

Biomass as Feedstocks for Solid Fuel Production: Advances in Sources, Conversion Techniques and Densification Methods



N. S. Saidu^{1,2}, H. A. Ajimotokan^{2,*} and K. R. Ajao²

¹Department of Mechanical Engineering, Kwara State University, Malete, Nigeria.

²Department of Mechanical Engineering, University of Ilorin, Ilorin, Nigeria.



ABSTRACT: The increasing global energy demand, driven by rapid population growth and socio-economic development, has intensified interest in affordable and sustainable energy alternatives. Biomass-based solid fuels offer a viable solution, given their renewability and potential to reduce reliance on fossil fuels. This paper provides a comprehensive overview of recent advances in biomass feedstocks, thermochemical conversion technologies, and emerging densification methods for solid fuel production. The overview focused on studies published in the last decade between 2015 and 2024, emphasising research on biomass sources, conversion techniques, and densification methods for solid fuel production. Key conversion pathways, including thermochemical pretreatment technologies such as pyrolysis and torrefaction, are examined alongside densification techniques such as briquetting and palletisation. The overview evaluated each method based on technoeconomic feasibility, environmental impact, and combustion efficiency. Current bioenergy generation trends revealed a primary reliance on wood (67%), followed by woody residues (5%), agricultural residues (4%), and energy crops (3%). These biomass sources vary significantly in availability, environmental footprint, and suitability as substitutes for low-grade coal and firewood for process heating in thermal applications. The findings highlight the potential of thermochemical conversion as a robust approach for developing an affordable and sustainable solid biofuel supply chain.

KEYWORDS: Solid fuel, Thermochemical degradation, Organic matter, Biomass sources, Climate impact.

[Received Feb. 17, 2025; Revised June. 24, 2025; Accepted Jun. 28, 2025]

Print ISSN: 0189-9546 | Online ISSN: 2437-2110

I. INTRODUCTION

Energy is the backbone of economic growth and national development, playing a crucial role in poverty reduction and industrialisation (Dubdub, 2023). In fact, energy is a major factor in determining the standard of living since its key services such as domestic and industrial needs, transportation, manufacturing, and commerce define a nation's progress (Yana *et al.*, 2022). It significantly improves the quality of life and supports industrial growth. Consequently, it is essential to develop energy solutions that can meet the rising energy demand and supply gaps due to rapid industrialisation and population growth (Yana *et al.*, 2022; Ajimotokan *et al.*, 2022). Besides, the global energy transition to renewable energy is now critical to reduce dependence on fossil fuels, which are depleting and pose environmental risks (Ajimotokan *et al.*, 2023; Oladosu *et al.*, 2023; Rabiun *et al.*, 2019). Compared to fossil fuels, renewable energy sources are often more cost-effective and efficient. For instance, wind turbine technology has become more reliable and is now a viable alternative, whether as a standalone system or in hybrid configurations. Likewise, the demand for solar energy in residential and commercial applications has surged and the use of biomass feedstock is now widely recognised as a renewable energy source that can deliver bioenergy and by-products

(Ajimotokan *et al.*, 2025; Ibitoye *et al.*, 2023a; Kumar *et al.*, 2023).

Biomass refers to any organic material derived from plants and animals that can be used as an alternative fuel, including woody biomass (such as stems, branches, shrubs, and twigs), non-woody biomass (like stalks, leaves, and grass), agricultural residues (such as bagasse, husks, shells, and cobs), and animal waste. These materials are generated through photosynthesis or other biological processes and can be converted into bioenergy and bioproducts (Ajimotokan *et al.*, 2019a; Ajimotokan *et al.*, 2019b; Ajimotokan *et al.*, 2019c). Biomass conversion into usable energy occurs through several thermochemical, biochemical, and physicochemical processes, including direct combustion, pyrolysis, gasification, anaerobic digestion (biogasification), and transesterification (biodiesel production) (Omosewo *et al.*, 2017). Among these, direct combustion remains the most widely applied method for heat and power generation (Akinrinola *et al.*, 2020). Pyrolysis and gasification, on the other hand, are promising for producing bio-oil, biogas, and biochar and syngas, respectively, which can be utilised for various industrial applications (Odejobi *et al.*, 2024). Biomass serves as one of the most abundant renewable energy resources globally, with rapid regrowth potential across different climatic regions. However, one of the challenges

*Corresponding author: ajimotokan.ha@unilorin.edu.ng

with raw biomass is its low energy density, high moisture content, and heterogeneous physical properties.

To improve handling, transportation, and combustion characteristics, biomass is often densified into solid biofuels through processes such as briquetting, pelletising, and cubing (Ajimotokan *et al.*, 2019b; Ajimotokan *et al.*, 2019c). These techniques involve compressing pulverised biomass feedstock under high pressure, often with binding agents, to enhance mechanical durability, energy density, and combustion efficiency (Yub *et al.*, 2018). Densified biomass fuels exhibit superior combustion properties compared to raw biomass. They have higher bulk and energy densities, lower moisture content, and their controlled shape and size of briquettes and pellets allow for more efficient storage, transport, and co-firing with coal in industrial and power generation applications (Ajimotokan *et al.*, 2019a).

Biomass energy can be processed into biofuel through various conversion techniques. The choice of a conversion pathway depends on factors such as feedstock type and availability, energy output requirements, economic feasibility and cost-efficiency, environmental impact and sustainability, and technological constraints and efficiency (Smith, 2020; Johnson & Lee, 2019). Thermochemical conversion methods such as pyrolysis, gasification, and torrefaction are effective for producing high-value energy carriers like biochar, syngas, and bio-oil (Miller *et al.*, 2021). Meanwhile, biochemical routes such as anaerobic digestion (biogas production) and fermentation (bioethanol production) leverage microbial metabolism to convert organic matter into usable energy forms (Ashraf *et al.*, 2019; Cai *et al.*, 2023; Hoang *et al.*, 2021; Sarker *et al.*, 2020). The direct combustion of biomass remains the most traditional approach for heat and power generation. However, combustion efficiency is highly dependent on fuel preparation, moisture content, and combustion chamber design. Advanced combustion technologies, such as fluidised bed combustion and gasification-based combined heat and power systems, significantly enhance thermal efficiency and emissions control (Siwal *et al.*, 2021).

Despite the growing body of research on biomass energy, certain knowledge gaps persist, namely limited research on the densification process and its influence on fuel performance across different biomass feedstocks, lack of comprehensive studies on combustion kinetics for optimising co-firing potential with coal, minimal exploration of decentralised biomass energy systems for rural electrification and off-grid applications, and insufficient lifecycle assessments on biomass-based fuels to evaluate their long-term environmental and economic sustainability. Recent advancements in computational modelling, artificial intelligence, and machine learning are opening new avenues for optimising biomass conversion technologies (Sharma *et al.*, 2023). Predictive models can help improve process efficiency, reduce waste, and optimise fuel formulations for enhanced performance (Williams & Clark, 2022).

Thus, this paper examines the review of recent research and technology development of biomass for solid fuel development with emphasis on biomass sources, conversion techniques, and densification methods. Emphasis on the significance of considering the environmental implication

were also presented. The complex and inclusive approach differentiates this study from previous reviews that had earlier distinctly focus on features of biomass as feedstock for developing solid fuels.

II. METHODOLOGY

A structured literature search strategy was implemented to ensure a comprehensive and focused review of biomass densification, conversion techniques, and combustion characteristics. Electronic citation databases, including Google Scholar, ScienceDirect, and Web of Science, were employed to identify relevant peer-reviewed articles. A keyword-based literature search methodology was employed to extract relevant studies (Ajimotokan, 2023). The search incorporated multiple keyword combinations, including biomass densification (such as pellets and briquettes), thermochemical and biochemical conversion (such as pyrolysis and gasification), processing parameters (such as particle size and residence time), material properties and durability indices (such as hydrophobicity and shatter index), and combustion and fuel characterisation (such as combustion, ash content, and fixed carbon content). Others include analytical methods (such as proximate and ultimate analyses), and kinetic modelling approaches (such as isothermal, non-isothermal, and carrier gas). To ensure methodological consistency, studies conducted based on standard methods such as American Society for Testing and Materials (ASTM) and the International Standard Organisation (ISO), among others were considered.

The selection of studies followed a systematic approach based on the inclusion and exclusion criteria adopted by Balali *et al.* (2023). The selection process followed a systematic approach, with inclusion criteria focusing on peer-reviewed studies published between 2015 and 2024 that examined biomass sources, conversion methods, and combustion efficiency. Exclusion criteria eliminated non-English publications, studies unrelated to biomass energy, and articles not available in full text. Extracted data were analysed based on key themes, including biomass feedstock types, processing techniques, combustion performance, and process optimization variables. The synthesis of findings provided a clear understanding of existing challenges, potential solutions, and research gaps in biomass densification and combustion. Established systematic review guidelines were followed to ensure transparency, consistency, and high-quality analysis throughout the study.

III. BIOMASS SOURCES

The potential biomass sources for energy production have been identified, including forestry residues, agricultural residues, energy crops, and industrial and municipal solid wastes. Among these, wood-based biomass accounts for approximately 67% of total bioenergy generation, while woody residues contribute 5% (Ibitoye *et al.* 2023b). Additionally, agricultural residues make up 4%, municipal solid wastes and energy crops each contribute 3%, and forest residues and other sources account for 1% (Ibitoye *et al.* 2023b). Table 1 provides a summary of these biomass sources, highlighting their applications in bioenergy production and associated limitations. This classification helps in

understanding the distribution of biomass feedstocks and their potential for sustainable energy generation. The detailed

description of these sources and their potential benefits and limitations is discussed.

