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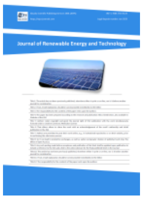

Effects of Temperature and Pressure Conditions on the Quantity and Quality of Bio-Oil Produced from Pyrolysis of Biomass Material: A Review

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Keywords

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Abstract: The pyrolysis process of biomass results in bio-oil which functions as a sustainable renewable fuel that can substitute for traditional fossil fuel resources. The research presents current findings about temperature and pressure effects on bio-oil manufacturing and its physical and chemical characteristics through new quantitative results from recent investigations. The amount of moisture in the system reduces the production of liquid products because the condensable organic compounds decrease from 19.6 wt.% to 15.2 wt.% when the moisture content rises from 2.7 wt.% to 10 wt.%. The process requires feedstock drying to reach moisture levels that stay under 10 wt.%. The optimal pyrolysis temperatures between 450–550°C produce the highest liquid yields between 45–75 wt.% from lignocellulosic and mixed biomasses which results in better bio-oil quality because of lower oxygen levels (from 42 to 28 wt.%) and lower water content (from 20-25 to 7–10 wt.%) and higher HHV values which increase from 18 to 25–30 MJ.kg^{-1} because of better dehydration and decarboxylation reactions. The characteristics of bio-oil become more stable and energy dense when pressure conditions reach 0.5-2 MPa because this leads to decreased oxygenate and moisture content, which results in higher HHV values from 27.8 to 31.4 MJ.kg^{-1} and prevents viscosity increase through polymerization. The vacuum conditions help to enhance aromatic compounds while protecting them from additional cracking that results in decreased overall production levels. The process has shown progress, but it still faces major challenges because bio-oils show unstable properties, and their high oxygen content and acidic nature make them difficult to apply in various industries. Research in the future needs to concentrate on developing complete process enhancement systems which combine catalytic upgrading with hydrogen-assisted or pressured pyrolysis and machine learning prediction systems and renewable thermal energy sources and waste heat recovery systems.

1. Introduction

Biomass pyrolysis is a thermochemical conversion process that occurs in the absence of oxygen and yields bio-oil and biochar alongside syngas. Bio-oil, however, has the most room for potential as a substitute for fossil fuels, as it is more environmentally friendly, energy-dense, and can be upended into transport fuels. The process involves heating organic material to 300–700°Cin the absence of oxygen to prevent combustion. (Al-Rumaihi et al., 2022). During pyrolysis, temperature is the most critical parameter, as it significantly affects both the quantity and quality of the yield. The temperature influences the reaction volatility, the

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rate of thermal decomposition, and the formation of condensable vapors that become bio-oil (Maulinda et al., 2023b). The number of volatiles in the reaction zone increases as chemical reactions progress, enhancing both the amount and quality of bio-oil(Basile et al., 2014).

Biomass pyrolysis represents an important solution for addressing the increasing global demand for sustainable energy and reducing greenhouse gas emissions. The production of bio-oil combats multiple issues, one being overdependence on fossil fuels, and with the help of agricultural and forestry waste, it aids the creation of a circular economy, helping with the ongoing energy crisis (Hansen et al., 2020; Sikarwar et al., 2016).

The properties of bio-oil that limit its widespread application can be improved through proper control of temperature and pressure during pyrolysis. Such properties include viscosity, water content, acidity, oxygen content, energy content, and stability. Thus, understanding the optimal conditions to operate the pyrolysis process is essential for producing a quality bio-oil that could either compete with fuels in the markets or be used as a precursor for various chemicals (Mostafazadeh et al., 2018; Kumar et al., 2020). Interest in bio-oil has grown because it can convert widely available biomass into a storable liquid energy carrier. For pyrolysis to be practical, operating conditions must be optimized alongside energy use, emissions, and cost.

In several studies conducted on various ranges of temperatures and pressures on bio-oil yield and quality, outcomes remain incomplete or conflicting due to the specificity of the integrations involving individual biomass and reactor designs. For this review, published studies have been collected, and their individual merits and demerits have been evaluated to form a cohesive review. It examines the effects of the interplay of temperature and pressure on the quantity and primary quality parameters of bio-oils (including viscosity, stability, and the total oxygen-containing functional groups of bio-oil). Additionally, the authors provide their research considerations in forthcoming studies. It is anticipated that the findings of the study will contribute to the enhancement of the bio-oil production process and its economic and ecological sustainability.

2. Methods

This review uses the structured literature synthesis method to analyze the effects of temperature and pressure on the quantity and quality of bio-oil produced from the pyrolysis of biomass. The study identified over 240 studies published between 2005 and 2025 from online libraries, including Google Scholar and Scopus, with the search parameters `biomass pyrolysis` and `bio-oil properties`. 128 studies were included based on having described the bio-oil's physicochemical properties under specific conditions quantitatively. The author ensures a high level of analysis and synthesis through the process of standardizing the data, the use of narrative comparative analysis to identify trends, and the use of comparative synthesis to analyze trends, The study also reviews techno-economic studies with a view to improving transparency and replicability regarding the effects of temperature and pressure on bio-oil to better understand the implications of optimizing the pyrolysis process.

3. Bio-Oil Production Process

Biomass pyrolysis produces bio-oil, a dark brown, viscous liquid composed of highly oxygenated molecules that are unstable and prone to aging (Gollakota et al., 2016; Gupta et al., 2021; Panwar & Paul, 2021; Su et al., 2022). It involves moderate temperatures and oxygen-free conditions to thermally depolymerize biomass. Slow pyrolysis, flash pyrolysis, and fast pyrolysis are classified based on the residence time of the solid feedstock in the reactor (Fahmy et al., 2020; Zhang & Zhang, 2019). During the process, condensable gas residence duration, temperature, and pressure all have a significant impact on solid, liquid, and gas yields. The resulting bio-oil is characterized by high water and oxygen contents, high viscosity and acidity, and trace amounts of nitrogen and sulfur (Lyu et al., 2015). To produce bio-oils, hemicellulose, cellulose, and lignin are rapidly depolymerized and fragmented by heating the biomass at very high rates (typically 300-700 °C/s) to temperatures between approximately 400 and 600 °C, followed by rapid cooling of the vapors. This rapid cooling prevents intermediate products from undergoing further conversion. Because biomass contains considerable amounts of oxygen, bio-oil elemental composition and physicochemical characteristics differ significantly from those of oil obtained from petroleum (Lee et al., 2020; Oh et al., 2021; Seo et al., 2022; Su et al., 2022). The chemical composition and key physicochemical characteristics of bio-oil and petroleum-derived oil are presented in Table 1.

Table 1. Typical physicochemical characteristics and content of bio-oil and heavy petroleum-derived oil (Agblevor et al., 2012; Czernik & Bridgwater, 2004; Zhang et al., 2007)

Properties/Elemental Composition	Bio-Oil (wt. %)	Heavy Petroleum-Derived Oil (wt. %)
Higher heating value - HHV (MJ/kg)	16-19	40
Viscosity (at 50 °C) (cP)	40-100	180
C	54-58	85
N	0-0.2	0.3
O	35-40	1.0
H	5.5-7.0	11
Ash	0-0.2	0.1
Water	15-30	0.1

Since bio-oil has a high concentration of oxygenated chemicals and moisture, its HHV is half that of heavy petroleum-derived oil. Pyrolysis parameters such as temperature, particle size, heating and residence time, feedstock type (hardwood, softwood, and herbaceous biomasses), and catalytic and non-catalytic pyrolysis have a major impact on the production of bio-oil (Lee et al., 2020; Oh et al., 2021).

The production and quality of bio-oil via pyrolysis are highly sensitive to operational parameters. Temperature dictates the thermal decomposition pathways of biomass components, with optimal bio-oil yields typically around 450–550 °C. Higher temperatures favor gas production and deoxygenation, while lower temperatures yield more char and aqueous fractions. (Guedes et al., 2018). Particle size influences heat transfer and secondary cracking reactions. Particles in the 0.5–1.4 mm range often maximize bio-oil yield and minimize water content (Aguilar et al., 2015). Rapid heating rates and short vapor residence times, which are common characteristics of fast and flash pyrolysis, enhance liquid yields (up to ~75 wt. %) by limiting char formation and secondary decomposition (Guedes et al., 2018; Jerzak et al., 2024; Oh et al., 2021; Talwar et al., 2025). Feedstock composition, hardwood, softwood, or herbaceous, affects bio-oil chemistry, with herbaceous materials often producing oils richer in acids and oxygenates (Carpenter et al., 2014). Catalytic pyrolysis (e.g., using zeolites or metal oxides) upgrades oil quality by cracking heavy oxygenates into lighter hydrocarbons, reducing acidity and oxygen content compared to non-catalytic processes (Nishu et al., 2020; Rahman et al., 2018; Reza et al., 2023; Sun et al., 2025).

3.1. Catalytic pyrolysis and reactor-design influences

Catalytic pyrolysis uses catalysts either inside the pyrolysis reactor (in-situ) or in a downstream vapor-upgrading step (ex-situ) to steer primary vapors away from highly reactive oxygenates (e.g., acids, aldehydes, sugars) toward more stable, energy-dense products (e.g., phenolics, aromatics, partially deoxygenated liquids), thereby reducing corrosivity and improving storage behavior (Brown, 2020; Sun et al., 2025). In-situ setups expose catalysts to biomass minerals/ash and char, often accelerating deactivation, while ex-situ upgrading decouples devolatilization and upgrading severity and could ease catalyst regeneration/operability at the expense of more reactor apparatus (Sun et al., 2025).

The yield–quality trade-off is largely determined by catalyst selection. Acidic zeolites (e.g., ZSM-5 family) usually encourage deoxygenation/aromatization but, through more vigorous cracking, can lower condensable yield to permanent gases and coke; metal/metal-oxide, and bifunctional catalysts can alter selectivity to particular pathways of oxygen removal (e.g., decarbonylation and decarboxylation, and in the presence of hydrogen, hydrogenation and stabilization coupled) (Shafaghat et al., 2024; Sun et al., 2025). Aiming to bypass coking and mineral poisoning, the most recent studies have concentrated on catalyst resilience, the upgrading approach of integrated staged upgrading (mild stabilization followed by more intense upgrading), and intentional manipulation of hot (and potentially active) vapor residence time to reduce secondary condensation before and polymerization to reduce polymerization before condensation (Brown, 2020; Shafaghat et al., 2024).

The application of pressurized pyrolysis and catalytic hydropyrolysis takes steps toward increased pressure (and in the case of hydropyrolysis, the addition of hydrogen), which may modify both the chemical kinetics and the mass transfer and provide the possibility of earlier stabilization of reactive fragments in the vapor phase and reduced downstream upgrading requirements. However, increased pressure may also provide longer effective vapor residence time and increased severity of secondary reactions (vapor removal and quenching are not well controlled) (Oh et al., 2021; Shafaghat et al., 2024).

It is the reactor design that will determine whether the catalytic/pressure advantages will yield consistent and repeatable yield and quality. Reactors designed for high heat transfer and short, controlled vapor residence times (characteristic of good fast pyrolysis systems) are usually good at preserving liquid yields because they limited the hot vapor cracking, whereas those designed to provide extended vapor contact times with the hot solids or walls, or those designed to provide delayed quenching are more likely to promote cracking and generate increased coke/char(Brown, 2020; Talwar et al., 2025).The newly developing microwave-assisted catalytic pyrolysis demonstrates that the combination of heating mode with catalyst/absorbent design can strongly determine selectivity and heating rates. However, it is still feedstock and reactor configuration dependent (Ke et al., 2024).

Reactor design includes both condensation and recovery: rapid quench and staged/fractional condensation increase product stability and inhibit secondary polymerization, while hot-vapor filtration minimizes aging and ash/char carryover (Lindfors et al., 2023; Pena-Vergara et al., 2025). Hence, catalytic/pressurized pyrolysis should be reported with catalyst location, vapor residence time, and quench/condensation strategy in addition to temperature and pressure (Brown, 2020).

