[10] Y. Li, R. Gupta, Q. Zhang, and S. You, "Review of biochar production via crop residue pyrolysis: Development and perspectives," *Bioresour. Technol.*, vol. 369, Art. no. 128423, 2023, doi: 10.1016/j.biortech.2022.128423.

[11] R. K. Mishra, D. J. P. Kumar, A. Narula, S. M. Chistie, and S. U. Naik, "Production and beneficial impact of biochar for environmental application: A review on types of feedstocks, chemical compositions, operating parameters, techno-economic study, and life cycle assessment," *Fuel*, vol. 343, Art. no. 127968, 2023, doi: 10.1016/j.fuel.2023.127968.

[12] S. Y. Foong, K. Y. Cheong, S. H. Kong, C. L. Yiin, P. N. Y. Yek, R. Safdar, R. K. Liew, S. K. Loh, and S. S. Lam, "Recent progress in the production and application of biochar and its composite in environmental biodegradation," *Bioresour. Technol.*, vol. 385, Art. no. 129592, 2023, doi: 10.1016/j.biortech.2023.129592.

[13] L. Campion, M. Bekchanova, R. Malina, and T. Kuppens, "The costs and benefits of biochar production and use: A systematic review," *J. Cleaner Prod.*, vol. 408, Art. no. 137138, 2023, doi: 10.1016/j.jclepro.2023.137138.

[14] E. Parvari, D. Mahajan, and E. L. Hewitt, "A review of biomass pyrolysis for production of fuels: Chemistry, processing, and techno-economic analysis," *Biomass*, vol. 5, no. 3, Art. no. 54, 2025, doi: 10.3390/biomass5030054.

[15] T. Matamba, A. Tahmasebi, J. Yu, A. Keshavarz, H. R. Abid, and S. Iglauer, "A review on biomass as a substitute energy source: Polygeneration influence and hydrogen rich gas formation via pyrolysis," *J. Anal. Appl. Pyrolysis*, vol. 175, Art. no. 106221, 2023, doi: 10.1016/j.jaap.2023.106221.

[16] P. Premchand, F. Demichelis, D. Chiaramonti, S. Bensaid, and D. Fino, "Biochar production from slow pyrolysis of biomass under CO_2 atmosphere: A review on the effect of CO_2 medium on biochar production, characterisation, and environmental applications," *J. Environ. Chem. Eng.*, vol. 11, no. 3, Art. no. 110009, 2023, doi: 10.1016/j.jece.2023.110009.

[17] A. Nanduri, S. S. Kulkarni, and P. L. Mills, "Experimental techniques to gain mechanistic insight into fast pyrolysis of lignocellulosic biomass: A state-of-the-art review," *Renew. Sustain. Energy Rev.*, vol. 148, Art. no. 111262, 2021, doi: 10.1016/j.rser.2021.111262.

[18] Y. Zhang, Y. Liang, S. Li, Y. Yuan, D. Zhang, Y. Wu, H. Xie, K. Brindhadevi, A. Pugazhendhi, and C. Xia, "A review of biomass pyrolysis gas: Forming mechanisms, influencing parameters, and product application upgrades," *Fuel*, vol. 347, Art. no. 128461, 2023, doi: 10.1016/j.fuel.2023.128461.

[19] H. El Bari, C. K. Fanezoune, B. Dorneanu, H. Arellano-Garcia, T. Majozi, Y. Elhenawy, O. Bayssi, A. Hirt, J. Peixinho, A. Dhahak, M. A. Gadalla, N. H. Khashaba, and F. H. Ashour, "Catalytic fast pyrolysis of lignocellulosic biomass: Recent advances and comprehensive overview," *J. Anal. Appl. Pyrolysis*, vol. 178, Art. no. 106390, 2024, doi: 10.1016/j.jaap.2024.106390.

[20] Z. Luo, W. Zhu, F. Miao, and J. Zhou, "Catalytic hydrodeoxygenation of pyrolysis bio-oil to jet fuel: A review," *Front. Energy*, vol. 18, no. 5, pp. 550–582, 2024, doi: 10.1007/s11708-024-0943-7.