Table 1: Summary of biomass sources, their application and limitations

Sources	Characteristics	Application	Limitation	References
Forestry residues	It is generated from milling operations such as sawdust, logging activities, trees and shrub residues.	The release of much heat when properly ignited, makes its application possible for technology with high temperature energy demand	Poor shelf life, inefficient handling properties, and financial feasibility.	(Hu <i>et al.</i> , 2024; Saravanakumar <i>et al.</i> , 2023; Yub <i>et al.</i> , 2018)
Agricultural residues	These are residues and wastes generated from post-harvest activities.	It could be used to meet energy demand for domestic uses in its raw and treated form.	They generally possess high moisture content, low calorific value, hydrophobic property, fibrous and tenacious nature, among others	(Bot <i>et al.</i> , 2024; Sadh <i>et al.</i> , 2023)
Energy crops	They are grown specifically for the purpose of energy resources	They posse high energy values which can be easily converted into biofuel through thermochemical or biochemical conversion routes.	Increase in production cost, requires considerable area of land, infrastructure and equipment, competition of water resources.	(Alherbawi <i>et al.</i> , 2021; Román-Figueroa <i>et al.</i> , 2017)
Industrial and municipal solid wastes	These are industrial by-products, municipal solid waste, and sewage sludge.	They are used as feedstock for bioenergy applications.	Their efficiency as feedstock for bioenergy is not yet adequately managed.	(Elif, 2024; Sarc & Viczek, 2024)

A. Forestry Residues

Forestry residues are by-products of milling operations and include materials such as sawdust, waste from logging activities, and remnants from trees and shrubs (Hu *et al.*, 2024; Laihonon *et al.*, 2024; Saravanakumar *et al.*, 2023). Fuelwood is primarily sourced from natural forests, woodlands, and managed forest plantations. According to the World Bioenergy Association, approximately 88% of biomass used for bioenergy originates from forest resources. This makes fuelwood a major energy source for small-scale industries in rural areas, as well as for heating and cooking in households across many developing nations (Saravanakumar *et al.*, 2023; Trejo-Pech *et al.*, 2024). Forestry residues are renewable source of energy because the time required for replenishment is short and they can be generated in large quantity from forestry activities.

Also, its application as sustainable energy sources have huge potentials in most countries, because it is readily available, conversion techniques are simple to construct, and it has promising features to replace fossil fuels (Ajimotokan *et al.*, 2019b). Biomass residue from forestry activities releases much heat when properly combusted, making its application possible for technology with high temperature energy demand (Amer *et al.*, 2021; Hossain *et al.*, 2024; Wu *et al.*, 2024). In the recent times, many technologies have been developed and tailored to convert forest residue into a rich usable energy

through different conversion means like torrefaction, pyrolysis, gasification, carbonation among others (Papari & Hawboldt, 2015; Saravanakumar *et al.*, 2023; Wu *et al.*, 2024). However, the choice of any of these thermochemical conversion methods depends on different combinations of factors like biomass sources, availability, and end uses among others. Each method has its merit and drawbacks with respect to environmental consequences, overall economics, and government policies (Pandey & Erbaugh, 2024).

Globally, it is estimated that about 30% of forest residues is used for domestic and industrial energy purposes (Pędzik *et al.*, 2022; Sahoo *et al.*, 2022). This relatively low usage could be attributed to some inherent properties of forestry residues such as low calorific value, high moisture content, hydrophilic nature, fibrous and tenacious nature, and low energy density (Ajimotokan *et al.*, 2019a; Akinrinola *et al.*, 2020; Hu *et al.*, 2024). Also, among the major setbacks facing the utilisation of forestry residues for energy application is its poor shelf life and inefficient handling properties (Saravanakumar *et al.*, 2023). Another apprehension in the use of forest residue as energy source is the financial feasibility (Casas-Ledón *et al.*, 2019). This requires substantial analysis as the overall cost of producing fuel from forest residue varied generally. Also, the financial decision can be influenced to some extent by other sources of energy such as fossil fuels, wind energy, solar energy among others. Therefore, adequate efforts are required

to replace fossil fuels with forest residue and overcome the logistic economics and social barriers in sustainable energy solutions (Awasthi *et al.*, 2022; How *et al.*, 2019).

B. Agricultural Residues

Agricultural residue, also known as agro-residue consists of residues and waste generated during post-harvest processes. Although produced in substantial quantities, agricultural residues remain largely underutilised. Examples include agricultural by-products such as crop stalks, cobs, straw, husks, and shells. (Kumar *et al.*, 2023; Ribeiro & Junior, 2023). These agricultural residues have traditionally served as sources of biomass in rural communities, primarily used for heat production in various bioenergy applications. Agricultural residues are abundant because crops are extensively grown in different part of the world (Bot *et al.*, 2024; Kumar *et al.*, 2022; Sadh *et al.*, 2023).

1) Potential and Challenges of Agricultural Residues for Bioenergy

Given that crops are extensively cultivated worldwide, agricultural residues are abundant, renewable, and widely available (Bot *et al.*, 2024; Sadh *et al.*, 2023). Despite these challenges, agricultural residues hold substantial potential as a direct energy resource and can be converted into biofuels to help meet growing energy demands in remote and off-grid settlements. Nonetheless, the utilisation of agricultural residues for bioenergy production faces technical and economic barriers. Studies have identified key limitations, including high moisture content, which increases drying requirements and affects combustion efficiency; low calorific value, making them less energy-dense compared to conventional fossil fuels; hydrophilic nature, leading to poor storage and handling properties; and fibrous and tenacious structure, which complicates processing and densification (Awasthi *et al.*, 2022; Kumar *et al.*, 2023; Saravanan *et al.*, 2023).

2) Conversion Pathways for Agricultural Residues

The selection of an appropriate conversion technology for agricultural residues depends on the feedstock type and intended energy application. Common thermochemical and biochemical processes for agricultural biomass conversion include direct combustion – used for heat and power generation; torrefaction – employed to enhance energy density and combustion properties; pyrolysis and gasification – employed to convert residues into bio-oil and syngas, respectively; and anaerobic digestion – employed to produce biogas from organic residues. Through effective utilisation and processing, agricultural residues present a viable alternative to fossil fuels while addressing sustainable energy challenges (Awasthi *et al.*, 2022; Saidu *et al.*, 2022; Ribeiro & Junior, 2023). Continued research and technological advancements are necessary to improve conversion efficiency and commercial viability.

C. Energy Crops

Energy crops refer to plant species cultivated specifically for the purpose of generating bioenergy (Alherbawi *et al.*, 2021; Román-Figueroa *et al.*, 2017). These crops possess high calorific value and can be efficiently transformed into biofuels

using either thermochemical or biochemical conversion processes. Unlike conventional food crops, energy crops are typically cultivated on marginal or degraded agricultural lands, reducing competition for arable farmland (Okafor *et al.*, 2022). Energy crops can be categorised into herbaceous energy crops (like miscanthus and switchgrass), wood energy crops (like eucalyptus and willows), industrial crops (like jatropha and soybean), agricultural crops (like cassava, oil palm, and sugarcane), and aquatic crops (like algae). These crops serve as a feedstock for bioenergy applications such as combustion, pyrolysis, gasification, and liquefaction, enabling the production of biofuels, syngas, and hydrogen fuel (Alherbawi *et al.*, 2021; Okafor *et al.*, 2022; Ugwu *et al.*, 2022).

1) Benefits of Energy Crop Cultivation

The agronomy of energy crops contributes significantly to rural economic development, as their cultivation can create local employment opportunities, reduce energy poverty, and enhance soil fertility (Sahoo *et al.*, 2022). Additionally, energy crops offer key environmental benefits, including carbon sequestration through photosynthesis. Energy crops absorb carbon dioxide, mitigating greenhouse gas emissions and reduction of harmful emissions. Compared to medium- and high-grade fossil fuels (such as coal and petroleum-based fuels), energy crops emit fewer pollutants during combustion (Bilandžija *et al.*, 2021; Hryhoriv *et al.*, 2024; Román-Figueroa *et al.*, 2017). The cultivation of energy crops can enhance soil nutrients, potentially improving food production when the land is subsequently used for agricultural purposes. Energy crops can be grown on borderline lands unsuitable for food production, ensuring a more resourceful approach to land use (Sahoo *et al.*, 2022).

2) Challenges and Limitations of Energy Crops

Despite their potential, energy crops face several economic, environmental, and logistical challenges, including high production costs. The cost of cultivation, land preparation, and harvesting can make energy crops economically uncompetitive compared to other energy sources. Large-scale production of energy crops necessitates significant land area, as well as processing infrastructure and equipment, and water resource competition. Energy crop cultivation requires substantial water inputs, raising concerns about competition with water supplies for food production and human consumption (Sahoo *et al.*, 2022).

3) Strategies for Sustainable Energy Crop Utilisation

To enhance the sustainability and economic feasibility of energy crops for bioenergy production, the following strategies can be adopted (Dumortier *et al.*, 2020): (i) development of water-efficient crops by advancing drought-resistant energy crop varieties can minimise water consumption; (ii) precision irrigation methods by implementing efficient water management systems can optimize water usage; and (iii) circular economy approaches by integrating life cycle assessment and waste-to-energy technologies can optimise energy crop utilisation while reducing environmental impact. By addressing these challenges through technological innovation, policy support, and sustainable farming practices, energy crops can play a pivotal role in renewable energy

generation and contribute to global energy security and carbon neutrality.