3.2. Potential Feedstock Utilized in the Pyrolysis Process

Several materials, ranging from biomass to plastic waste, have demonstrated promising potential for conversion into bio-oil or char through the pyrolysis process. Lignocellulosic biomass (woody and herbaceous materials) has historically dominated pyrolysis research due to its abundance and relatively uniform composition. Many types of biomasses can be used to make bio-oil, including microalgae, municipal solid waste, animal manure, and various industrial by-products. Each of these has its opportunities and challenges (Gao et al., 2014; Hebuka & Iddphonce, 2023; Miao & Wu, 2004).

Microalgae are special because they have a lot of lipids (20-50% of their weight) and grow quickly. This means the bio-oil made from them has an energy value (31-36 MJ/kg) even higher than many lignocellulosic oils (Gao et al., 2014; Miao & Wu, 2004). However, microalgae have a lot of moisture (>60%), so they need to be dried before being converted into bio-oil, which can use a lot of energy unless waste heat is used (Miao & Wu, 2004). The high protein content in microalgae also means there's a lot of nitrogen in the bio-oil, which can lead to NO_x emissions when burned and can quickly deactivate catalysts used to upgrade the bio-oil. Macroalgae, like seaweed, are also being looked at for oil production because of their mineral content and the fact that they can be grown in seawater. However, their high salt content can cause problems in the reactors, like fouling and corrosion (J. J. Liu et al., 2022; Rony, 2024).

Municipal solid waste (MSW) and refuse-derived fuels (RDF) are materials being used to make bio-oil. They can take a mix of plastics, paper, and organic waste. Turn it into useful products. The amount of bio-oil produced from MSW can vary a lot (20-50% by weight). The waste often needs to be sorted and shredded before being processed (Chen et al., 2014; Pelagalli et al., 2024). Food and agricultural waste, like fruit peels and nut shells, have moisture and ash content, but the bio-oil produced from them can contain oxygenated acids that need to be stabilized (Agarwal, 2014; Pelagalli et al., 2024). Animal manure and sewage sludge have a lot of nitrogen and sulfur, so the bio-oil made from them doesn't have fuel properties unless special catalysts are used, which makes processing more complicated.

Industrial residues, like distillers' grains and paper sludges are available at low cost and can be used to make bio-oil. The amount of bio-oil produced (30-60% by weight) depends on how they've been treated and what minerals they contain (Ibitoye et al., 2023). Some biomass blends, like mixing wood chips with spent grain have been shown to produce bio-oil with properties like a more moderate oxygen content (35-45%) and higher energy value (Osman et al., 2023). Generally, there are several biomass materials that could be utilized for bio-oil production; however, quality issues of the fuel have remained a challenge to its commercial applications.

Moisture content plays a crucial quantitative role in determining pyrolysis efficiency and organic liquid yield.

Empirical studies demonstrate that increasing feedstock moisture reduces the organic liquid fraction almost linearly. For example, Eke et al. (2019) reported that increasing moisture from approximately 2.7 wt. % to 10 wt. % reduced the organic liquid yield from 19.6 wt. % to 15.2 wt. %—equivalent to a decline of roughly 0.60 wt. % liquid yield per 1 wt. % moisture increase.

This reduction occurs because moisture increases the energy required for heating and vaporization, prolongs residence time, and intensifies secondary cracking reactions, which collectively suppress condensable vapor formation (Fonseca et al., 2019).

These findings justify the widely accepted guideline that feedstock for fast pyrolysis should be conditioned to ≤10 wt. % moisture unless low-temperature waste heat or solar drying is available.

3.3. Effect of Temperature on Bio-Oil Yield and Quality

Bio-oil production is highly sensitive to reactor temperature, which controls the balance between volatilization and thermal cracking. The main role of temperature in biomass pyrolysis is to supply the heat needed to break the varied connections in the feedstock. Temperature directly affects calorific values, product distribution, and the rate of biomass decomposition (Toscano Miranda et al., 2021). Several studies have investigated how temperature affects the ultimate bio-oil output, demonstrating that greater yields are attainable at temperatures ranging from 450 to 550 °C. According to Kan et al. (2016), bio-oil yields can range between 50 and 70 wt.% at 400-600°C, with the highest yields at 500 °C due to excellent depolymerization kinetics and condensable vapor production as shown in Eq. 1. A study on rapid sawdust pyrolysis found a peak bio-oil output of 62 wt.% at 500 °C(Salehi et al., 2011). Sohaib et al. (2017) noted that pyrolysis of sugarcane bagasse occurs rapidly at 500 °C, producing modest amounts of gas and charcoal and yielding 60.4% bio-oil. Likewise, a study by Lin & Chen (2015) found that pyrolyzing sugarcane bagasse at 500 °C resulted in comparable bio-oil yields of 55% after 30 minutes of reaction.

$$\text{Biomass } (C_xH_yO_z) \xrightarrow{400-600^{\circ}C} \text{Bio-oil} + \text{Gases } (CO_2, CO, CH_4) \tag{1}$$

Temperature influences not only bio-oil yield but also its quality attributes. Between 450–550°C, oxygen content typically declines from ~42 wt.% to ~28 wt.%, while HHV increases from ~18 to 25–30 MJ/kg. This improvement results from enhanced decarboxylation and dehydration pathways. The water content of bio-oil also goes down from 25 wt.% to 7–10 wt.%, making the bio-oil uniform and stable. When the temperature is too high and above 550 °C,it can cause secondary cracking. This means the yield is lower, and lighter gases are produced. On the other hand, when the temperature is too low, below 400 °C, the bio-oil that is produced has a lot of oxygen in it and is not very stable.

Other studies show that the temperature change from 400 to 500 °C on the pyrolysis of rice husk improved bio-oil yield from 11.3% to 35.9% (Tsai et al., 2007). A similar study states that in a fixed-bed reactor, the ideal pyrolysis temperature for rice husks is between 300 and 450 °C (Biswas et al., 2017). When the temperature is above 450 °C, bio-oil production rapidly decreases, while at a temperature below 300 °C pyrolyze of rice husks becomes ineffective. It could therefore be confirmed that temperature exerts a stronger influence on yield than heating rate or residence time (Guedes et al., 2018).

Optimizing pyrolysis temperature within 450–550 °C is critical for maximizing bio-oil output. Experimental findings reveal that yields increase steadily up to approximately 475 °C for lignocellulosic feedstock such as nut shells, including groundnut and coconut shells, beyond which non-condensable gas production accelerates, and liquid yields decline (Pahnila et al., 2023; Suntorn Suttibak, 2013). This is also demonstrated in various other investigations, such as that conducted by Li et al. 2021,which demonstrates that when the temperature rises from 350 °C to 550 °C, non-condensable gas yields increase at the cost of liquid fractions. Similar investigations show that pyrolysis of Mimusopselengi increases bio-oil output from 18.3 wt. % at 300 °C to 34.1 wt. % at 500 °C (Maulinda et al., 2023a), whereas beechwood in an auger reactor obtains 53 wt. % at 500 °C (Campusano et al., 2024).

On a similar aspect, advanced response-surface methodologies identified an optimal setpoint of 535.96 °C for agricultural residues such as energy cane and Chinese tallow tree, achieving a record 75.14 wt.% bio oil with finely tuned reaction time and particle size parameters(Aguilar et al., 2015; Faisal et al., 2024; Wakatuntu et al., 2023).Also, palm oil industry wastes (empty fruit bunches, mesocarp fibers, and palm kernel shells) deliver among the highest yields, with fast and flash pyrolysis processes routinely reaching 75–80 wt. % bio-oil at temperatures between 500 and 550 °C under rapid heating rates and finely tuned reactor conditions (Abnisa et al., 2011; Pitoyo et al., 2022).Furthermore, woody biomasses, both softwoods (e.g., pine) and hardwoods (e.g., beech) in fluidized bed reactors, likewise follow this trend, producing 60–75 wt. % bio-oil at optimal temperatures near 525–550 °C before yields decline at higher temperatures (Heo et al., 2010; Jerzak et al., 2024).

In multiple process classifications, the rapid pyrolysis systems that work around 500 °C outdo slow (300-950°C) and intermediate spanning regimes in liquid yield production (Aboelela et al., 2023). Autothermal corn stover pyrolysis at 500°C, liquid yield is also high at 60 wt.%, which further confirms the high temperature 500 °C preference across different reactor designs (Polin et al., 2019). Further increase in temperature above the optimal range causes secondary cracking of the volatiles into CO, CO2, and light hydrocarbons, which reduces the yield of bio-oil(Li et al., 2021).The optimal yield of bio-oil during the pyrolysis process is achieved when the biomass composition (cellulose/hemicellulose-rich feedstocks), particle size (less than 1 mm), and fast pyrolysis conditions (temperature 450-550°C, heating rate above 100°C/s, less than 2 seconds residence time) are in the right proportions. The right feedstock and oxygen adjustment lower the secondary cracking and improves yield (Al-Rumaihi et al., 2022; Lachos-Perez et al., 2023). Given the production of bio-oil along a range of temperature conditions, the yields of bio-oil demonstrate a high range of 38–47 wt. % for the elemental composition of bio-oils oxygen. This elemental composition yields non-volatility, non-corrosiveness, and a high moisture content (~47 wt. %), high acidity (3.14–3.57 pH), and a low heating value (16.42–22.95 MJ/kg) (Kumar et al., 2022; Liu et al., 2011). The high acidity of bio-oil causes a problem of corrosiveness and contributes to the complications of handling and storage of bio-oil, as well as the phase separation. The presence of large numbers of carboxylic acids, phenols, ketones, and carbonyls (which are of high abundance) makes bio-oils thermally unstable and prone to polymerization, increased viscosity, and decreases the bio-oil quality during storage (Cai et al., 2019; Lachos-Perez et al., 2023). The high instability and abundance of oxygen in the bio-oil mean that a lot of post-production bio-oil upgrading, such as catalytic hydro-de-oxygenation, solvent blending, and / or alkaline treatments to decrease the amount of oxygen present and increase the stability and calorific value of bio-oils, are necessary to use bio-oils as a dropping fuel or as a feedstock for chemicals (Zhang et al., 2017).

Temperature and pressure clearly affect both yield and composition, but many studies still report them in isolation or without enough process detail to explain changes in fuel quality. Their effects are further influenced by heating rate, vapor residence duration, and feedstock qualities, which determine how much vapor cracks before being quenched and condensed (Fu et al., 2022; Xiong et al., 2018; A. Zhao et al., 2022). Particle size and feedstock moisture, for example, modulate heat transfer and phase change phenomena (Fonseca et al., 2019; Nelson et al., 2023) while the carrier gas flow rate and reactor design control the vapor sweep and quenching rates (Brassard et al., 2017; Supramono et al., 2019) and system pressure and condensation configuration determine the split between condensable and permanent gases (Cerciello et al., 2021; Rueangsan et al., 2023). Catalysts can shift product selectivity, but the direction of change depends on catalyst acidity, coking rate, and how quickly vapors are removed and quenched (Reza et al., 2023).

3.4. Feedstock Specific Temperature Sensitivities

Distinct biomass types exhibit unique optimal temperatures due to compositional differences, as shown in Table 2. The presented findings reveal how the optimal operating temperature contributes to enhancing various bio-oil characteristics for some biomass materials. For example, rice straw waste yields peak bio-oil at 550 °C (54.40 wt.%) but drops significantly at lower or higher temperatures (Shrivastava et al., 2021). Lignin-rich softwoods, exemplified by red oak, generate 28.7 wt. % phenolic oil at 500 °C under catalytic fractionation conditions (Elliott et al., 2015). Corn stover fast pyrolysis achieves 60 wt. % liquid yield at 500°C, highlighting its mixed carbohydrate-lignin matrix (Polin et al., 2019). Microwave-assisted pyrolysis of corn straw also peaks at 500 °C with a competitive 46.7 wt. % yield, demonstrating the feedstock–technology interplay (Zhao et al., 2021). Conversely, carbohydrate-dense Mimusopselengi favors moderate 500 °C conditions but delivers lower overall yields due to its high ash content (Maulinda et al., 2023a).

Table 2. Summary of Optimal Pyrolysis Conditions and Key Bio-oil Properties for Selected Biomass Feedstocks.