[21] F. G. Nugroho, A. S. Ansari, N. T. Rochman, S. S. Khadtare, V. G. Sree, N. K. Shrestha, A. F. Hafiyyan, H. Im, and A. T. A. Ahmed, "Utilizing Indonesian empty palm fruit bunches: Biochar synthesis via temperatures dependent pyrolysis," *Nanomaterials*, vol. 15, no. 1, Art. no. 50, 2025, doi: 10.3390/nano15010050.

[22] D. Y. Chae, J. K. Kim, K. B. Park, and J. S. Kim, "Thermal, thermo-oxidative, and catalytic degradation of palm kernel shells using a continuous two-stage pyrolysis process for the production of phenols-rich bio-oil," *Fuel*, vol. 385, Art. no. 134103, 2025, doi: 10.1016/j.fuel.2024.134103.

[23] L. K. H. Pham, S. Kongparakul, G. Guan, N. Chanlek, D.-V. N. Vo, N. V. Cuong, A. Watanabe, and C. Samart, "CO_2-assisted fast pyrolysis of palm kernel shells over a Ni–Ce/CN catalyst for the selective production of bio-oil," *Fuel*, vol. 371, Art. no. 132038, 2024, doi: 10.1016/j.fuel.2024.132038.

[24] K. A. K. M. Hakim, E. S. Tan, S. H. Habib, R. S. R. M. Hafriz, and A. Salmiaton, "Investigation of waste-derived and low-cost calcium oxide-based catalysts in co-pyrolysis of EFB-HDPE to produce high quality bio-oil," *J. Anal. Appl. Pyrolysis*, vol. 177, Art. no. 106375, 2024, doi: 10.1016/j.jaap.2024.106375.

[25] H. Zhang, S. Ju, X. Jin, Y. Yuan, Y. Wu, A. K. Nadda, A. Pugazhendhi, L. Cai, and C. Xia, "A review of sensor applications towards precise control of pyrolysis of solid waste and biomasses," *Renew. Sustain. Energy Rev.*, vol. 169, Art. no. 112915, 2022, doi: 10.1016/j.rser.2022.112915.

[26] N. Abdullah, H. Gerhauser, and A. V. Bridgwater, "Bio-oil from fast pyrolysis of oil palm empty fruit bunches," *J. Phys. Sci.*, vol. 18, no. 1, pp. 57–74, 2007.

[27] M. Asadullah, N. S. Ab Rasid, S. A. S. A. Kadir, and A. Azdarpour, "Production and detailed characterization of bio-oil from fast pyrolysis of palm kernel shell," *Biomass Bioenergy*, vol. 59, pp. 316–324, 2013, doi: 10.1016/j.biombioe.2013.08.037.

[28] M. Shahbaz, S. Yusup, M. Y. Naz, and S. A. Sulaiman, "Fluidization of palm kernel shell, palm oil fronds, and empty fruit bunches in a swirling fluidized bed gasifier," *Part. Sci. Technol.*, vol. 35, no. 2, pp. 150–157, 2017, doi: 10.1080/02726351.2016.1139021.

[29] Y. Uemura, A. Norizan, H. A. Afif, N. Osman, W. N. Omar, B. Abdullah, and T. Tsutsui, "Fast pyrolysis of oil palm kernel shell in a fluidized bed reactor: The effect of biomass size on the yields of pyrolysis products," *Appl. Mech. Mater.*, vol. 625, pp. 608–611, 2014, doi: 10.4028/www.scientific.net/AMM.625.608.

[30] M. A. Sukiran, F. Abnisa, S. Syafiie, W. M. A. W. Daud, A. B. Nasrin, A. A. Aziz, and S. K. Loh, "Experimental and modelling study of the torrefaction of empty fruit bunches as a potential fuel for palm oil mill boilers," *Biomass Bioenergy*, vol. 136, Art. no. 105530, 2020, doi: 10.1016/j.biombioe.2020.105530.