D. Industrial and Municipal Wastes

Industrial and municipal waste comprises common waste streams such as municipal solid waste (MSW), sewage sludge, and industrial residues. MSW and other by-products rich in organic matter serve as viable feedstocks for bioenergy production. For example, the anaerobic digestion of MSW to produce biogas a methane-rich renewable fuel is considered an environmentally friendly energy solution (Molino *et al.*, 2016). These waste sources do not require land allocation or irrigation systems, thereby reducing production costs. Utilising industrial and municipal wastes for energy generation is both economically viable and environmentally sound. Although MSW generation is an unavoidable aspect of modern life, its potential as a sustainable and efficient energy resource remains underutilized due to reduction inefficiencies and other sustainability challenges (Sarc & Viczek, 2024). Nonetheless, ongoing efforts aim to enhance the conversion of a substantial portion of MSW and related residues into biofuels. This transformation can play a crucial role in poverty alleviation and the enhancement of socio-economic conditions by fostering job creation and supporting improved public infrastructure (Molino *et al.*, 2016; Odejobi *et al.*, 2024).

1) Economic and Environmental Sustainability

The utilisation of industrial and municipal waste as an energy resource presents significant economic and environmental advantages, namely cost-effectiveness – since MSW is a by-product of urban and industrial activities, its conversion into biofuels reduces waste disposal costs and offers a low-cost energy alternative; job creation and socio-economic benefits. Waste-to-energy projects can create employment opportunities, in particular in waste management, biogas production, and energy distribution, improving the socio-economic welfare of communities (Molino *et al.*, 2016; Odejobi *et al.*, 2024); and waste management and pollution control. Converting MSW into energy reduces landfill waste, lowers methane emissions, and mitigates environmental pollution (Sarc & Viczek, 2024).

2) Challenges and Future Prospects of Industrial and Municipal Solid Wastes

Despite its potential, industrial and MSW-based bioenergy production faces key challenges. These challenges include waste reduction and sustainability concerns, and technological and logistical barriers. The increasing production of municipal waste poses management challenges, in particular regarding segregation, collection, and processing efficiency (Sarc & Viczek, 2024). The conversion of heterogeneous waste streams into consistent, high-quality biofuels requires advanced sorting, pre-processing, and conversion technologies. Effective waste-to-energy policies, incentives, and regulatory frameworks are needed to support large-scale MSW bioenergy projects (Odejobi *et al.*, 2024). However, continuous innovations in waste-to-energy technologies such as advanced anaerobic digestion, gasification, and pyrolysis are making MSW-based bioenergy more efficient and sustainable. Governments and industries are also investing in circular

economy models to maximise waste utilisation while minimising environmental impacts (Sarc & Viczek, 2024).

By optimising waste-to-energy conversion processes and addressing logistical and regulatory barriers, industrial and MSW bioenergy can significantly contribute to sustainable energy production, climate change mitigation, and urban waste management solutions.

E. Biomass Conversion Techniques

Efficiently processed biomass-based fuels have significant potential to replace fossil fuels, addressing critical environmental, health, and economic challenges linked to carbon emissions and fossil fuel dependency. The global shift toward renewable bioenergy solutions has led to an increased focus on thermochemical conversion routes as the fastest and most scalable method for ensuring sustainability in the biofuel supply chain (Chaves *et al.*, 2024; Molino *et al.*, 2016). With the growing emphasis on biomass-derived energy as a viable alternative to finite fossil-based fuels, this review focused on thermochemical conversion methods, exploring their efficiency, scalability, and sustainability in meeting global energy demands.

Biomass is a versatile energy resource that can be processed into energy, fuels, and valuable chemical compounds through a range of conversion techniques (Hossain *et al.*, 2024; Jha *et al.*, 2022a; Ross, 2019; Ugwu *et al.*, 2022). However, raw biomass is often characterised by high moisture content, low heating value, hygroscopic properties, and low energy density, which negatively impact thermal efficiency, storage, handling, and logistics. To enhance the usability of biomass for biofuel applications, efficient processing methods are necessary to improve fuel properties and overall performance.

Recent advancements in biomass processing technologies have focused on enhancing energy efficiency, storage stability, and conversion efficiency. The most commonly explored biomass upgrading methods include pyrolysis – a thermochemical process that decomposes biomass in the absence of oxygen to produce biochar, bio-oil, and biogas (Chen *et al.*, 2021; Thengane *et al.*, 2022); torrefaction – a mild thermal treatment that removes moisture and volatile compounds, increasing energy density and hydrophobicity (Kongto *et al.*, 2023; Tameková *et al.*, 2021); gasification – a high-temperature conversion process that converts biomass into syngas, which can be further refined into hydrogen, methane, or liquid fuels (Chaves *et al.*, 2024); liquefaction – a process that converts biomass into liquid biofuels under moderate temperature and pressure conditions (Nour *et al.*, 2021); and briquetting, pelletisation, and cubing – mechanical densification methods that enhance biomass fuel compactness, transportability, and energy efficiency (Chen *et al.*, 2021).

Figure 1 depicts the flow diagram of traditional and sustainable methods of biomass conversion techniques and products.

F. Pyrolysis

Pyrolysis is a thermochemical process that converts biomass feedstock into energy-rich fuels by thermally decomposing its lignocellulosic components in an oxygen-free environment, typically within a temperature range of 400–

600°C (Chong *et al.*, 2019; Van Geem, 2019). At these temperatures, cellulose, hemicellulose, and portions of lignin degrade into smaller, volatile molecules. This reaction produces both condensable and non-condensable gases. The former condenses into bio-oil (often referred to as tar), while the latter are released as syngas. In addition, a solid carbon-rich residue known as biochar is also formed as a valuable by-product.

Pyrolysis is classified based on temperature range, residence time, and heating rate (Hameed *et al.*, 2019). The major product yield depends on the operating conditions: low-temperature pyrolysis ($\leq 450^\circ\text{C}$, long residence time, low heating rate) that primarily yields biochar; moderate-temperature pyrolysis ($\sim 550^\circ\text{C}$, short residence time) that maximises bio-oil production (Wang *et al.*, 2016; Zhang *et al.*, 2018); and high-temperature pyrolysis ($> 850^\circ\text{C}$, longer residence time, high heating rate) that produces mostly non-condensable gases (Omosewo *et al.*, 2017).

The thermal degradation of biomass in pyrolysis generally occurs in three distinct steps: drying stage – the stage that moisture is removed from the biomass feedstock; primary decomposition – at relatively low temperatures, volatile gases such as hydrogen, carbon monoxide, carbon dioxide, and steam are released, along with char, tar, and mineral ash. This is driven by a process known as thermal scission, which breaks chemical bonds within the biomass (Papari & Hawboldt, 2015); secondary reactions – occur at higher temperatures ($> 500^\circ\text{C}$) when the primary reaction products, in particular tar, undergo further decomposition; and the final product distribution in pyrolysis is influenced by several parameters, including biomass feedstock composition, particle size, and process conditions. The end product of pyrolysis depends upon the nature of the biomass feedstock, particle size distribution and pyrolysis operating conditions.

Based on residence time and operating conditions, pyrolysis can be categorised into slow pyrolysis – long residence time, low heating rate, maximising biochar yield; fast pyrolysis – short residence time, moderate heating rate, maximising bio-oil production; flash pyrolysis – extremely short residence time, high heating rate, producing a high fraction of volatile gases; and hydro-pyrolysis – employs a pressurised hydrogen environment to enhance bio-oil stability (Cai *et al.*, 2018; Nour *et al.*, 2021).

1) Slow Pyrolysis

Slow pyrolysis is a thermal conversion process characterised by low heating rates typically between 0.1°C and 2°C per minute and extended residence times for both vapour and solid phases, ranging from 5 to 30 minutes (Li *et al.*, 2024). A well-known application of this process is the carbonisation of biomass to produce charcoal. Optimal moisture content for carbonization generally falls within the range of 15–20%, while feedstock particle size can vary significantly from compact pellets to whole logs (Alam *et al.*, 2024; Cheng *et al.*, 2020). During slow pyrolysis, volatile compounds released in the vapour phase undergo further secondary reactions, promoting the formation of solid char and additional liquid by-products. This process is particularly favourable for maximising solid fuel yield, and as such, most research in this domain focuses on char production. Literature indicates that

minimizing vapor residence time can suppress secondary reactions, thereby enhancing the overall yield of solid products (Li *et al.*, 2024). These characteristics make slow pyrolysis especially suitable for applications where biochar or solid fuel is the primary target product.

2) Fast Pyrolysis

Fast pyrolysis is regarded as an advanced thermochemical conversion technique that is attracting increasing global interest to produce liquid fuels from finely milled biomass feedstocks (Bridgwater, 2018; El Bari *et al.*, 2024). In this process, biomass is rapidly heated in a reactor to temperatures between 450°C and 600°C , with a very short vapour residence time typically less than two seconds (El Bari *et al.*, 2024; Khudayar *et al.*, 2024; Wang *et al.*, 2024). To maximise the yield of bio-oil and prevent further cracking of pyrolysis vapours into non-condensable gases, the process parameters particularly temperature, residence time, and heating rate are carefully controlled.

Fast pyrolysis is capable of producing up to 75 wt.% of bio-oil on a dry-feed basis, which can be utilized in thermal engines and refineries, or serve as an energy carrier in various applications (Khudayar *et al.*, 2024; Zhu *et al.*, 2024). The process typically operates at high heating rates, often exceeding 1000°C per minute, and the resulting vapors are rapidly cooled and condensed to recover the liquid product (Ma *et al.*, 2024; Zhu *et al.*, 2024). The bio-oil obtained is generally a dark brown, homogeneous liquid with an energy content approximately half that of conventional petroleum-derived fuel oil. Feedstock quality plays a significant role in determining the efficiency of bio-oil production; biomass with low ash content has been shown to yield higher amounts of bio-oil under fast pyrolysis conditions (Khudayar *et al.*, 2024; Velázquez-Martí *et al.*, 2018). This highlights the importance of selecting appropriate biomass types and optimising operating parameters to enhance liquid fuel yield and quality.