Biomass	Technology	Opt. Temp. (°C)	Peak Bio-Oil Yield (wt. %)	Key Bio-Oil Characteristics	References
Rice straw	Fluidized-bed fast pyrolysis	~500	43 - 50 wt. %	HHV: ~31 MJ/kg pH: ~2.4–2.8 Composition: high in phenols, furans, organic acids; water content ~7–10 wt. %	Pattiya & Suttibak, 2012
Red oak	Catalytic fractionation of CFP	~500	28.7 wt. % (phenolic oil)	Moisture: 17.3 wt. % Water-insoluble: 37.3 wt. % C: 65.6 wt. % (db) O: very low (≤0.8 wt. % acids)	Elliott et al., 2015
Corn stover	Fluidized-bed fast pyrolysis	~500	~60 wt. %	Water: 4.9–7.9 wt. % Acids: acetic 5.9 wt. %, propionic 7.3 wt. % Methoxyphenol: 0.61 wt. % HHV: ~18–20 MJ/kg	Mullen et al., 2010
Corn straw	Microwave-assisted pyrolysis	500	46.7 wt. %	Phenol content: 49.4 area % Major peaks: phenol 8.7 %, o-cresol 3.1 %, guaiacol 5.0 %, syringol 5.4 % Biochar catalyst: K-rich-char	Zhao et al., 2021
Mimusopselengi (Spanish cherry)	Fixed-bed pyrolysis (90 min)	500	34.13 wt. %	Density: 1.15 g/cm³ Viscosity: 1.84 cP pH: 4.41 HHV: 19.91 MJ/kg Composition: phenol-rich, but high acidity/cracking tar	Maulinda et al., 2023a

3.5. Effect of Temperature on Bio-Oil Quality

Multiple sources show that the temperature directly influences the yield and composition of bio-oils as well as stability and handling. Oil with elevated water content and low heating value is produced at low temperatures (<450 °C) and contains high quantities of acids, ketones, and oxygenates (Afrah et al., 2024; Farobie et al., 2022; Lyu et al., 2015). Oil produced at 450–550 °C contains a high concentration of aromatics and phenolics due to the cracking of lignin and the moderation of the ketone and acid fractions (Afrah et al., 2024; Fan et al., 2017; Maulinda et al., 2023a). Secondary cracking is dominant beyond 550°C and leads to a loss of quality and yield of bio-oil due to the increase of gaseous volatiles (Wang et al., 2016). The stability of bio-oils is compromised with a decrease in oxygen content as the temperature of bio-oils increases from ~42 wt. % at 400 °C to ~18 wt. % at 700 °C, and a calorific value increase is seen without further upgrading (Adegoke et al., 2021; Wang et al., 2016). Inhomogeneity and viscosity are both correlated to temperature; moderate temperatures (~500 °C) produced bio-oils with low viscosity and improved phasing, while high temperatures produced bio-oils that contain high volumes of water that negatively impact storage and are prone to extensive polymer cracking, negatively impacting pumpability (Cai et al., 2016; Maulinda et al., 2023a). For most fast-pyrolysis systems, 450–550 °C is the practical starting window for high liquid yields. Whether quality improves within that window still depends on feedstock minerals, vapor residence time, and the condensation train.

The studies show consistent results with thermal cracking of lignin and the resulting increase of phenolic and aromatic hydrocarbons, and the simultaneous decrease in concentration of ketones and organic acids at higher pyrolysis temperatures (≥500 °C). In Yunnan pine, ester and alcohol contents rose from ~8 % to ~20 % as temperature increased from 400 °C to 700 °C, while ketones and acids dropped from ~22 % to ~6 % (Wang et al., 2016). Studies report that at 300 °C, bio-oil contains predominantly fatty acids and aldehydes, whereas at 500 °C,the profile shifts toward phenol and catechol derivatives, indicating enhanced aromaticity (Maulinda et al., 2023a) as shown in Figure 1. Selective pyrolysis of corn straw yielded bio-oil with aromatic hydrocarbon content climbing from 43.8 wt % at 400 °C to 46.7 wt % at 500 °C, underscoring the temperature-driven boost in desirable monocyclic aromatics (Zhao et al., 2021). Table 3 further provides a summary of the effect of temperature change on various

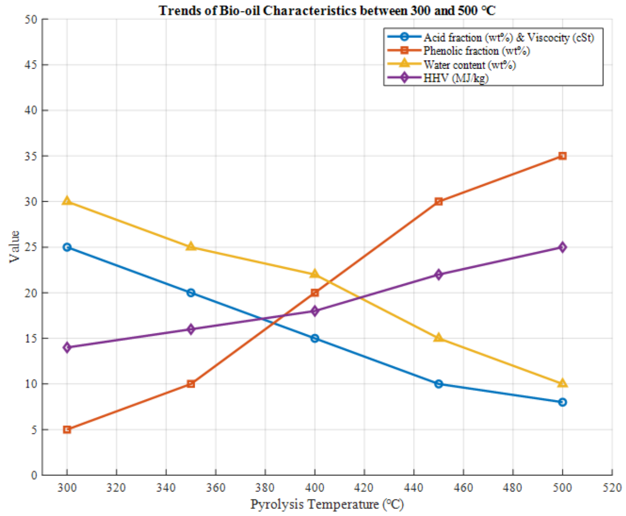

Figure 1. Trends in bio-oil characteristics based on pyrolysis temperature (300–500 °C).

Table 3. Effect of Pyrolysis Temperature on Key Bio-Oil Quality Parameters.

Parameter	**Low Temperature (<450°C)**	**Optimal Range (450–550°C)**	**Improvement**	**Key Benefits**	**References**
Oxygen Content	~42 wt.%	~28 wt.%	14 wt.% absolute decrease	Higher energy density, lower corrosivity	(Lachos-Perez et al., 2023; Vilas-Boas et al., 2024)
Higher Heating Value (HHV)	~18 MJ/kg	25–30 MJ/kg	7–12 MJ/kg gain	Competitive with heavy fuel oils	(Awad et al., 2024; Guedes et al., 2018)
Water Content	20–25 wt.%	7–10 wt.%	Halved (50% reduction)	Mitigates phase separation, reduces pretreatment	(Paenpong et al., 2018; Pitoyo et al., 2022)
Viscosity	~15 cP	8–10 cP	30–50% reduction	Enhanced pumpability and blending	(Lachos-Perez et al., 2023; Rowland et al., 2024)
Aromatic/Phenolic Compounds	Baseline	Up to 40% higher	40% increase relative to low temps	Boosts catalytic upgrading and end-product yield	(Al-Rumaihi et al., 2022; Li et al., 2012)
Recommended Reactor Types	Any (lower heat transfer demand)	Fluidized-bed, spouted-bed	-	-	

bio-oil characteristics. It is evidenced that when the pyrolysis process operates within the optimal temperature range (450 – 550 °C), properties of the produced bio-oil are enhanced.

Table 4 shows the chemical composition of bio-oils derived from diverse biomass feedstocks across pyrolysis temperatures ranging from 300–700 °C. The results in Table4 show that temperature shifts the balance between oxygenates and aromatics, but the direction and magnitude vary by feedstock and reactor configuration. Research on lignin decomposition notes that the main breakdown happens between 400 and 600 °C, where ether links break, releasing compounds. The highest yields of phenolics often occur at 450 °C. Beyond this temperature, further breakdown limits increase (Lu & Gu, 2022). Studies on Yunnan pine show that at temperatures, the carbon-number distribution shifts towards lighter C_5–C_{10} species, showing that heavy lignocellulosic chains break down further (Wang et al., 2016). Overall,500°C seems to be the temperature for maximizing aromatics and phenolics while keeping enough liquid for further use.

Table 4. Chemical Composition of Bio-Oils Derived from Various Biomass Feedstocks at Different Pyrolysis Temperatures.

Biomass Feedstock	Pyrolysis Temp (°C)	Major Compounds Identified	Notable Composition Changes with Temperature	Aromatic/Phenolic Content (%)	Reference
Yunnan pine	400–700	Esters, alcohol, ketones, acids	**Esters & alcohols:** ↑ from ~8 % to ~20 %. **ketones & acids:** ↓ from ~22 % to ~6 %	Moderate to High at 500–600 °C	(Wang et al., 2016)
Mimusopselengi	300 → 500	Fatty acids, aldehydes → phenol, catechol derivatives	**At 300 °C:** fatty acids dominate; **At 500 °C:** strong shift to phenolics	High at 500 °C	(Maulinda et al., 2023a)
Corn straw	400 → 500	Monocyclic aromatics, phenolics	Aromatic hydrocarbons ↑ from 43.8 wt. % to 46.7 wt. %	High, peaking near 500 °C	(Zhao et al., 2021)
Red oak (softwood)	~500	Guaiacols, syringols, phenol derivatives	High lignin → high phenolic oil (~28.7 wt. %) under catalytic pyrolysis	Very High	(Kawamoto, 2017; Lu & Gu, 2022)
Corn stover	~500	Acetic acid, propionic acid, and methoxyphenols	**Oxygenates dominate;** modest aromatic content due to mixed carbohydrate–lignin	Moderate	(Wang et al., 2019)
Rice straw	~500–550	Phenol, furfural, levoglucosan, acids	Peak bio-oil yield (~54 wt. %) at 550 °C with higher phenolic and furan content	Moderate to High	(El-Sayed, 2025)
Switchgrass	400 → 550	Ketones, acids → phenolics, hydrocarbons	**Increasing aromatics & hydrocarbons;** acids/ketones decline with temperature	Moderate to High	(He et al., 2009)
Wheat straw	400 → 550	Phenols, aldehydes, acids	**Higher phenol content at 500 °C;** aldehyde and acid fractions decrease	Moderate	(Ateş &Işikdağ, 2008)

3.5.1. Effect of Pyrolysis Temperature on Oxygen Content and Stability of Bio-oil

Table 3 shows that oxygen content is a factor in determining bio-oil stability, acidity, and energy value. Tests show that oxygen content drops significantly from 41.77 ± 0.67 wt % at 400 °C to 18.32 ± 0.60 wt % at 700 °C. This decrease is linked to an increase in energy value from 22.67 ± 0.68 to 31.36 ± 0.70 MJ/kg(Wang et al., 2016). Similar trends were observed in Swietenia macrophylla wood pyrolysis with oxygen content around 42.6 % at 450 °C and hydrogen 6.6 % (Gouda et al., 2017). Using zeolite catalysts in pyrolysis at around 500 °C reduces oxygen content to below 35 wt. % and improves stability by reducing reactive oxygen compounds (Rowland et al., 2024). Storage stability tests on coconut-core bio-oil indicate phase separation begins after ~4 days at 40 °C, highlighting the need to control oxygenates that catalyze polymerization (Duarte et al., 2016). Upgraded fast pyrolysis oils (Stabilized Deoxygenated Pyrolysis Oil) with ∼5 wt.% oxygen demonstrates excellent long-term stability, underscoring the benefit of deoxygenation (Ohra-Aho et al., 2024). Operating around 500 °C is essential for Mimusopselengi and similar biomasses to reduce oxygen content from ~40 wt % toward 25–30 wt %, dramatically improving thermal and storage stability, though additional upgrading (esterification/hydrogenation) is recommended for applications requiring fuel-grade durability (Maulinda et al., 2023a).

3.5.2. Effect of Pyrolysis Temperature on Viscosity and Homogeneity of Bio-oil

Viscosity governs handling, atomization, and pipeline flow. All viscosity values reported in this review are standardized to centipoise (cP) measured at 40°C, while all pressure values are expressed in megapascals (MPa) to maintain consistency across studies. The study conducted on the pyrolysis of Mimusopselengi reports bio-oil viscosities between 1.31–1.60 cP at 40 °C, with higher pyrolysis temperatures yielding slightly increased viscosities due to enhanced polymerization of aromatics and phenolics (Maulinda et al., 2023a). Conversely, fast pyrolysis oils from beech wood show that higher reaction temperatures during pyrolysis translate into more viscous oils (due to heavier phenolic oligomers), though these viscosities remain Newtonian and decrease rapidly (>90 %) when heated from 30 °C to 80 °C during use (Cai et al., 2016).Research confirms that at low pyrolysis temperatures, bio-oil has high moisture and low viscosity (<1.3 cP), whereas at 500 °C, moisture content falls and viscosity rises, improving spray characteristics for combustion (Maulinda et al., 2023a). Homogeneity is impacted by phase separation: water and light oxygenate can form an aqueous layer if not removed, but oils produced at 500–550 °C exhibit stable single-phase behavior for days under ambient conditions (Duarte et al., 2016). Thus, controlling pyrolysis temperature within a moderate range (450 –550) yields bio-oils with optimal viscosity and homogeneity for direct use or minimal upgrading.