3) Flash Pyrolysis

Flash pyrolysis is a highly rapid thermochemical conversion process, distinguished by the instantaneous devolatilization of lignocellulosic biomass in an oxygen-deficient environment. This process operates at extremely high heating rates typically between $1,000^\circ\text{C}$ and $10,000^\circ\text{C}$ per minute and features ultra-short vapor residence times. Flash pyrolysis is increasingly recognized as a promising approach for producing bio-oil with performance characteristics comparable to petroleum-derived fuels (Lindstrom *et al.*, 2024; Mellalou *et al.*, 2024; Zhu *et al.*, 2024).

The operating temperature range for flash pyrolysis generally spans from 770 – $1,030^\circ\text{C}$, under which conditions bio-oil yields can reach approximately 70%. The resulting bio-oil may be utilized in various energy applications, including heat and power generation. However, despite its high conversion efficiency, the process presents notable challenges. The bio-oil produced is often a heterogeneous mixture, exhibiting corrosive properties and limited thermal stability. These drawbacks are primarily attributed to the high oxygen content in the crude bio-oil, which adversely affects its chemical and physical properties. Upgrading techniques such as hydrogenation have been shown to enhance the quality of

the bio-oil by improving its thermal stability and reducing oxygen content (Marques *et al.*, 2024; Pietraccini *et al.*, 2023; Zha *et al.*, 2023).

4) Hydro-Pyrolysis

Hydro-pyrolysis is a hydrogen-assisted pyrolytic process conducted under high-pressure hydrogen environments. The presence of hydrogen prevents the formation of free radicals, thereby reducing unsaturated hydrocarbons and improving bio-oil quality (Dyjakon *et al.*, 2021; Marques *et al.*, 2024; Wu *et al.*, 2023; Yan *et al.*, 2023). This process facilitates systematic bond breaking, leading to the formation of stable hydrocarbon compounds. Experimental studies indicate that conducting hydro-pyrolysis at 30 bar yields a maximum fraction of phenolic derivatives, which are valuable as biofuels and chemical feedstocks. However, a higher bio-oil yield is generally obtained under a nitrogen atmosphere (Alam *et al.*, 2024; Dan *et al.*, 2015; Marques *et al.*, 2024).

G. Torrefaction

Torrefaction, an effective biomass pretreatment method that enhances fuel quality, energy density, and hydrophobicity, is a thermochemical pretreatment process conducted at temperatures ranging from 200–300°C in an inert atmosphere. This process enhances the handling, milling, co-firing, and energy properties of biomass, converting it into a high-quality solid biofuel (Amer *et al.*, 2019; Cahyanti *et al.*, 2021; Ibitoye *et al.*, 2023a; Ikegwu *et al.*, 2021). Torrefied biomass is considered an improved version of raw biomass due to its higher energy density and hydrophobicity, making it more suitable for fuel applications. Current research on torrefaction has made significant progress, but most studies have focused on individual biomass feedstocks, rather than diverse biomass blends (Chen *et al.*, 2012; Nwabunwanne *et al.*, 2021).

Torrefaction can be categorised into three regimes based on temperature: light torrefaction – torrefaction in the temperature range of ~240°C; mild torrefaction – torrefaction in the temperature range of ~270°C; and severe torrefaction – torrefaction in the temperature range of ~300°C. For most lignocellulosic biomass, torrefaction temperature has a stronger influence on chemical composition than other parameters, and the solid yield of torrefied biomass decreases as temperature increases, leading to a higher energy density fuel (Javanmard *et al.*, 2023; Phang *et al.*, 2024; Chen *et al.*, 2021; Iglesias *et al.*, 2023).

The key influencing factors – torrefaction process and mechanisms, temperature, residence time, and biomass composition that determine the final mass yield, energy content, and combustion characteristics of the torrefied product are discussed.

1) Torrefaction Process and Mechanisms

Using torrefaction for pre-treatment of biomass involve two main steps. The major and the most energy intensive stage

in the process of torrefaction is drying. This stage is characterised by the removal of surface and bound water from the biomass. This occurs at a temperature range of 50–150°C. Water due to chemical reactions is removed through a process called thermo-condensation in the initial stage of the heating (Ajimotokan *et al.*, 2025). This occurs at temperature range of 160–180°C and results in the formation of carbon dioxide. Continuation of the degradation of hemicelluloses was observed at a temperature between 180–270°C. Hemicellulose degradation begins, with the emission of moisture, carbon dioxide, and acetic acid. The process is exothermic and leads to browning of biomass (Barontini *et al.*, 2021; Mamvura & Danha, 2020; Mandefro & Jabasingh, 2021; Thengane *et al.*, 2022). At 280°C, the reaction becomes fully exothermic, and gas production increases, leading to carbon monoxide formation (Irawan, 2021; Mandefro & Jabasingh, 2021). Torrefaction at temperatures above 300°C is not recommended, as it may trigger extensive devolatilisation, initiating pyrolytic reactions.

2) The Effects of Torrefaction Operating Parameters on Biomass Residues

Several key parameters influence torrefaction performance, including temperature, residence time, particle size, biomass type, heating rate, and type of carrier gas. Among these, temperature, residence time, and particle size have the most significant effects on densification properties, pyrolytic behaviour, and combustion characteristics (Ajimotokan *et al.*, 2025; Thengane *et al.*, 2022).

3) The Effects of Torrefying Temperature on Biomass Properties

The effect of torrefaction temperature on biomass properties is illustrated in Figure 2, showing the effects of temperature on HHV and mass yield of different biomass. As temperature increases, biomass undergoes higher mass loss due to the decomposition of hemicellulose and volatile compounds. Increase in calorific value produces a more energy-dense product while a reduction in carbon-to-oxygen ratio improves combustion efficiency (Elbersen *et al.*, 2017; Kim & Choi, 2018). In Table 2, results show that at higher torrefaction temperatures, fixed carbon and ash content increase while the moisture and volatile matter decrease, leading to a more stable fuel (Dyjakon *et al.*, 2021; Iglesias *et al.*, 2023; Phang *et al.*, 2024). Figure 3 depicts a carbon content improvement and a reduction in hydrogen to oxygen ratio with an increasing torrefaction severity. For example, in torrefied corncob, fixed carbon increased from 18–30% at 250°C and further to 52% at 300°C; the ash content increased from 3% to 5% at 250°C, reaching 6% at 300°C; while the volatile matter decreased from 79–65% at 250°C, and further to 42% at 300°C (Velázquez-Martí *et al.*, 2018; Hoang *et al.*, 2021; Mishra *et al.*, 2024).

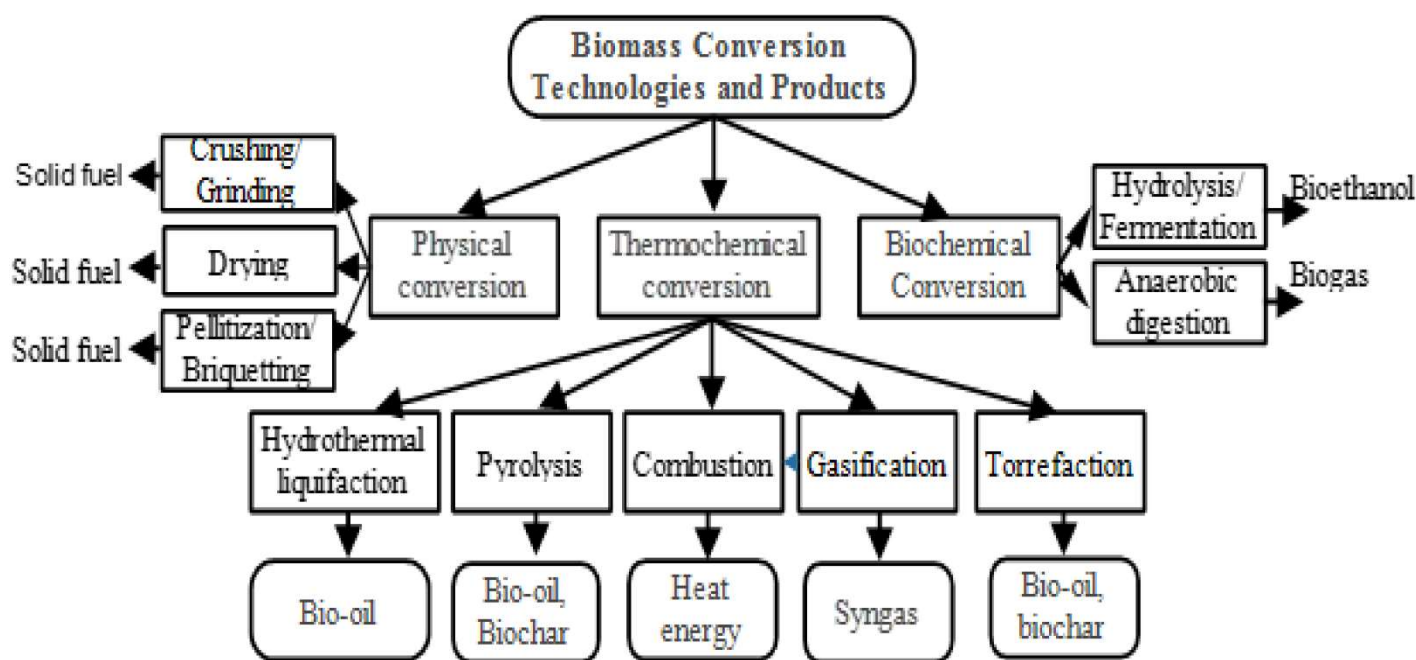


Figure 1: Flow diagram of traditional and sustainable method to biomass conversion (Maitlo, *et al.*, 2022)

4) The Effects of Residence Time

While temperature is the dominant factor in torrefaction, residence time also influences the final biomass properties. Longer residence time improves biofuel properties, but its effect diminishes after one hour (Casas-Ledón *et al.*, 2019; Iglesias *et al.*, 2023). Extended residence time enhances carbon content but reduces overall solid yield due to prolonged decomposition (Thengane *et al.*, 2022). Carbon dioxide levels decrease, while carbon monoxide content gradually increases, indicating progressive biomass degradation.