3.6. Effects of Pressure Conditions on the Yield and Quality of Bio-Oil

Pressure conditions are pivotal in determining the yield and quality of bio-oil from biomass pyrolysis. Both atmospheric (0.101 MPa) and vacuum (<0.010 MPa) pressures can be used for pyrolysis (Lachos-Perez et al., 2023). Compared to air pyrolysis, vacuum pyrolysis offers several advantages: it lowers vapor residence time and prevents secondary reactions such as cracking and repolymerization, and permits the removal of the main components generated during the breakdown of biomass (Lachos-Perez et al., 2023). Although vacuum pyrolysis can improve bio-oil quality, it may also generate large volumes of pyrolytic water (Pahnila et al., 2023).

High moisture level lowers the bio-oil energy density and flame temperature, which might cause ignition problems (Pahnila et al., 2023). A concise overview of the three pressure regimes shows that operating at atmospheric pressure (≈0.1 MPa) in fast pyrolysis typically maximizes bio-oil yields (45–75 wt.%) by balancing rapid vapor removal and limited secondary cracking (Rasaq et al., 2021). Raising pressure to moderate levels (1–5 MPa) can increase devolatilization and shift product distribution, but effects are feedstock and reactor-dependent. Some studies report up to a 15 % increase in yield, while others note substantial decreases once polymerization and char formation dominate (Niemelä et al., 2021; Rasaq et al., 2021). Conversely, sub-atmospheric (vacuum) pyrolysis (0.05–0.2 MPa) can suppress secondary reactions and improve oil quality by enriching phenolic and aromatic fractions by preserving lignin-derived monomers, improves thermal stability and inhibits polymerization during storage, lowers overall oxygen content by about 5–10 wt.%, lowers total acid number, raises higher heating value by 1–3 MJ/kg, lowers water content by 5–8 wt.%, and lowers viscosity by 20–40 %but often at the expense of overall yield and with higher energy costs(Niemelä et al., 2021; Rasaq et al., 2021).

3.6.1. Pyrolysis at Atmospheric Pressure

Pyrolysis at atmospheric pressure (≈0.1 MPa) remains the most widely deployed mode due to simplicity and cost-effectiveness. Typical fluidized-bed fast pyrolysis at 450–550 °C yields between 45% and 75% bio-oil by weight, depending on feedstock moisture and composition (Inayat et al., 2022; Raza et al., 2021). Entrained-flow and ablative reactors under these conditions report yields of 50–65 % for lignocellulosic biomass such as poplar and pine sawdust (Inayat et al., 2022; Struhs et al., 2022). Low heating values (15–20 MJ/kg) and a high-water content (15–30 wt.%) are the results of the resultant oils, which usually contain 25–40 wt.% oxygenated species (acids, ketones, and phenolics) (Hernando et al., 2021; Inayat et al., 2022). Heat transfer and reactor design are crucial. While fixed beds experience temperature gradients and produce lower yields (~45%) under the same conditions, fluidized beds minimize secondary cracking and char formation by achieving uniform temperature profiles and rapid vapor removal (Bridgwater, 2012). Pienihäkkinen et al. (2022) found that modest pressure variations (±0.02 MPa) in atmospheric regimes had minimal influence on vapor residence periods, making this technique suitable for scaling up.

3.6.2. Elevated Pressure Pyrolysis

Operating at atmospheric pressure (1–20 MPa) can improve gas–solid interactions and enable deeper devolatilization. Moderate pressure increase (1–3 MPa) has shown a rise of bio-oil yields by up to 10–15 % relative to atmospheric runs, attributed to suppressed vapor condensation and improved heat transfer (Wang et al., 2023). Beyond ~5 MPa, secondary cracking and polymerization are intensified, leading to an increase of char and water formation, reducing bio-oil yields significantly, e.g., from 44.97 % to 20.24 % when pressure rises to ~10 MPa (Xu & Li, 2017). Hydro pyrolysis under hydrogen at 5–20 MPa yields oils with lower oxygen content (<20 wt. %) and improved stability, with bio-oil yields in the 65–75 % range, though requiring high-strength reactors and hydrogen supply (Raza et al., 2021).

3.6.3. Sub-Atmospheric Pressure Pyrolysis

Under vacuum pyrolysis (0.05–0.2 MPa), the evaporation is enhanced, diminishing secondary cracking, and the resultant oils are characterized by a lower tar content and acidity. A significant low-pressure chemical shift is the abundance of monocyclic aromatic hydrocarbons. For instance, maximum bio-oil yield (55 %) was obtained from ablative vacuum pyrolysis of tobacco residues at 600 °C under ~0.05 MPa showing high heating value and good chemical composition such as alkanes and aromatics (Khuenkaeo et al., 2021). However, most vacuum systems are returning yields of 40–60 %, frequently slightly below their atmospheric-level equivalents, because of losses to non-condensable gases and difficulties in capturing vapor (Raza et al., 2021). Energy requirements to sustain vacuum pressure (s) may lead to high operational costs if not combined with waste heat utilization (Raza et al., 2021). In general, vacuum pyrolysis gives better quality oils at the expense of lower yields and higher processing energy.

3.6.4. Effects of Pressure on Bio-Oil Quality

Recent controlled studies demonstrate that increasing pressure above atmospheric pressure (0.1 MPa) to moderate pressures of around 0.5–2 MPa has a dramatic effect on bio-oil quality. At 0.5 MPa, oxygen content is reduced from 45 wt. % to 26 wt. %, and HHV increases from 27.8 to 31.4 MJ/kg, corresponding to an enhancement in13% (Wang et al., 2021).

Storage stability as well is greatly enhanced: the time to phase separation goes from 7 days out to ~10 days, an improvement of about 40% under the conditions used here, due to less reactive oxygenates (Rowland et al., 2024).

These influences demonstrate that pressure is a key dimension for the control of pyrolysis in addition to temperature conditions.

High-pressure pyrolysis is an effective process to upgrade the quality of bio-oil (reduce oxygen and water content, enrich caloric power, saturate storage properties). At elevated pressures (0.5 – 13.8 MPa), increased secondary reactions mixing decarboxylation and polymerization, result in an elemental composition shift toward lower O/C and higher H/C ratios, increasing HHV from 18–21 MJ/kg to over 30 MJ/kg at pressured runs (Li et al., 2015; Rasaq et al., 2021). Whereas hydrotreatment at 10 -13.8 MPa lowers the oxygen level of catalytic fast pyrolysis oil from 35-50 wt. % to 0.1–11 wt. % (Iisa et al., 2017; Rowland et al., 2024), storage stability requires oxygen levels below ~20 wt.%. Beyond this value, a fast growth of viscosity results from polymerization (Rowland et al., 2024). At the same time, pressure facilitates aromatic and polycyclic hydrocarbons formation, with a transition from pyrogenetic oil (18% of the bio-oil) to gasoline-range aromatics (up to 35%) and suppression of light oxygenates, though an increase in phenolics can also function as chemical platform for CCRs., expanding potential applications from hybrid fuels to chemical platforms (Baehr et al., 2024; Osman et al., 2023). Physically, the bio-oil prepared at 0.5 MPa has a water content of 10–15 wt. %, which is a dramatic decrease over the bio-oil obtained at 0.1 MPa, 20–30 wt. %. Furthermore, at the same pressure, bio-oil is generated with densities close to 1.05 g/mL and viscosities of about 180 cP that are much lower than their atmospheric values (300–500 cP), which enables pumping and storing of bio-oil (Cerciello et al., 2021; Wang et al., 2021). Typically, simply varying the process pressure, particularly in conjunction with hydrogen or catalytic beds, provides a feasible route to produce higher-stability, higher-energy-density bio-oils for further upgrading or as a fuel product. Furthermore, the bio-oils have relatively strong acidic characteristics from organic acids (e.g., acetic acid and formic acid), having a low pH (usually 2–4) that may lead to corrosion control problems and catalyst effectiveness in storage and processing facilities(Zheng & Wei, 2011).

Moreover, pyrolysis pressure has shown significant effects on oxygen removal and bio-oil stability improvement. It is reported in studies that high oxygen (about 35–50 wt. %) may negatively affect the mechanical properties and fatigue performance of Mg alloy. High nitrogen (1-3 wt. %), oxygen (30–43 wt. %) amounts in atmospheric FP oils lead to low heating values (18–21 MJ/kg) and high acidity (Total Acid Number, TAN >80 mg KOH/g)(Li et al., 2015; Pahnila et al., 2023). Increased pressures (≥0.5 MPa) promoted secondary cracking, decarboxylation, and polymerization reactions leading to the CO and CO_2 elution of de-oxygenates, causing the oxygen content of FP to be reduced by 20–40% compared with atmospheric pressures and increasing HHV values by 15–30%. As reported from (Baehr et al., 2024; Wang et al., 2021) Fast pyrolysis at 0.5 MPa reduces the Oxygen contents to 45 wt. % to 26 wt. %, HHV increased from 27.75 to 31.40 MJ/kg, and the viscosity reduced by ~40%. In catalytic fast pyrolysis, depending on the hydro processing Oils at a pressure of 10–13.8 MPa are produced with Oxygen contents of 0.08–11 wt. %, with calorific values of >35 MJ/kg and TAN <10 mg KOH/g was found (Iisa et al., 2017; Rowland et al., 2024). Accelerated aging studies show that oils >20 wt. % O2 experience a rapid increase in η and gel formation, while those below this limit show little increase in viscosity over 24 h at 100 °C (Rowland et al., 2024). In addition, pressing treatments lower the water content of 25–30 wt. % (at 0.1 MPa) to 10–15 wt. %, which restricts hydrolytic polymerization, and increases thermal and storage stability (Cerciello et al., 2021; Pienihäkkinen et al., 2022). In general, higher pressures increase the partial vapor pressure, are conducive to deoxygenation, and tend to induce changes of atomic ratios (O/C, H/C) towards those of petroleum crudes in bio-oil, yielding a more stabilized bio-oil that can be blended/pipelined for upgrading or long-term storage.

3.7. Interplay Between Temperature, Pressure, Feedstock Composition, and Bio-Oil Stabilization

The yield and quality of bio-oil are determined by temperature, pressure, and feedstock composition. Temperature influences primary depolymerization and thermal cracking. Pressure affects effective vapor residence time and secondary vapor-phase reactions. Feedstock composition includes lignin-derived phenolics, ash, alkali-driven catalytic cracking, char, and moisture-driven dilution and phase behavior. Under similar heating and quench conditions, higher pressure can alter product distributions and liquid composition by boosting secondary reactions. Therefore, we should consider the effects of pressure in relation to residence time and condensation design rather than as a separate factor (Cerciello et al., 2021; Pienihäkkinen et al., 2022). Hydrogen-assisted operation, such as hydro pyrolysis and catalytic hydro pyrolysis, can also change these pathways. It does this by stabilizing reactive fragments and promoting deoxygenation routes. However, outcomes still depend on temperature, hydrogen partial pressure, and catalyst resistance to coking and mineral poisoning (Ma et al., 2024; Oh et al., 2021; Shafaghat et al., 2024). Blending feedstock can offer another advantage by providing in-situ hydrogen radicals. For example, co-pyrolysis of corn stover with polypropylene boosted oil yield and lowered oxygenates compared to using biomass alone (Wu et al., 2020).