5) Influence of Biomass Composition on Torrefaction

Lignocellulosic biomass consists of three major polymeric components – hemicellulose, cellulose, and lignin – each undergoing thermal degradation at different rates. The hemicellulose – the most reactive component, exhibits limited devolatilisation and carbonisation below 250°C. Above 250°C, extensive decomposition and carbonisation occur. Higher lignin content results in a more thermally stable torrefied product (Cai *et al.*, 2018; Elbersen *et al.*, 2017; Hoang *et al.*, 2021; Kim & Choi, 2018). The breakdown of the hemicellulose matrix is responsible for reducing biomass tenacity and moisture loss, while hydrophobic properties improve due to the destruction of hydroxyl (-OH) groups, reducing the ability of biomass to form hydrogen bonds.

H. Liquefaction

Liquefaction is an advanced thermochemical conversion technique that depolymerises lignocellulosic biomass into a viscous, energy-dense bio-crude oil through solvolysis reactions under subcritical or near-critical conditions (Basar *et al.*, 2021). The process typically operates within a temperature

range of 250–400°C and pressures of 5–20 MPa to maintain the solvent – commonly water (in hydrothermal liquefaction) or polar organic solvents such as ethanol, methanol, or acetone – in a liquid phase, thereby facilitating rapid heat and mass transfer (Toor *et al.*, 2011; Tekin *et al.*, 2014). The reaction environment promotes the breakdown of biopolymers (cellulose, hemicellulose, and lignin) into smaller oxygenated hydrocarbons, while simultaneously minimising gasification and char formation (Elliott *et al.*, 2015).

The liquefaction process follows a multi-step reaction mechanism, involving depolymerisation – the breakdown of biomass macromolecules (cellulose, hemicellulose, and lignin) into monomers; monomer decomposition – a further degradation of monomers through dehydration (i.e., removal of water molecules), decarboxylation (i.e., release of carbon dioxide), and deamination (i.e., removal of amine groups) (Dong *et al.*, 2024); fragmentation and instability – the formation of small, reactive molecular fragments; and rearrangement and polymerisation – light fragments undergo condensation, cyclisation, and polymerisation, leading to the formation of new bio-oil compounds.

Although liquefaction operates at lower temperatures than pyrolysis, it requires high-pressure conditions, making the design and operation of liquefaction reactors more complex than pyrolytic reactors. This complexity increases reactor and feeding system costs, though overall investment costs remain lower than other advanced conversion technologies (Basar *et al.*, 2021; Dong *et al.*, 2024).

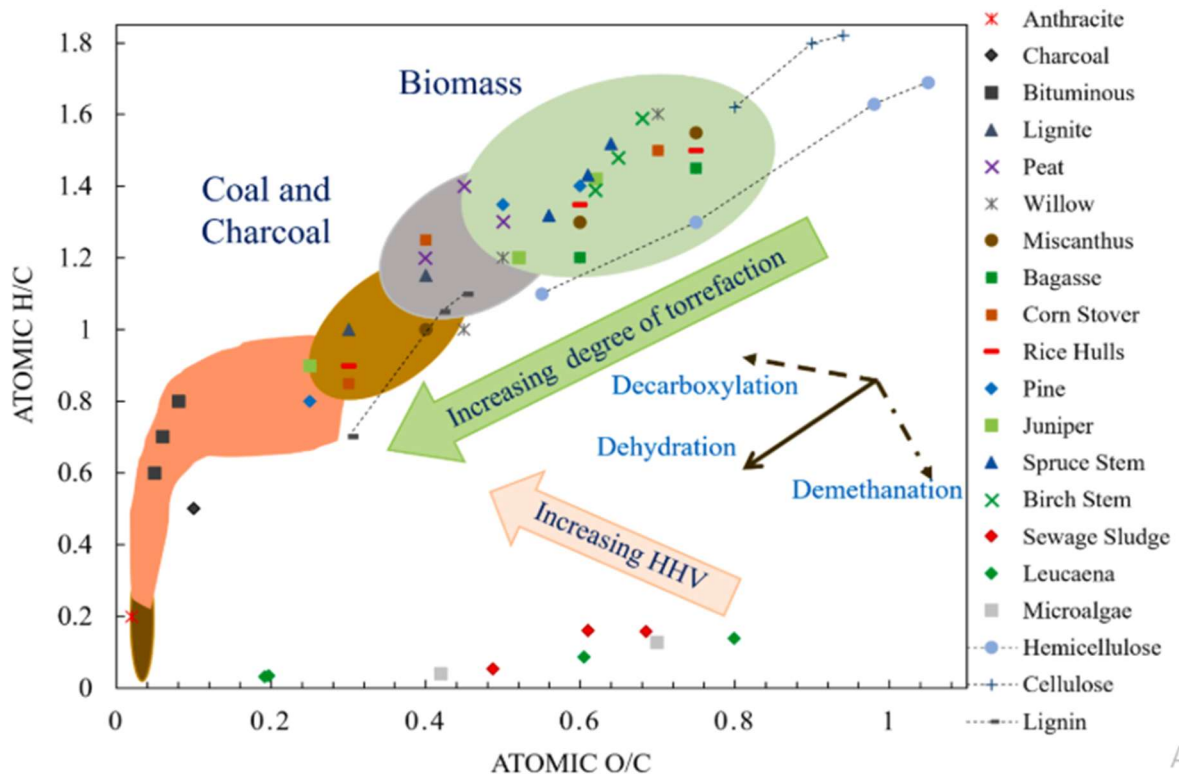
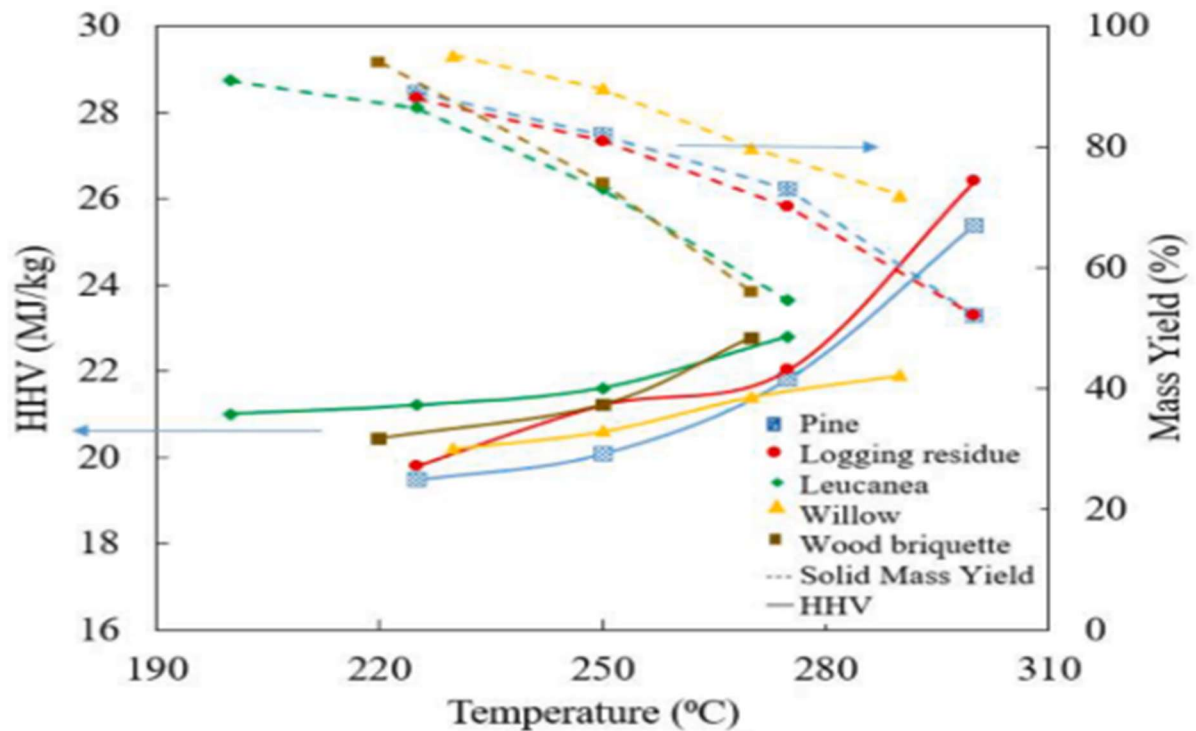


Table 2: Effects of temperature and residence time on biomass yield

Biomass	Temperature	Residence time	HHV	Energy yield	Mass yield	References
Cornstalk	Raw	-	15.30	-	-	Sarker <i>et al.</i> , 2021
	220	-	16.40	93.20	84.0	
	240	-	16.40	87.60	83.6	
	260	-	17.40	70.00	79.9	
	280	-	17.00	60.30	71.5	
Barley Straw	Raw		17.35	-	-	Sarker <i>et al.</i> , 2020
	220	30	18.80	75.00	69.00	
	220	60	19.41	76.00	68.00	
	260	30	20.19	70.00	61.00	
	260	60	20.92	71.00	59.00	
	300	30	21.97	55.00	44.00	
	300	60	22.89	55.00	42.00	
Oat hull	Raw		19.01	-	-	Sarker <i>et al.</i> , 2020
	220	30	17.96	91.00	87.00	
	220	60	18.50	85.00	79.00	
	260	30	19.79	95.00	81.00	
	260	60	20.67	91.00	75.00	
	300	30	22.54	73.00	55.00	
	300	60	23.31	69.00	50.00	
Canola hull	Raw		17.84	-	-	Sarker <i>et al.</i> , 2020
	220	30	19.58	90.00	82.00	
	220	60	20.12	92.00	81.00	
	260	30	21.17	92.00	77.00	
	260	60	22.38	73.00	58.00	
	300	30	24.64	66.00	48.00	
	300	60	25.26	65.00	46.00	
Rubber wood	Raw	-	19.41	-	-	Kongto <i>et al.</i> , 2023
	200	-	20.43	96.03	90.32	
	250	-	22.20	81.20	70.23	
	300	-	27.15	57.48	40.64	

I. Gasification

Biomass gasification is an advanced thermochemical process that is increasingly recognized for its high efficiency and cost reduction in biomass-based electricity generation, particularly when integrated with gas turbine technology. This process partially oxidises organic feedstock to produce syngas, a mixture of combustible gases, which can be used for direct combustion to generate process heat and steam and electricity generation in gas turbines or fuel cells (Molino *et al.*, 2016).