Since temperature, pressure, and feedstock interactions manage oxygen functionality and solids carryover into the collected liquid, we should view stabilization as a staged, system-level approach. Process-level stabilizing strategies include quick quench, staged or fractional condensation, and hot-vapor filtering and particle removal, which assist in preventing secondary polymerization and phase instability in the hot vapor zone (Brown, 2020; Pena-Vergara et al., 2025). Post-production stabilization focuses on addressing remaining reactivity and storage aging. This is often monitored with accelerated aging and carbonyl-based metrics. It can advance from modest stabilization to deeper hydro treatment when fuel-like properties are required (Black & Ferrell, 2020; IEA Bioenergy Task 34, 2024). Recent evidence from long-term storage of stabilized and deoxygenated pyrolysis oils suggests that reducing oxygen content and managing reactive species can help preserve fuel and blend properties over extended storage periods (Ohra-Aho et al., 2024).

4. Future Prospect

Pyrolysis of biomass is a method that could be used for the production of sustainable biofuels and for the mitigation of fossil CO_2 production. Using the 2023 predictions for fossil CO_2 production (37.4 Gt) (Jerzak et al., 2024), there is a clearly established need for the development of renewable methods. The bio-oil yield from a pyrolysis process tends to be site and feedstock-dependent. Liquid oil yield (after accounting for the production of char and gas) has been recorded at 9–40.6% (with ~41.3% char and ~12–28% gas) (Osman et al., 2023). Lignocellulosic feedstock (e.g., straw and wood) tends to give more favorable results (Aboelela et al., 2023), and, in the case of fast pyrolysis, yields ~60–75% liquid. The yields from wet or algal biomass tend to be lower as a result of the relatively high amounts of moisture and ash. The optimum feedstock formulation is still the subject of ongoing research and will include all biomass sources (lignocellulosic, algal, and agricultural residue). For example, the co-pyrolysis of biomass and plastic or hydrogen donor substances has been shown to have synergistic effects in terms of useful oil production (Hebuka & Iddphonce, 2023; Jerzak et al., 2024; Osman et al., 2023). Also of importance is the fact that certain by-products of pyrolysis (e.g., biochar) have positive climate effects by helping to sequester ∼2.7 t CO_2/t char (Osman et al., 2023).

There have also been significant improvements in the past few years, regarding the design of new reactors, the use of new methods of heating, and the development of new catalytic process which all serve to improve the yield and the quality of the bio-oil produced. Fast pyrolysis in fluidized-bed reactors yields 50–75 wt. % with optimized heating rates ($>10^4$ °C/s) at ~500 °C (Jerzak et al., 2024). With designed absorbents and catalysts, microwave catalytic pyrolysis achieves efficient volumetric heating, with yields up to 65 wt. % at 480–490 °C with vacuum (Ke et al., 2024). Inductive heating of fluidized bed achieves uniform rapid heating, reduces residence time and secondary cracking, and pilot studies report yields increases of 10–20% and lower emissions (Yan et al., 2024). Along with inductive heating, hybrid flow chemistry has made continuous high-temperature high-pressure pyrolysis simple to upscale (Kirschning et al., 2012).

Catalysts and additives have also been essential to enhance yields and modify the composition of the oils. Zeolite catalysts enhance the cracking of heavier oxygenates, which may increase hydrocarbon constituents but also may lower total oil yield (Lachos-Perez et al., 2023). Oxygen, and the content of the water, along with viscosity, combustibility, and stability can be improved through viscosity, CaO, and proprietary catalysts of pyrolysis which are designed to be catalytic (Inayat et al., 2022). The rotating-cone, auger, and plasma reactors show improved heat transfer and solids handling with pilot yields of up to 65 wt. % and continuous operation potential (Jerzak et al., 2024). Electrified heating, such as distributed resistive and microwave heating, offers new possibilities for improved sustainability as they can utilize renewable electricity (Yang et al., 2024).

Another novel method is high-pressure pyrolysis. Operating at elevated pressures with rapid heating can improve yields and alter the product distribution towards greater amounts of the desirable condensable oils (Rasaq et al., 2021). In practice, the adjustment of temperature as well as the vapor residence time is critical, and optimal yields of oils are typically within the range of approximately 450 – 550 °C (Lachos-Perez et al., 2023).

The economic feasibility and sustainability of pyrolysis systems can be significantly improved through the Integration of Renewable Thermal Energy and Waste-Heat Recovery. Direct heating of pyrolysis reactors by concentrating solar-thermal collectors such as Fresnel lens, parabolic dish, and heliostat fields has been able to reduce the fossil energy requirements (Ke et al., 2024). In addition, the energy recovered from the combustion of non-condensable gases or char can also be used for pre-drying of biomass feedstocks, significantly reducing drying-related energy penalties (Inayat et al., 2022).

All techno-economic analyses, demonstrate that incorporating pyrolysis with solar thermal or process waste heat reduces the operational cost, improves energy return on investment (EROI), and reduces the net greenhouse gas emissions over the life of the project (Sorunmu et al., 2020).

Future efforts should emphasize supported integrated biorefinery, designs, and policies. Important fields of focus should be the optimization of hybrid reactor designs, e.g., fast and slow pyrolysis stages (Jerzak et al., 2024); the design of new catalysts from renewable resources for the selective upgrading of vapors (Jerzak et al., 2024); the enhanced co-pyrolysis of a wider range of feedstocks, in particular, plastic and food waste, to improve yield and waste valorization (Jerzak et al., 2024). Techno-economic and life cycle analysis are foundational studies that demonstrate that pyrolysis becomes more feasible with scale and process optimization (Jerzak et al., 2024; Osman et al., 2023). Keeping focus on environmental sustainability, for example, microwave- or plasma-assisted pyrolysis can provide innovative ways to improve operational and energy efficiency and reduce emissions (Jerzak et al., 2024). Furthermore, policy and international collaboration will fuel the streamlining of the process. Subsidies for low-carbon fuels and harmonization of standards will boost the commercialization of pyrolysis technologies (Jerzak et al., 2024). In conclusion, the future outlook for biomass pyrolysis encompasses improved reactor systems, innovative catalysts, comprehensive techno-economic analyses, and encouraging policies that all utilize the diversity of feedstocks to increase both the quantity and quality of bio-oil produced (Jerzak et al., 2024; Osman et al., 2023).

5. Conclusion

Biomass pyrolysis is pivotal for sustaining energy across the world, aiding in the decarbonization of transportation and industries, and completing the carbon cycle. This review shows that the most dominant pyrolysis technique remains the atmospheric pressure biomass pyrolysis, and this stems from the simplicity and the cost-effectiveness of the process.

For the process to be controlled successfully, optimal operating temperatures of between 450 and 550 degrees Celsius are required, and at this range, between 45% and 75% (depending on evaporative moisture and biomaterial composition) is achievable bio-oil yield by weight. Most studies on this range also tend to report overall improvement in bio-oil quality (i.e., reductions of oxygen and water content and increases in higher heating value; HHV), and this, while reducing, is not sufficient to eliminate the need for downstream stabilization and upgrading.

The pressure gives an additional control lever that could steer quality. Moderate pressurization is often linked to more effective deoxygenation and less acidity (therefore better upgradability), although results are highly dependent on reactor configuration and vapor management. In general, the greatest yield quality increases are seen when temperature and pressure are harmonized with the reactor's hydrodynamics and condensation approach. While many studies have looked at temperature and pressure effects in isolation, the literature is particularly deficient in the research of the interaction of the two, particularly on bio-oil, and thus this is of importance in future research.

There is a lack of T-P studies that are of yield and major quality indicators of T-P studies, true pressure effects without the confounding influence of residence time, quench, and reactor design, under- reporting of reactor design/ condensation details, and a lack of evaluation of long- duration, scale-relevant evaluation of operability, fouling/corrosion, catalyst deactivation, and cost.

Future work should aim for the construction of integrated T-P and residence time operating maps with appropriate reporting, achievement of a sufficient quantity of comparable baseline studies in the domain of pressured/catalytic (and H_2-assist) pyrolysis, improvement of the design of the quenching unit of the reactor to minimize the occurrence of secondary reaction, establishment of quantifiable limits of the desired stabilization/upgrading, and building harmonized datasets for AI/ML-enabled optimization and transferable scale-up guidance.

References

Abnisa, F., Wan Daud, W. M. A., & Sahu, J. N. (2011). Optimization and characterization studies on bio-oil production from palm shell by pyrolysis using response surface methodology. Biomass and Bioenergy, 35(8), 3604–3616. https://doi.org/10.1016/J.BIOMBIOE.2011.05.011

Aboelela, D., Saleh, H., Attia, A. M., Elhenawy, Y., Majozi, T., &Bassyouni, M. (2023). Recent Advances in Biomass Pyrolysis Processes for Bioenergy Production: Optimization of Operating Conditions. Sustainability 2023, Vol. 15, Page 11238, 15(14), 11238. https://doi.org/10.3390/SU151411238

Adegoke, I. A., Ogunsanwo, O. Y., & Ige, A. R. (2021). Bio-Fuel Properties and Elemental Analysis of Bio-Oil Produced from Pyrolysis of Gmelina Arborea. Acta Chemica Malaysia, 5(1), 38–41. https://doi.org/10.2478/acmy-2021-0006

Afrah, B. D., Riady, M. I., Arsadha, J. P., Rimadhina, R., Cundari, L., & 'izzah, R. Z. (2024). Effect of Pyrolysis Temperature and Biomass Composition on Bio-Oil Characteristics. Ecological Engineering & Environmental Technology, 25(3), 264–274. https://doi.org/10.12912/27197050/181152

Agarwal, M. (2014). An Investigation on the Pyrolysis of Municipal Solid Waste. Ph. D. Thesis, RMIT University, Australia

Agblevor, F. A., Mante, O., McClung, R., & Oyama, S. T. (2012). Co-processing of standard gas oil and biocrude oil to hydrocarbon fuels. Biomass and Bioenergy, 45, 130–137. https://doi.org/10.1016/J.BIOMBIOE.2012.05.024

Aguilar, G., D. Muley, P., Henkel, C., &Boldor, D. (2015). Effects of biomass particle size on yield and composition of pyrolysis bio-oil derived from Chinese tallow tree (TriadicaSebifera L.) and energy cane (Saccharum complex) in an inductively heated reactor. AIMS Energy, 3(4), 838–850. https://doi.org/10.3934/ENERGY.2015.4.838

Al-Rumaihi, A., Shahbaz, M., Mckay, G., Mackey, H., & Al-Ansari, T. (2022). A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. Renewable and Sustainable Energy Reviews, 167, 112715. https://doi.org/10.1016/J.RSER.2022.112715

Ateş, F., &Işikdağ, M. A. (2008). Evaluation of the role of the pyrolysis temperature in straw biomass samples and characterization of the oils by GC/MS. Energy and Fuels, 22(3), 1936–1943. https://doi.org/10.1021/EF7006276

Awad, M. I., Makkawi, Y., & Hassan, N. M. (2024). Yield and Energy Modeling for Biochar and Bio-Oil Using Pyrolysis Temperature and Biomass Constituents. ACS Omega, 9(16), 18654–18667. https://doi.org/10.1021/acsomega.4c01646

Baehr, C., Meyer Muñoz, T., Raffelt, K., & Dahmen, N. (2024). Viscosity Reduction of Fast Pyrolysis Bio-Oil by Using CO2 as an Additive. Energy and Fuels, 38(7), 6012–6019. https://doi.org/10.1021/acs.energyfuels.3c04201

Basile, L., Tugnoli, A., Stramigioli, C., & Cozzani, V. (2014). Influence of pressure on the heat of biomass pyrolysis. Fuel, 137, 277–284. https://doi.org/10.1016/J.FUEL.2014.07.071

Biswas, B., Pandey, N., Bisht, Y., Singh, R., Kumar, J., & Bhaskar, T. (2017). Pyrolysis of agricultural biomass residues: Comparative study of corn cob, wheat straw, rice straw and rice husk. Bioresource Technology, 237, 57–63. https://doi.org/10.1016/J.BIORTECH.2017.02.046

Black, S., & Ferrell, J. R. (2020). Accelerated aging of fast pyrolysis bio-oil: a new method based on carbonyl titration. RSC Advances, 10(17), 10046–10054. https://doi.org/10.1039/d0ra00046a

Brassard, P., Godbout, S., & Raghavan, V. (2017). Pyrolysis in auger reactors for biochar and bio-oil production: A review. Biosystems Engineering, 161, 80–92. https://doi.org/10.1016/J.BIOSYSTEMSENG.2017.06.020

Bridgwater, A. V. (2012). Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy, 38, 68–94. https://doi.org/10.1016/J.BIOMBIOE.2011.01.048

Brown, R. C. (2020). Heterodoxy in Fast Pyrolysis of Biomass. Energy & Fuels, 35(2), 987–1010. https://doi.org/10.1021/acs.energyfuels.0c03512

Cai, J., Banks, S. W., Yang, Y., Darbar, S., & Bridgwater, T. (2016). Viscosity of Aged Bio-oils from Fast Pyrolysis of Beech Wood and Miscanthus: Shear Rate and Temperature Dependence. Energy and Fuels, 30(6), 4999–5004. https://doi.org/10.1021/ACS.ENERGYFUELS.6B00640

Cai, W., Kang, N., Jang, M. K., Sun, C., Liu, R., & Luo, Z. (2019). Long term storage stability of bio-oil from rice husk fast pyrolysis. Energy, 186. https://doi.org/10.1016/J.ENERGY.2019.115882

Campusano, B., Jabbour, M., Abdelouahed, L., Mignot, M., Devouge-Boyer, C., &Taouk, B. (2024). Improvement of Properties of Bio-Oil from Biomass Pyrolysis in Auger Reactor Coupled to Fluidized Catalytic Bed Reactor. Processes 2024, Vol. 12, Page 2368, 12(11), 2368. https://doi.org/10.3390/PR12112368

Carpenter, D., Westover, T. L., Czernik, S., & Jablonski, W. (2014). Biomass feedstocks for renewable fuel production: a review of the impacts of feedstock and pretreatment on the yield and product distribution of fast pyrolysis bio-oils and vapors. Green Chemistry, 16(2), 384–406. https://doi.org/10.1039/C3GC41631C

Cerciello, F., Apicella, B., Russo, C., Cortese, L., & Senneca, O. (2021). Effects of pressure on lignocellulosic biomass fast pyrolysis in nitrogen and carbon dioxide. Fuel, 287, 119604. https://doi.org/10.1016/J.FUEL.2020.119604

Chen, D., Yin, L., Wang, H., & He, P. (2014). Pyrolysis technologies for municipal solid waste: A review. Waste Management, 34(12), 2466–2486. https://doi.org/10.1016/J.WASMAN.2014.08.004

Czernik, S., & Bridgwater, A. V. (2004). Overview of applications of biomass fast pyrolysis oil. Energy and Fuels, 18(2), 590–598. https://doi.org/10.1021/ef034067u

Duarte, S. J., Lin, J., Alviso, D., & Rolón, J. C. (2016). Effect of Temperature and Particle Size on the Yield of Bio-oil, Produced from Conventional Coconut Core Pyrolysis. International Journal of Chemical Engineering and Applications, 7(2), 102–108. https://doi.org/10.7763/IJCEA.2016.V7.551

Eke, J., Onwudili, J. A., & Bridgwater, A. V. (2019). Influence of Moisture Contents on the Fast Pyrolysis of Trommel Fines in a Bubbling Fluidized Bed Reactor. Waste and Biomass Valorization 2019 11:7, 11(7), 3711–3722. https://doi.org/10.1007/S12649-018-00560-2

Elliott, D. C., Wang, H., Rover, M., Whitmer, L., Smith, R., & Brown, R. (2015). Hydrocarbon Liquid Production via Catalytic Hydroprocessing of Phenolic Oils Fractionated from Fast Pyrolysis of Red Oak and Corn Stover. ACS Sustainable Chemistry and Engineering, 3(5), 892–902. https://doi.org/10.1021/acssuschemeng.5b00015

El-Sayed, S. A. (2025). Chemical products yielded from different pyrolysis processes of rice waste residues: a comprehensive review. Biomass Conversion and Biorefinery 2025, 1-41. https://doi.org/10.1007/S13399-025-06624-3

Fahmy, T. Y. A., Fahmy, Y., Mobarak, F., El-Sakhawy, M., & Abou-Zeid, R. E. (2020). Biomass pyrolysis: past, present, and future. Environment, Development and Sustainability, 22(1), 17–32. https://doi.org/10.1007/S10668-018-0200-5

Faisal, F., Rasul, M. G., Chowdhury, A. A., & Jahirul, M. I. (2024). Optimisation of Process Parameters to Maximise the Oil Yield from Pyrolysis of Mixed Waste Plastics. Sustainability 2024, Vol. 16, Page 2619, 16(7), 2619. https://doi.org/10.3390/SU16072619

Fan, L., Zhang, Y., Liu, S., Zhou, N., Chen, P., Cheng, Y., Addy, M., Lu, Q., Omar, M. M., Liu, Y., Wang, Y., Dai, L., Anderson, E., Peng, P., Lei, H., & Ruan, R. (2017). Bio-oil from fast pyrolysis of lignin: Effects of process and upgrading parameters. Bioresource Technology, 241, 1118–1126. https://doi.org/10.1016/J.BIORTECH.2017.05.129

Farobie, O., Amrullah, A., Bayu, A., Syaftika, N., Anis, L. A., &Hartulistiyoso, E. (2022). In-depth study of bio-oil and biochar production from macroalgae Sargassum sp. via slow pyrolysis. RSC Advances, 12(16), 9567–9578. https://doi.org/10.1039/D2RA00702A

Fonseca, F. G., Funke, A., Niebel, A., Soares Dias, A. P., & Dahmen, N. (2019). Moisture content as a design and operational parameter for fast pyrolysis. Journal of Analytical and Applied Pyrolysis, 139, 73–86. https://doi.org/10.1016/J.JAAP.2019.01.012

Fu, J., Liu, J., Xu, W., Chen, Z., Evrendilek, F., & Sun, S. (2022). Torrefaction, temperature, and heating rate dependencies of pyrolysis of coffee grounds: Its performances, bio-oils, and emissions. Bioresource Technology, 345, 126346. https://doi.org/10.1016/J.BIORTECH.2021.126346

Gao, C., Wang, Y., Shen, Y., Yan, D., He, X., Dai, J., & Wu, Q. (2014). Oil accumulation mechanisms of the oleaginous microalga Chlorella protothecoides revealed through its genome, transcriptomes, and proteomes. BMC Genomics, 15(1), 582. https://doi.org/10.1186/1471-2164-15-582)

Gollakota, A. R. K., Reddy, M., Subramanyam, M. D., & Kishore, N. (2016). A review on the upgradation techniques of pyrolysis oil. Renewable and Sustainable Energy Reviews, 58, 1543–1568. https://doi.org/10.1016/J.RSER.2015.12.180

Gouda, N., Singh, R. K., Meher, S. N., & Panda, A. K. (2017). Production and characterization of bio oil and bio char from flax seed residue obtained from supercritical fluid extraction industry. Journal of the Energy Institute, 90(2), 265–275. https://doi.org/10.1016/J.JOEI.2016.01.003

Guedes, R. E., Luna, A. S., & Torres, A. R. (2018). Operating parameters for bio-oil production in biomass pyrolysis: A review. Journal of Analytical and Applied Pyrolysis, 129, 134–149. https://doi.org/10.1016/J.JAAP.2017.11.019

Gupta, S., Mondal, P., Borugadda, V. B., & Dalai, A. K. (2021). Advances in upgradation of pyrolysis bio-oil and biochar towards improvement in bio-refinery economics: A comprehensive review. Environmental Technology & Innovation, 21, 101276. https://doi.org/10.1016/J.ETI.2020.101276

Hansen, S., Mirkouei, A., & Diaz, L. A. (2020). A comprehensive state-of-technology review for upgrading bio-oil to renewable or blended hydrocarbon fuels. Renewable and Sustainable Energy Reviews, 118, 109548. https://doi.org/10.1016/J.RSER.2019.109548

He, R., Ye, X. P., English, B. C., & Satrio, J. A. (2009). Influence of pyrolysis condition on switchgrass bio-oil yield and physicochemical properties. Bioresource Technology, 100(21), 5305–5311. https://doi.org/10.1016/J.BIORTECH.2009.02.069

Hebuka, E., & Iddphonce, R. (2023). Enhancing properties of bio-oil produced from plastic waste: A case study utilized plastic waste from Dar-es-Salaam dump sites. Journal of Renewable and Sustainable Energy, 15(5). https://doi.org/10.1063/5.0167121

Heo, H. S., Park, H. J., Yim, J. H., Sohn, J. M., Park, J., Kim, S. S., Ryu, C., Jeon, J. K., & Park, Y. K. (2010). Influence of operation variables on fast pyrolysis of Miscanthus sinensis var. purpurascens. Bioresource Technology, 101(10), 3672–3677. https://doi.org/10.1016/J.BIORTECH.2009.12.078

Hernando, H., Gómez-Pozuelo, G., Botas, J. A., & Serrano, D. P. (2021). Evaluating fractional pyrolysis for bio-oil speciation into holocellulose and lignin derived compounds. Journal of Analytical and Applied Pyrolysis, 154, 105019. https://doi.org/10.1016/J.JAAP.2021.105019

Ibitoye, S. E., Mahamood, R. M., Jen, T. C., Loha, C., & Akinlabi, E. T. (2023). An overview of biomass solid fuels: Biomass sources, processing methods, and morphological and microstructural properties. Journal of Bioresources and Bioproducts, 8(4), 333–360. https://doi.org/10.1016/J.JOBAB.2023.09.005

IEA Bioenergy Task 34. (2024). Flexibility by fast pyrolysis in renewable energy systems. Task34.Ieabioenergy.Com https://task34.ieabioenergy.com/wp-content/uploads/sites/3/2024/10/Flexibility-by-FPBO-2024-Final.pdf

Iisa, K., French, R. J., Orton, K. A., Dutta, A., &Schaidle, J. A. (2017). Production of low-oxygen bio-oil via ex situ catalytic fast pyrolysis and hydrotreating. Fuel, 207, 413–422. https://doi.org/10.1016/j.fuel.2017.06.098

Inayat, A., Ahmed, A., Tariq, R., Waris, A., Jamil, F., Ahmed, S. F., Ghenai, C., & Park, Y. K. (2022). Techno-Economical Evaluation of Bio-Oil Production via Biomass Fast Pyrolysis Process: A Review. Frontiers in Energy Research, 9, 770355. https://doi.org/10.3389/FENRG.2021.770355/BIBTEX

Jerzak, W., Acha, E., & Li, B. (2024). Comprehensive Review of Biomass Pyrolysis: Conventional and Advanced Technologies, Reactor Designs, Product Compositions and Yields, and Techno-Economic Analysis. Energies 2024, Vol. 17, Page 5082, 17(20), 5082. https://doi.org/10.3390/EN17205082

Kan, T., Strezov, V., & Evans, T. J. (2016). Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. Renewable and Sustainable Energy Reviews, 57, 1126–1140. https://doi.org/10.1016/J.RSER.2015.12.185

Kawamoto, H. (2017). Lignin pyrolysis reactions. Journal of Wood Science 2017 63:2, 63(2), 117–132. https://doi.org/10.1007/S10086-016-1606-Z

Ke, L., Zhou, N., Wu, Q., Zeng, Y., Tian, X., Zhang, J., Fan, L., Ruan, R., & Wang, Y. (2024). Microwave catalytic pyrolysis of biomass: a review focusing on absorbents and catalysts. Npj Materials Sustainability 2024 2:1, 2(1), 1–20. https://doi.org/10.1038/s44296-024-00027-7

Mostafazadeh, A. K., Solomatnikova, O., Drogui, P., & Tyagi, R. D. (2018). A review of recent research and developments in fast pyrolysis and bio-oil upgrading. Biomass Conversion and Biorefinery, 8(3), 739–773. https://doi.org/10.1007/S13399-018-0320-Z