Gasification occurs at high temperatures ranging from 800–1,300°C in either closed-top or open-top gasifiers, which may operate under atmospheric or elevated pressures. Compared with coal gasification, biomass gasification has a comparative advantage due to its lower sulphur content, reducing SO₂ emissions, and lower reactivity, minimising unwanted by-products (Chaves *et al.*, 2024). The gasification process yields a producer gas, which is an energy-rich mixture of combustible gases, consisting of hydrogen, carbon monoxide, and methane; impurities such as carbon dioxide,

nitrogen, sulphur compounds, alkali compounds, and tars (Shahabuddin *et al.*, 2020).

Hydrogen is one of the most promising alternative fuels, particularly for internal combustion engines and fuel cells (Berríos *et al.*, 2016; Li *et al.*, 2020). Gasification has been identified as one of the most efficient thermochemical pathways for hydrogen production from biomass (Casas-Ledón *et al.*, 2019; Bridgwater & Toft, 2011). However, gasification can become energy-intensive when processing biomass with high moisture content, leading to energy imbalances (García *et al.*, 2018). This can be mitigated by introducing carbon dioxide into the gasification atmosphere to optimise reactions, and by steam gasification, which enhances hydrogen production by shifting syngas composition toward higher hydrogen yield (Casas-Ledón *et al.*, 2019; Yang *et al.*, 2014; hao *et al.*, 2017; Xiu & Shahbazi, 2012).

J. Comparison of Thermochemical Pretreatment Methods

Table 3 presents a comparative analysis of different thermochemical pretreatment methods, highlighting their applications, advantages, and limitations

Table 3: Different thermochemical pretreatment methods, areas of applications, advantages and drawbacks

Methods	Description	Application	Advantages	Drawbacks	References
Pyrolysis	It is a thermochemical process for converting biomass feedstock into energy fuel by thermally decomposing its lignocellulosic structure in non-oxidative environment at a temperature range between 400°C to 600°C.	Conversion of biomass feedstock into energy fuel in form of solid, liquid or gas.	The bio-oil produced can generate maximum yield of bio-oil of phenolic derivatives that could be obtained in nitrogen atmosphere.	The major downsides are heterogenous mixture of the oil, corrosiveness and poor thermal stability of the bio-oil produced.	Nour <i>et al.</i> , 2021
Torrefaction	It is a thermochemical pretreatment process carried out at a temperature range of 200°C to 300°C in an inert condition that transforms biomass into a relatively superior handling, milling, co-firing and clean energy solid biofuel.	It is used to produce solid fuel (target) from raw lignocellulose biomass.	Improved energy density and the end product usually exhibits hydrophobic property.	It necessitates high energy input.	Amer <i>et al.</i> , 2019
Liquefaction	Liquefaction is an alternative thermochemical conversion method of converting biomass feedstock into bio-oil fraction (goal), char and gas fractions at low temperature (250°C to 400°C) under high pressure ranging between 5 to 20 MPa in water or other apt solvent.	It is used for converting biomass feedstock into bio-oil fraction (goal), char and gas fractions.	It can be used to produce high quality bio-oil from biomass.	Due to the design complexity of the reactor and the feeding system, the reactor is more expensive than some other thermochemical reactors.	Dong <i>et al.</i> , 2024
Gasification	Gasification process takes place at temperature ranges from 800°C to 1300°C, it is usually carried out in closed top or open top gasifiers which can be operated at atmospheric pressure or higher.	It is usually carried out in closed top or open top gasifiers to produce fuel in gaseous state.	Improved efficiency and reduction in cost of biomass electricity generation when used in a gas turbine technology.	It could consume more energy than the output energy of the end -product if not properly engineered.	Chang <i>et al.</i> , 2023

K. Densification

Densification is a mechanical process that enhances the bulk density of biomass by compressing it into fuel of various shapes using applied pressure. This process disrupts the cellular structure of the biomass, allowing for improved handling, transport, and combustion properties (Albashabsheh & Heier Stamm, 2021; Vaish *et al.*, 2022). The densified products, known as solid biofuels, serve as an efficient energy source and can also be utilised for chemical production (Eling *et al.*, 2024). The densification process involves mechanical biomass conversion processes, phases of biomass densification, key parameters affecting biomass

densification, key densification techniques, and quality assessment of densified fuel.

1) Mechanical Biomass Conversion Processes

Mechanical biomass conversion involves physically altering the structure of the feedstock through chipping, grinding, and milling. This process results in densified solid fuels such as briquettes, pellets, and cubes, with final product characteristics determined by die dimensions (Eling *et al.*, 2024; Sarker *et al.*, 2023).

2) Phases of Biomass Densification

The densification process occurs in three distinct phases. These phases are particle rearrangement, i.e., particles move into a closely packed formation while retaining their properties; plastic and elastic deformation – particles experience deformation, leading to increased contact and bonding via van der Waals electrostatic forces; compaction and density optimisation – at higher pressures, the biomass volume significantly decreases, and the final product achieves true density of its component materials (Acampora *et al.*, 2021; Albashabsheh & Heier Stamm, 2021; Sarker *et al.*, 2023; Stelte *et al.*, 2012a; Vaish *et al.*, 2022).

3) Key Parameters Affecting Biomass Densification

Biomass moisture content, temperature, and feedstock composition are critical in determining the quality of densified fuels. The moisture content (8–12%) – optimal levels are necessary to balance binding strength and structural integrity. Excess moisture reduces product stability (Ajimotokan *et al.* 2019a; Ajimotokan *et al.* 2019b; Bot *et al.*, 2024; Mekonen *et al.*, 2024; Oladosu *et al.*, 2023). Relatively high temperatures generally result in stronger densified fuels due to increased biomass plasticity, while excessive moisture can reduce binding efficiency by lowering wall friction (Ajimotokan *et al.*, 2025; Eling *et al.*, 2024; Gong *et al.*, 2023; Song & Hall, 2020).

4) Densification Techniques

The two principal densification techniques employed for the production of solid biofuels from biomass residues are briquetting and pelleting. Briquettes are typically cylindrical in shape, with diameters ranging from approximately 60–100 mm and lengths up to 300 mm, making them relatively large and more suitable for industrial-scale thermal applications such as boiler and furnace operations (Stelte *et al.*, 2012b). In contrast, pellets are more compact, generally cylindrical with diameters between 6 and 12 mm and lengths of 10–30 mm, which makes them ideal for small-scale domestic heating systems due to their ease of handling, uniformity, and better combustion efficiency (Stelte *et al.*, 2012b; Sui *et al.*, 2024). Figure 4 depicts the typical pellets.

The densification process of bio-residues into briquettes or pellets significantly enhances the energy density, mechanical durability, and storage characteristics of biomass, contributing to improved logistics and end-use performance. Table 4 presents a comparative analysis of different densification process methods, highlighting their applications, advantages, and limitations.



Figure 4: The pellets

a) The Effects of Biogenic Feedstock Composition on Densified Fuel

The chemical composition of biomass plays a crucial role in determining the efficiency of densification, the energy required, and the final fuel quality, including its strength (shatter index), durability, and moisture resistance (Sarker *et al.*, 2021, 2022). Various chemical components within biomass contribute differently to the densification process (Kongto *et al.*, 2024; Anggraeni *et al.*, 2021; Sarker *et al.*, 2020). The key biogenic components and their influence are lignocellulosic constituents, i.e., the three main polymeric fractions in biomass – lignin, cellulose, and hemicellulose – affect densified fuel durability; and lipids and organic components, which facilitate hydrophobic properties improve moisture resistance (Lavergne *et al.*, 2021; Picchio *et al.*, 2020; Yu *et al.*, 2024). However, lignin is the primary component responsible for binding strength, rather than overall durability; and moisture content, which optimal moisture level (10% to 12% w/w) varies between feedstocks but is essential for proper compaction and adhesion (Miguel *et al.*, 2022; Yang *et al.*, 2022). A high lipid fraction can reduce densification energy requirements by acting as a natural lubricant, whereas an excessive hemicellulose fraction can create voids and increase elastic spring-back, reducing final fuel density and mechanical stability (Ismail *et al.*, 2023; Deshannavar *et al.*, 2018; Lavergne *et al.*, 2021).

b) Operating Parameters Affecting Densification

The operating parameters that affect densification include die temperature, which should be carefully set to soften lignin, enhancing its binding effect. However, excessive heat can trigger decomposition, reducing fuel integrity (Miguel *et al.*, 2022; Yang *et al.*, 2022); and high pressure, which is necessary to compress particles, create flow, and enhance molecular interpenetration, leading to solid fuel formation (Eling *et al.*, 2024; Gong *et al.*, 2023; Pradhan *et al.*, 2021).