Khuenkaeo, N., Phromphithak, S., Onsree, T., Naqvi, S. R., &Tippayawong, N. (2021). Production and characterization of bio-oils from fast pyrolysis of tobacco processing wastes in an ablative reactor under vacuum. PLoS ONE, 16(7), e0254485. https://doi.org/10.1371/JOURNAL.PONE.0254485

Kirschning, A., Kupracz, L., & Hartwig, J. (2012). New Synthetic Opportunities in Miniaturized Flow Reactors with Inductive Heating. Chemistry Letters, 41(6), 562–570. https://doi.org/10.1246/CL.2012.562

Kumar, M., Upadhyay, S. N., & Mishra, P. K. (2022). Pyrolysis of Sugarcane (Saccharum officinarum L.) Leaves and Characterization of Products. ACS Omega, 7(32), 28052–28064. https://doi.org/10.1021/acsomega.2c02076

Kumar, R., Strezov, V., Weldekidan, H., He, J., Singh, S., Kan, T., &Dastjerdi, B. (2020). Lignocellulose biomass pyrolysis for bio-oil production: A review of biomass pre-treatment methods for production of drop-in fuels. Renewable and Sustainable Energy Reviews, 123, 109763. https://doi.org/10.1016/J.RSER.2020.109763

Lee, D. J., Lu, J. S., & Chang, J. S. (2020). Pyrolysis synergy of municipal solid waste (MSW): A review. Bioresource Technology, 318, 123912. https://doi.org/10.1016/J.BIORTECH.2020.123912

Li, H., Xia, S., Li, Y., Ma, P., & Zhao, C. (2015). Stability evaluation of fast pyrolysis oil from rice straw. Chemical Engineering Science, 135, 258–265. https://doi.org/10.1016/J.CES.2015.03.065

Li, P., Shi, X., Wang, X., Song, J., Fang, S., Bai, J., Zhang, G., Chang, C., & Pang, S. (2021). Bio-oil from biomass fast pyrolysis: Yields, related properties and energy consumption analysis of the pyrolysis system. Journal of Cleaner Production, 328, 129613. https://doi.org/10.1016/J.JCLEPRO.2021.129613

Li, R., Zhong, Z., Jin, B., & Zheng, A. (2012). Selection of temperature for bio-oil production from pyrolysis of algae from lake blooms. Energy and Fuels, 26(5), 2996–3002. https://doi.org/10.1021/EF300180R

Lin, B. J., & Chen, W. H. (2015). Sugarcane bagasse pyrolysis in a carbon dioxide atmosphere with conventional and microwave-assisted heating. Frontiers in Energy Research, 3(FEB), 72029. https://doi.org/10.3389/FENRG.2015.00004

Lindfors, C., Nieminen, M., Alhalabi, T., Pienihäkkinen, E., Lahtinen, J., &Oasmaa, A. (2023). Novel Hot Vapor Filter Design for Biomass Pyrolysis. Energy & Fuels, 37(6), 4460–4469. https://doi.org/10.1021/acs.energyfuels.2c04285

Liu, J. J., Dickson, R., Niaz, H., Van Hal, J. W., Dijkstra, J. W., &Fasahati, P. (2022). Production of fuels and chemicals from macroalgal biomass: Current status, potentials, challenges, and prospects. Renewable and Sustainable Energy Reviews, 169, 112954. https://doi.org/10.1016/J.RSER.2022.112954

Liu, R. H., Shen, C. J., Wu, H. J., Deng, C. J., & Liu, S. Y. (2011). Characterisation of bio-oil from fast pyrolysis of rice husk in a fluidised bed reactor. Journal of the Energy Institute, 84(2), 73–79. https://doi.org/10.1179/014426011X12968328625397

Lu, X., & Gu, X. (2022). A review on lignin pyrolysis: pyrolytic behavior, mechanism, and relevant upgrading for improving process efficiency. Biotechnology for Biofuels and Bioproducts 2022 15:1, 15(1), 1–43. https://doi.org/10.1186/S13068-022-02203-0

Lyu, G., Wu, S., & Zhang, H. (2015). Estimation and comparison of bio-oil components from different pyrolysis conditions. Frontiers in Energy Research, 3(JUN), 137763. https://doi.org/10.3389/fenrg.2015.00028

Ma, C., Kumagai, S., Watanabe, A., Watanabe, C., Teramae, N., Yoshioka, T., & Kim, Y. M. (2024). Thermal and catalytic fast hydropyrolysis of lignin: Optimization for selective production of aromatics using high-pressure tandem μ-reactor – gas chromatography/mass spectrometry. Chemical Engineering Journal, 479, 147524. https://doi.org/10.1016/j.cej.2023.147524

Lachos-Perez, D., Martins-Vieira, J. C., Missau, J., Anshu, K., Siakpebru, O. K., Thengane, S. K., ... & Bertuol, D. A. (2023). Review on biomass pyrolysis with a focus on bio-oil upgrading techniques. Analytica, 4(2), 182-205. https://doi.org/10.3390/ANALYTICA4020015

Maulinda, L., Husin, H., Arahman, N., Rosnelly, C. M., Syukri, M., Nurhazanah, Nasution, F., & Ahmadi. (2023a). The Influence of Pyrolysis Time and Temperature on the Composition and Properties of Bio-Oil Prepared from Tanjong Leaves (Mimusopselengi). Sustainability 2023, Vol. 15, Page 13851, 15(18), 13851. https://doi.org/10.3390/SU151813851

Maulinda, L., Husin, H., Rahman, N. A., Rosnelly, C. M., Nasution, F., Abidin, N. Z., Faisal, Yani, F. T., & Ahmadi. (2023b). Effects of temperature and times on the product distribution of bio-oils derived from Typha latifolia pyrolysis as renewable energy. Results in Engineering, 18, 101163. https://doi.org/10.1016/J.RINENG.2023.101163

Miao, X., & Wu, Q. (2004). High yield bio-oil production from fast pyrolysis by metabolic controlling of Chlorella protothecoides. Journal of Biotechnology, 110(1), 85–93. https://doi.org/10.1016/J.JBIOTEC.2004.01.013

Mullen, C. A., Boateng, A. A., Goldberg, N. M., Lima, I. M., Laird, D. A., & Hicks, K. B. (2010). Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. Biomass and Bioenergy, 34(1), 67–74. https://doi.org/10.1016/J.BIOMBIOE.2009.09.012

Nelson, E. S., Sadare, O., & Daramola, M. (2023). Effect of biomass particle size on yield and composition of bio-oil produced from Empty Palm Fruit Bunch. https://doi.org/10.21203/rs.3.rs-2530158/v1

Niemelä, N. P., Nowak Delgado, R., de Riese, T., Tolvanen, H., Fendt, S., Spliethoff, H., &Joronen, T. (2021). Fuel-specific devolatilization parameters for detailed comparison of pulverized biomass fuels. Fuel, 286. https://doi.org/10.1016/J.FUEL.2020.119309

Nishu, Liu, R., Rahman, M. M., Sarker, M., Chai, M., Li, C., & Cai, J. (2020). A review on the catalytic pyrolysis of biomass for the bio-oil production with ZSM-5: Focus on structure. Fuel Processing Technology, 199, 106301. https://doi.org/10.1016/j.fuproc.2019.106301

Oh, S., Lee, J., Lam, S. S., Kwon, E. E., Ha, J. M., Tsang, D. C. W., Ok, Y. S., Chen, W. H., & Park, Y. K. (2021). Fast hydropyrolysis of biomass Conversion: A comparative review. Bioresource Technology, 342, 126067. https://doi.org/10.1016/J.BIORTECH.2021.126067

Ohra-Aho, T., Oasmaa, A., Koponen, P., Nyyssönen, S., Tuominen, V., & Aakko-Saksa, P. (2024). Quality and Storage Properties of Upgraded Fast Pyrolysis Bio-Oil for Marine Transport. *Energy and Fuels*, *38*(20), 19566–19583. https://doi.org/10.1021/acs.energyfuels.4c02868

Osman, A. I., Farghali, M., Ihara, I., Elgarahy, A. M., Ayyad, A., Mehta, N., Ng, K. H., Abd El-Monaem, E. M., Eltaweil, A. S., Hosny, M., Hamed, S. M., Fawzy, S., Yap, P. S., & Rooney, D. W. (2023). Materials, fuels, upgrading, economy, and life cycle assessment of the pyrolysis of algal and lignocellulosic biomass: a review. Environmental Chemistry Letters 2023 21:3, 21(3), 1419–1476. https://doi.org/10.1007/S10311-023-01573-7

Paenpong, C., Chunluang, W., &Pratoomchai, N. (2018). Upgrading of Bio-oils from the Fast Pyrolysis of Longan Wood over the Low CostCatalysts in a Fluidized Bed Reactor. Asian Health, Science and Technology Reports, 26(4), 94–106. https://doi.org/10.14456/NUJST.2018.26

Pahnila, M., Koskela, A., Sulasalmi, P., & Fabritius, T. (2023). A Review of Pyrolysis Technologies and the Effect of Process Parameters on Biocarbon Properties. Energies 2023, Vol. 16, Page 6936, 16(19), 6936. https://doi.org/10.3390/EN16196936

Panwar, N. L., & Paul, A. S. (2021). An overview of recent development in bio-oil upgrading and separation techniques. In Environmental Engineering Research (Vol. 26, Number 5). Korean Society of Environmental Engineers. https://doi.org/10.4491/eer.2020.382

Pattiya, A., &Suttibak, S. (2012). Influence of a glass wool hot vapour filter on yields and properties of bio-oil derived from rapid pyrolysis of paddy residues. Bioresource Technology, 116, 107–113. https://doi.org/10.1016/J.BIORTECH.2012.03.116

Pelagalli, V., Langone, M., Matassa, S., Race, M., Tuffi, R., Papirio, S., Lens, P. N. L., Lazzazzara, M., Frugis, A., Petta, L., & Esposito, G. (2024). Pyrolysis of municipal sewage sludge: challenges, opportunities and new valorization routes for biochar, bio-oil, and pyrolysis gas. Environmental Science: Water Research & Technology, 10(10), 2282–2312. https://doi.org/10.1039/D4EW00278D

Pena-Vergara, G., Castro, L. R., Gasparetto, C. A., &Bizzo, W. A. (2025). Improving bio-oil fractions through fractional condensation of pyrolysis vapors from Eucalyptus globulus biomass residues in a prototype auger reactor. Journal of Analytical and Applied Pyrolysis, 192, 107329. https://doi.org/10.1016/j.energy.2021.122243

Pienihäkkinen, E., Lindfors, C., Ohra-Aho, T., &Oasmaa, A. (2022). Improving Fast Pyrolysis Bio-Oil Yield and Quality by Alkali Removal from Feedstock. Energy and Fuels, 36(7), 3654–3664. https://doi.org/10.1021/acs.energyfuels.1c04331

Pitoyo, J., Eka Suharto, T., Jamilatun, S., Dahlan, A., Ringroad Selatan, J., & Istimewa Yogyakarta, D. (2022). Bio-oil from Oil Palm Shell Pyrolysis as Renewable Energy: A Review. CHEMICA: Jurnal Teknik Kimia, 9(2), 67–79. https://doi.org/10.26555/CHEMICA.V9I2.22355

Polin, J. P., Carr, H. D., Whitmer, L. E., Smith, R. G., & Brown, R. C. (2019). Conventional and autothermal pyrolysis of corn stover: Overcoming the processing challenges of high-ash agricultural residues. Journal of Analytical and Applied Pyrolysis, 143, 104679. https://doi.org/10.1016/J.JAAP.2019.104679

Rahman, M. M., Liu, R., & Cai, J. (2018). Catalytic fast pyrolysis of biomass over zeolites for high quality bio-oil – A review. Fuel Processing Technology, 180, 32–46. https://doi.org/10.1016/J.FUPROC.2018.08.002

Rasaq, W. A., Golonka, M., Scholz, M., &Białowiec, A. (2021). Opportunities and Challenges of High-Pressure Fast Pyrolysis of Biomass: A Review. Energies 2021, Vol. 14, Page 5426, 14(17), 5426. https://doi.org/10.3390/EN14175426