Table 4: Different densification methods, areas of applications, Advantages and drawback

Densification Process Methods	Descriptions	Advantages	Drawbacks	Applications	References
Piston press	It involves densifying biomass feedstock by employing a piston press to produce fuels in solid form.	It can be used to produce solid fuel in form of pellets with uniform shape. This method is suitable for producing fuel in small-scale.	High initial investments cost, low rate of production and electricity requirement.	Suitable for small-scale production from all biomass sources.	Menya & Atim, 2024; Gong <i>et al.</i> , 2023; Sarker <i>et al.</i> , 2023; Eling <i>et al.</i> , 2024.
Extrusion	It entails compression of biogenic feedstock using die and extruder to produce highly dense solid fuel.	It can be used for continuous production of solid fuels with uniform shape and high density.	High initial investment cost is a major disadvantage.	Appropriate for continuous production of solid fuel from agricultural and forestry activities.	Sarker <i>et al.</i> , 2023; Song & Hall, 2020; Vaish <i>et al.</i> , 2022; Eling <i>et al.</i> , 2024.
Pellet mill	It entails production of solid fuels by compression of biogenic feedstock to produce pellets through a die.	They have ability to create a dense, uniform fuel source from various biomass materials.	It has high initial investment cost.	Suitable for continuous production of solid fuel from agricultural and forestry activities.	Song & Hall, 2020; Vaish <i>et al.</i> , 2022; Menya & Atim, 2024; Eling <i>et al.</i> , 2024.
Screw press	It entails compaction of biogenic feedstock into the press by a rotating screw to produce pellets with the aid of a tapered die.	It can be used for small to medium - scale production of solid fuel. It is energy efficient and requires minimal electricity input.	High operating and maintenance cost, fuel produced from this method exhibit low density.	Appropriate for continuous production of solid fuel from agricultural and forestry activities.	Sarker <i>et al.</i> , 2023; Menya & Atim, 2024; Vaish <i>et al.</i> , 2022.

5) *Quality Assessment of Densified Fuel*

After densification, standardised testing is essential to evaluate fuel performance. These tests include density test to determine mass density and fuel compactness, and compressive strength test to assess the fuel's resistance to rupture during handling, storage, and transport. Low compressive strength indicates weak H-bonding, van der Waals forces, and mechanical interlocking (Iglesias *et al.*, 2023; Sarker *et al.*, 2021). High hemicellulose content has been linked to poor density and compression resistance, leading to greater void formation (Arewa *et al.*, 2016; Elinge *et al.*, 2019).

L. Co-Densification as an Innovative Approach

Recent advancements have introduced co-densification, which involves combining multiple biomass sources to optimise densification properties. This method is in particular useful when dealing with feedstocks that lack sufficient binding properties, as they can be blended with biomass rich in natural binders to enhance fuel quality (Kpalo *et al.*, 2020; Sarker *et al.*, 2021; Song & Hall, 2020).

M. The Effects of Thermochemical Pretreatment on Densified Biomass Fuel

Thermochemical pretreatment methods, such as torrefaction, have been shown to significantly influence

densification by reducing energy consumption, improving fuel quality, and enhancing pyrolytic performance (Akhtar *et al.*, 2021; Jha *et al.*, 2022b; Thengane *et al.*, 2022). Torrefaction leads to the removal of volatile hemicelluloses, which disrupts the biomass matrix, making it more brittle and easier to compress. The process alters biomass interlocking, facilitating denser and more uniform solid fuels (Akhtar *et al.*, 2021; Gizaw *et al.*, 2024). Pyrolysis on the other hand are used for improving the physicochemical properties of biomass. Although, pyrolysis is suitable for bio-oil, yet, biochar from pyrolysis is brittle and hence proper design of densification is necessary. Gasification is used for fuel in gaseous form and hence its discussion is limited in this overview.

N. Advantages of Thermochemical Pretreatment

The advantages of thermochemical pretreatment include lower energy requirement because torrefied biomass is easier to grind and densify, reducing the input energy required for mechanical processing (Iglesias *et al.*, 2023); enhanced fuel properties as torrefied biomass exhibits higher heating values, greater hydrophobicity, and improved combustion characteristics compared to untreated biomass; brittle and fine particle formation because thermochemical pretreatment breaks down hemicellulose, making the

material less reactive and more grindable (Akhtar *et al.*, 2021; Gizaw *et al.*, 2024; Sarker *et al.*, 2020).

IV. Conclusions

This study comprehensively reviewed biomass-based solid fuel production, focusing on various biomass sources, conversion techniques, and densification methods. Through an extensive review of literature on bioenergy production, it was found that wood-based biomass remains the predominant feedstock, accounting for approximately 67% of total biomass utilisation. Other significant sources include woody residues (5%), agricultural residues (4%), industrial and municipal solid waste (3%), energy crops (3%), and forest residues (1%), among others. Key conversion pathways, including pyrolysis, torrefaction, gasification, and liquefaction were evaluated based on their efficiency and impact on fuel quality. Among these, torrefaction emerged as the most effective method for solid fuel development, owing to its ability to improve solid fuel characteristics by reducing moisture content and enhancing energy density. This makes torrefied biomass a strong candidate for replacing low-rank coal and firewood. The review also examined densification techniques, emphasising the importance of feedstock composition, processing temperature, and moisture content as critical parameters influencing solid fuel quality. Elevated temperature and moisture levels were found to significantly affect both energy input requirements and the properties of the final fuel product. A notable innovation identified in this review is the development of hybrid solid fuels, which involve blending multiple biomass types. This strategy improves densification efficiency, enhances combustion performance, and broadens the spectrum of usable feedstocks. As such, hybridisation represents a promising pathway for optimising solid biofuel production. Future research should prioritise the scaling-up of hybrid densification technologies, the optimisation of torrefaction parameters for hybrid fuels, and the exploration of novel biomass sources to advance the sustainability and economic viability of biomass-derived solid fuels.

AUTHOR CONTRIBUTIONS

N.S. Saidu: Conceptualisation, Data curation, Formal analysis, Writing – Original draft, Writing – Review & editing.

H.A. Ajimotokan: Visualisation, Conceptualisation, Writing – Review & editing. **K.R. Ajao:** Writing – Review & editing.

REFERENCES

- Acampora, A., Civitarese, V., Sperandio, G., & Rezaei, N.** (2021). Qualitative characterization of the pellet obtained from hazelnut and olive tree pruning. *Energies*, 14(14), 4083.
- Ajimotokan, H. A., Saidu, N. S., Aladodo, M. A., Oladosu, K., Samuel, O. D., Abdulrahman, K. O., El-Suleiman, A., Yaru S. S., & Ajao, K. R.** (2025). Combustion characteristics of torrefied corncob and African birch wood residues at higher heating rate. *Scientific African*, 27, e02494.
- Ajimotokan, H. A.** (2023). *Research Techniques: Qualitative, quantitative and mixed-methods approaches for engineers*. Swam, Switzerland: Springer, Cham.
- Ajimotokan, H. A., Ajao, K. R., Rabi, A. B., Yahaya, T., Nasir, A., Adegun, I. K., & Popoola, O. T.** (2023). Performance analysis and sensitivity of system parameters on the performance of trilateral-cycle power generator systems. *Australian Journal of Mechanical Engineering*, 20(1), 133-143.
- Ajimotokan, H. A., Ayuba, I. & Ibrahim, H. K.** (2022). Thermo-economic feasibility analysis of trilateral-cycle power generators for waste heat recovery-to-power applications. *Journal of Thermal Engineering*. 8(6), 786–797.
- Ajimotokan, H. A., Ehindero, A. O., Ajao, K. S., Adeleke, A. A., Ikubanni, P. P., & Shuaib-Babata, Y. L.** (2019a). Combustion characteristics of fuel briquettes made from charcoal particles and sawdust agglomerates. *Scientific African*, 6, e00202.
- Ajimotokan, H. A., Ibitoye, S. E., Odusote, J. K., Adesoye, O. A., & Omoniyi, P. O.** (2019b). Physico-mechanical properties of composite briquettes from corncob and rice husk. *Journal of Bioresource and Bioproducts*, 4(3), 159–65.
- Ajimotokan, H. A., Ibitoye, S. E., Odusote, J. K., Adesoye, O. A., & Omoniyi, P. O.** (2019c). Physico-mechanical characterisation of fuel briquettes made from blends of corncob and rice husk. *Journal of Physics: Conference Series*, 1378(2), 022008.
- Akhtar, J., Imran, M., Ali, A. M., Nawaz, Z., Muhammad, A., Butt, R. K., Jillani, M. S., & Naeem, H. A.** (2021). Torrefaction and thermochemical properties of agriculture residues. *Energies*, 14(14), 4218.
- Akinrinola, F. S., Ikechukwu, N., Darvell, L. I., Jones, J. M., & Williams, A.** (2020). The potential use of torrefied Nigerian biomass for combustion applications. *Journal of the Energy Institute*, 93(4), 1726–1736.
- Alam, M., Sarkar, I., Chanda, N., Ghosh, S., & Loha, C.** (2024). Enhancing syngas production and hydrogen content in syngas from catalytic slow pyrolysis of biomass in a pilot scale fixed bed reactor. *Biomass Conversion and Biorefinery*, 15, 6237–6249.
- Albabsheh, N. T., & Heier Stamm, J. L.** (2021). Optimization of lignocellulosic biomass-to-biofuel supply chains with densification: Literature review. *Biomass and Bioenergy*, 144, 105888.
- Alherbawi, M., McKay, G., Mackey, H. R., & Ansari, T.** (2021). A novel integrated pathway for Jet biofuel production from whole energy crops: A Jatropha curcas case study. *Energy Conversion and Management*, 229, 113662.
- Amer, M., Nour, M., Ahmed, M., El-Sharkawy, I., Ookawara, S., Nada, S., & Elwardany, A.** (2021). Kinetics and physical analyses for pyrolyzed Egyptian agricultural and woody biomasses: effect of microwave drying. *Biomass Conversion and Biorefinery*, 11(6), 2855–2868.
- Amer, M., Nour, M., Ahmed, M., Ookawara, S., Nada, S., & Elwardany, A.** (2019). The effect of microwave drying pretreatment on dry torrefaction of agricultural biomasses. *Bioresource Technology*, 286, 121400.