Raza, M., Inayat, A., Ahmed, A., Jamil, F., Ghenai, C., Naqvi, S. R., Shanableh, A., Ayoub, M., Waris, A., & Park, Y. K. (2021). Progress of the Pyrolyzer Reactors and Advanced Technologies for Biomass Pyrolysis Processing. Sustainability 2021, Vol. 13, Page 11061, 13(19), 11061. https://doi.org/10.3390/SU131911061

Reza, M. S., Zhanar Baktybaevna, I., Afroze, S., Kuterbekov, K., Kabyshev, A., Bekmyrza, K. Z., Kubenova, M. M., Bakar, M. S. A., Azad, A. K., Roy, H., & Islam, M. S. (2023). Influence of Catalyst on the Yield and Quality of Bio-Oil for the Catalytic Pyrolysis of Biomass: A Comprehensive Review. Energies 2023, Vol. 16, Page 5547, 16(14), 5547. https://doi.org/10.3390/EN16145547

Rony, M. (2024). Thermal Performance Analysis and Process Optimization for Converting Marine Biomass (Seaweed) into Pyrolysis Oil. (Doctoral dissertation, CQUniversity). https://doi.org/10.25946/27600426

Rowland, S. M., Martinez, R., Wrasman, C. J., Iisa, K., Nimlos, M. R., & Griffin, M. B. (2024). Thermal Reactivity of Bio-Oil Produced from Catalytic Fast Pyrolysis of Biomass. Energy and Fuels, 38(20), 19626–19638. https://doi.org/10.1021/acs.energyfuels.4c03430

Rueangsan, K., Sonsupap, S., Promsampao, N., Chollacoop, N., &Pattiya, A. (2023). Effect of condensation-assisted solid media on the production of bio-oil by fast pyrolysis of cassava residues in a free-fall reactor. Journal of the Energy Institute, 107, 101189. https://doi.org/10.1016/J.JOEI.2023.101189

Salehi, E., Abedi, J., & Harding, T. (2011). Bio-oil from sawdust: Effect of operating parameters on the yield and quality of pyrolysis products. Energy and Fuels, 25(9), 4145–4154. https://doi.org/10.1021/ef200688y

Seo, M. W., Lee, S. H., Nam, H., Lee, D., Tokmurzin, D., Wang, S., & Park, Y. K. (2022). Recent advances of thermochemical conversion processes for biorefinery. Bioresource Technology, 343, 126109 . https://doi.org/10.1016/J.BIORTECH.2021.126109

Shafaghat, H., Johansson, A. C., Wikberg, E., Narvesjö, J., Wagner, J. B., &Öhrman, O. (2024). Customized Atmospheric Catalytic Hydropyrolysis of Biomass to High-Quality Bio-Oil Suitable for Coprocessing in Refining Units. Energy & Fuels, 38(6), 5288–5302. https://doi.org/10.1021/acs.energyfuels.3c05078

Shrivastava, P., Kumar, A., Tekasakul, P., Lam, S. S., &Palamanit, A. (2021). Comparative Investigation of Yield and Quality of Bio-Oil and Biochar from Pyrolysis of Woody and Non-Woody Biomasses. Energies 2021, Vol. 14, Page 1092, 14(4), 1092. https://doi.org/10.3390/EN14041092

Sikarwar, V. S., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M. Z., Shah, N., Anthony, E. J., & Fennell, P. S. (2016). An overview of advances in biomass gasification. Energy & Environmental Science, 9(10), 2939–2977. https://doi.org/10.1039/C6EE00935B

Sohaib, Q., Muhammad, A., & Younas, M. (2017). Fast pyrolysis of sugarcane bagasse: Effect of pyrolysis conditions on final product distribution and properties. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 39(2), 184–190. https://doi.org/10.1080/15567036.2016.1212292

Sorunmu, Y., Billen, P., &Spatari, S. (2020). A review of thermochemical upgrading of pyrolysis bio-oil: Techno-economic analysis, life cycle assessment, and technology readiness. GCB Bioenergy, 12(1), 4–18. https://doi.org/10.1111/GCBB.12658

Struhs, E., Sotoudehnia, F., Mirkouei, A., McDonald, A. G., & Ramirez-Corredores, M. M. (2022). Effect of feedstocks and free-fall pyrolysis on bio-oil and biochar attributes. Journal of Analytical and Applied Pyrolysis, 166, 105616. https://doi.org/10.1016/J.JAAP.2022.105616

Su, G., Ong, H. C., Gan, Y. Y., Chen, W. H., Chong, C. T., & Ok, Y. S. (2022). Co-pyrolysis of microalgae and other biomass wastes for the production of high-quality bio-oil: Progress and prospective. Bioresource Technology, 344, 126096. https://doi.org/10.1016/J.BIORTECH.2021.126096

Sun, W., Yan, Y., Wei, Y., Ma, J., Niu, Z., & Hu, G. (2025). Catalytic Pyrolysis of Biomass: A Review of Zeolite, Carbonaceous, and Metal Oxide Catalysts. Nanomaterials 2025, Vol. 15,15(7). https://doi.org/10.3390/nano15070493

SuntornSuttibak. (2013). Characterization of bio-oil produced obtained fast pyrolysis of groundnuts shell. International Journal of Biosciences (IJB), 3(7), 82–89. https://doi.org/10.12692/ijb/3.7.82-89

Supramono, D., Lana, E. H., Setiadi, &Nasikin, M. (2019). Effect of carrier gas flow rate on bio-oil yield and composition in corn cobs and polypropylene plastic slow co-pyrolysis. Evergreen, 6(2), 47–54. https://doi.org/10.5109/2320999

Talwar, P., Agudelo, M. A., & Nanda, S. (2025). Pyrolysis Process, Reactors, Products, and Applications: A Review. Energies 2025, Vol. 18,18(11). https://doi.org/10.3390/en18112979

Toscano Miranda, N., Lopes Motta, I., Maciel Filho, R., & Wolf Maciel, M. R. (2021). Sugarcane bagasse pyrolysis: A review of operating conditions and products properties. Renewable and Sustainable Energy Reviews, 149, 111394. https://doi.org/10.1016/J.RSER.2021.111394

Tsai, W. T., Lee, M. K., & Chang, Y. M. (2007). Fast pyrolysis of rice husk: Product yields and compositions. Bioresource Technology, 98(1), 22–28. https://doi.org/10.1016/J.BIORTECH.2005.12.005

Vilas-Boas, A. C. M., Tarelho, L. A. C., Oliveira, H. S. M., Silva, F. G. C. S., Pio, D. T., & Matos, M. A. A. (2024). Valorisation of residual biomass by pyrolysis: influence of process conditions on products. Sustainable Energy & Fuels, 8(2), 379–396. https://doi.org/10.1039/D3SE01216F

Wakatuntu, J., Olupot, P. W., Jjagwe, J., Menya, E., &Okure, M. (2023). Optimization of pyrolysis conditions for production of rice husk-based bio-oil as an energy carrier. Results in Engineering, 17, 100947. https://doi.org/10.1016/J.RINENG.2023.100947

Wang, F., Zheng, Y., Huang, Y., Yang, X., Liu, C., Kang, J., & Zheng, Z. (2016). Effect of temperature on characteristics of bio-oil and bio-char during pyrolysis of Yunnan pine. Journal of Biobased Materials and Bioenergy, 10(2), 81–89. https://doi.org/10.1166/JBMB.2016.1580

Wang, J., Wang, S., Lu, J., Yang, M., & Wu, Y. (2021). Improved Bio-Oil Quality from Pyrolysis of Pine Biomass in Pressurized Hydrogen. Applied Sciences 2022, Vol. 12, Page 46, 12(1), 46. https://doi.org/10.3390/APP12010046

Wang, L., Yi, W., Zhang, A., Li, Z., Cai, H., & Li, Y. (2019). Catalytic Fast Pyrolysis of Corn Stalk for Phenols Production With Solid Catalysts. Frontiers in Energy Research, 7, 473162. https://doi.org/10.3389/FENRG.2019.00086/BIBTEX

Wang, Q., Zhang, X., Cui, D., Sun, S., Wang, Z., Wang, Y., Xu, F., Wang, Z., & Zhang, J. (2023). Effect of pressure on the pyrolysis and gasification mechanism of corn stovers from kinetics. Journal of Analytical and Applied Pyrolysis, 176, 106267. https://doi.org/10.1016/J.JAAP.2023.106267

Wu, F., Ben, H., Yang, Y., Jia, H., Wang, R., & Han, G. (2020). Effects of Different Conditions on Co-Pyrolysis Behavior of Corn Stover and Polypropylene. Polymers, 12(4), 973. https://doi.org/10.3390/POLYM12040973

Xiong, Z., Wang, Y., Syed-Hassan, S. S. A., Hu, X., Han, H., Su, S., Xu, K., Jiang, L., Guo, J., Berthold, E. E. S., Hu, S., & Xiang, J. (2018). Effects of heating rate on the evolution of bio-oil during its pyrolysis. Energy Conversion and Management, 163, 420-427. https://doi.org/10.1016/J.ENCONMAN.2018.02.078

Xu, B., & Li, A. (2017). Effect of high-pressure on pine sawdust pyrolysis: Products distribution and characteristics In AIP Conference Proceedings (Vol. 1864, No. 1, p. 020116). AIP Publishing LLC.https://doi.org/10.1063/1.4992933

Yan, Y., Li, N., Pan, Y., Shi, L., Xie, G., Liu, Z., & Liu, Q. (2024). Hydrogen-rich syngas production from tobacco stem pyrolysis in an electromagnetic induction heating fluidized bed reactor. International Journal of Hydrogen Energy, 68, 1271–1280. https://doi.org/10.1016/J.IJHYDENE.2024.04.344

Yang, H., Nuran Zaini, I., Pan, R., Jin, Y., Wang, Y., Li, L., Caballero, J. J. B., Shi, Z., Subasi, Y., Nurdiawati, A., Wang, S., Shen, Y., Wang, T., Wang, Y., Sandström, L., Jönsson, P. G., Yang, W., & Han, T. (2024). Distributed electrified heating for efficient hydrogen production. Nature Communications 2024 15:1, 15(1), 1–10. https://doi.org/10.1038/s41467-024-47534-8

Zhang, J., & Zhang, X. (2019). The thermochemical conversion of biomass into biofuels. Biomass, Biopolymer-Based Materials, and Bioenergy: Construction, Biomedical, and Other Industrial Applications, 327–368. https://doi.org/10.1016/B978-0-08-102426-3.00015-1

Zhang, L., Luo, Y., Wijayapala, R., & Walters, K. B. (2017). Alcohol Stabilization of Low Water Content Pyrolysis Oil during High Temperature Treatment. Energy and Fuels, 31(12), 13666–13674.https://doi.org/10.1021/acs.energyfuels.7b02276

Zhang, Q., Chang, J., Wang, T., & Xu, Y. (2007). Review of biomass pyrolysis oil properties and upgrading research. Energy Conversion and Management, 48(1), 87–92. https://doi.org/10.1016/J.ENCONMAN.2006.05.010

Zhao, A., Liu, S., Yao, J., Huang, F., He, Z., & Liu, J. (2022). Characteristics of bio-oil and biochar from cotton stalk pyrolysis: Effects of torrefaction temperature and duration in an ammonia environment. Bioresource Technology, 343, 126145. https://doi.org/10.1016/J.BIORTECH.2021.126145

Zhao, Z., Jiang, Z., Xu, H., & Yan, K. (2021). Selective Production of Phenol-Rich Bio-Oil From Corn Straw Waste by Direct Microwave Pyrolysis Without Extra Catalyst. Frontiers in Chemistry, 9, 700887. https://doi.org/10.3389/FCHEM.2021.700887/FULL

Zheng, J. L., & Wei, Q. (2011). Improving the quality of fast pyrolysis bio-oil by reduced pressure distillation. Biomass and Bioenergy, 35(5), 1804–1810. https://doi.org/10.1016/J.BIOMBIOE.2011.01.006