- Anggraeni, S., Hoffah, S.N., Nandiyanto, A.B.D., Bilad, M.R.,** (2021). Effects of particle size and composition of cassava peels and rice husk on the briquette performance. *Journal of Engineering Science and Technology*, 16(1), 527–542.
- Arewa, M.E., Daniel, I.C., Kuye, A.,** (2016). Characterisation and comparison of rice husk briquettes with cassava peels and cassava starch as binders. *Biofuels* 7(6), 671–675.
- Ashraf, A., Sattar, H., & Munir, S.** (2019). Thermal decomposition study and pyrolysis kinetics of coal and agricultural residues under non-isothermal conditions. *Fuel*, 79(120), 504–514.
- Awasthi, M. K., Sindhu, R., Sirohi, R., Kumar, V., Ahluwalia, V., Binod, P., Juneja, A., Kumar, D., Yan, B., Sarsaiya, S., Zhang, Z., Pandey, A., & Taherzadeh, M. J.** (2022). Agricultural waste biorefinery development towards circular bio-economy. *Renewable and Sustainable Energy Reviews*, 158, 112122.
- Balali, A., Yunusa-Kaltungo, A., & Edwards, R.** (2023). A systematic review of passive energy consumption optimisation strategy selection for buildings through multiple criteria decision-making techniques. *Renewable and Sustainable Energy Reviews*, 171, 113013.
- Barontini, F., Biagini, E., & Tognotti, L.** (2021). Influence of Torrefaction on Biomass Devolatilization. *ACS Omega*, 6(31), 20264–20278.
- Basar, I. A., Liu, H., Carrere, H., Trably, E., & Eskicioglu, C.** (2021). A review on key design and operational parameters to optimize and develop hydrothermal liquefaction of biomass for biorefinery applications. *Green Chemistry*, 23(4), 1404–1446.
- Berrios, M., Cáceres, C., & Calvo, L.** (2016). Hydrogen production from biomass gasification: A review. *Renewable and Sustainable Energy Reviews*, 56, 212–228.
- Bilandžija, D., Bilandžija, N., & Zgorelec, Ž.** (2021). Sequestration potential of energy crop *Miscanthus x giganteus* cultivated in continental part of Croatia. *Journal of Central European Agriculture*, 22(1), 188–200.
- Bot, B. V., Tamba, J. G., & Sosso, O. T.** (2024). Assessment of biomass briquette energy potential from agricultural residues in Cameroon. *Biomass Conversion and Biorefinery*, 14(2), 1905–1917.
- Bridgwater, T.** (2018). Challenges and opportunities in fast pyrolysis of biomass: Part I. *Johnson Matthey Technology Review*, 62(1), 118–130.
- Bridgwater, A. V., & Toft, A. J.** (2011). Biomass fast pyrolysis. *Renewable and Sustainable Energy Reviews*, 15(9), 4307–4321.
- Cahyanti, M. N., Doddapaneni, T. R. K. C., Madisoo, M., Pärn, L., Virro, I., & Kikas, T.** (2021). Torrefaction of agricultural and wood waste: Comparative analysis of selected fuel characteristics. *Energies*, 14(10), 2774.
- Cai, J., Xu, D., Dong, Z., Yu, X., Yang, Y., Banks, S. W., & Bridgwater, A. V.** (2018). Processing thermogravimetric analysis data for isoconversional kinetic analysis of lignocellulosic biomass pyrolysis: Case study of corn stalk. *Renewable and Sustainable Energy Reviews*, 82, 2705–2715.
- Cai, W., Wang, X., Zhu, Z., Kumar, R., Nana Amaniampong, P., Zhao, J., & Hu, Z. T.** (2023). Synergetic effects in the co-pyrolysis of lignocellulosic biomass and plastic waste for renewable fuels and chemicals. *Fuel*, 353, 129210.
- Casas-Ledón, Y., Flores, M., Jiménez, R., Ronsse, F., Dewulf, J., & Arteaga-Pérez, L. E.** (2019). On the environmental and economic issues associated with the forestry residues-to-heat and electricity route in Chile: Sawdust gasification as a case study. *Energy*, 12(132) 763–776.
- Chang, Y.J., Chang, J.S., & Lee, D.J.** (2023). Gasification of biomass for syngas production: Research update and stoichiometry diagram presentation. *Bioresource Technology*, 12(95), 129535.
- Chaves, M., Torres, C., Tenorio, C., Moya, R., & Arias-Aguilar, D.** (2024). Syngas characterization and electric performance evaluation of gasification process using forest plantation biomass. *Waste and Biomass Valorization*, 15(3), 1291–1308.
- Chen, W. H., Lin, B. J., Lin, Y. Y., Chu, Y. S., Ubando, A. T., Show, P. L., Ong, H. C., Chang, J. S., Ho, S. H., Culaba, A. B., Pétrissans, A., & Pétrissans, M.** (2021). Progress in biomass torrefaction: principles, applications and challenges. *Progress in Energy and Combustion Science*, 10(8), 100887.
- Chen, W. H., Lu, K. M., & Tsai, C. M.** (2012). An experimental analysis on property and structure variations of agricultural wastes undergoing torrefaction. *Applied Energy*, 05(05), 318–325.
- Cheng, F., Luo, H., & Colosi, L. M.** (2020). Slow pyrolysis as a platform for negative emissions technology: An integration of machine learning models, life cycle assessment, and economic analysis. *Energy Conversion and Management*, 11(32), 113258.
- Chong, C. T., Mong, G. R., Ng, J.-H., Chong, W. W., Ani, F. N., Lam, S. S., & Ong, H. C.** (2019). Pyrolysis characteristics and kinetic studies of horse manure using thermogravimetric analysis. *Energy Conversion and Management*, 11(7), 1260–1267.
- Dan, M., Senila, L., Roman, M., Mihet, M., & Lazar, M. D.** (2015). From wood wastes to hydrogen – preparation and catalytic steam reforming of crude bio-ethanol obtained from fir wood. *Renewable Energy*, 7(50), 27–36.
- Deshannavar, U.B., Hegde, P.G., Dhalayat, Z., Patil, V., Gavas, S.,** (2018). Production and characterization of agro-based briquettes and estimation of calorific value by regression analysis: An energy application. *Materials Science and Energy Technology*, 1 (2), 175–181.
- Dong, S., Liu, Z., & Yang, X.** (2024). Hydrothermal liquefaction of biomass for jet fuel precursors: A review. *Chinese Chemical Letters*, 35(8), 109142.
- Dubdub, I.** (2023). Kinetics study of polypropylene pyrolysis by non-isothermal thermogravimetric analysis. *Materials*, 16(2), 584.

- Dumortier, J., Dokoochaki, H., Eloheid, A., Hayes, D. J., Laird, D., & Miguez, F. E.** (2020). Global land-use and carbon emission implications from biochar application to cropland in the United States. *Journal of Cleaner Production*, 258, 120684.
- Dyjakon, A., Noszczyk, T., Sobol, L., & Misiakiewicz, D.** (2021). Influence of torrefaction temperature and climatic chamber operation time on hydrophobic properties of agri-food biomass investigated Using the EMC Method. *Energies*, 14(17), 5299.
- El Bari, H., Fanezoune, C. K., Dorneanu, B., Arellano-Garcia, H., Majoz, T., Elhenawy, Y., Bayssi, O., Hirt, A., Peixinho, J., Dhahak, A., Gadalla, M. A., Khashaba, N. H., & Ashour, F. H.** (2024). Catalytic fast pyrolysis of lignocellulosic biomass: Recent advances and comprehensive overview. *Journal of Analytical and Applied Pyrolysis*, 178, 106390.
- Elbersen, W., Lammens, T. M., Alakangas, E. A., Annevelink, B., Harmsen, P., & Elbersen, B.** (2017). Lignocellulosic biomass quality. In *Modeling and Optimization of Biomass Supply Chains*, (55–78).
- Elif, G. A.** (2024). Anaerobic mono and co-digestion of agro-industrial waste and municipal sewage sludge: Biogas production potential, kinetic modelling, and digestate characteristics. *Fuel*, 355, 129468.
- Eling, J., Okot, D. K., Menya, E., & Atim, M. R.** (2024). Densification of raw and torrefied biomass: A review. *Biomass and Bioenergy*, 184, 107210.
- Elinge, C.M., Birnin-Yauri, A.U., Senchi, D.S., Ige, A.R., Ajakaye, J., Yusuf, A., & Abubakar, R.K.** (2019). Studies on the combustion profile of briquettes produced from carbonized rice husk using different binders at moderate temperature and die pressure. *Journal of Advanced Academic Research* 5(3), 70-77.
- Elliott, D. C., Biller, P., Ross, A. B., Schmidt, A. J., & Jones, S. B.** (2015). Hydrothermal liquefaction of biomass: Developments from batch to continuous process. *Bioresource Technology*, 178, 147–156.
- García, L. E., González, A. G., & Ríos, L. A.** (2018). The effect of biomass moisture content on the gasification process: A review. *Energy & Fuels*, 32(7), 7055-7072.
- Gizaw, D. G., Periyasamy, S., Baylie, H., Tassew Redda, Z., Asaithambi, P., Jayakumar, M., Baskar, G., & Pugazhendhi, A.** (2024). Advances in solid biofuels production through torrefaction: Potential biomass, types of torrefaction and reactors, influencing process parameters and future opportunities – A review. *Process Safety and Environmental Protection*, 4(7), 1307–1319.
- Gong, C., Meng, X., Thygesen, L. G., Sheng, K., Pu, Y., Wang, L., Ragauskas, A., Zhang, X., & Thomsen, S. T.** (2023). The significance of biomass densification in biological-based biorefineries: A critical review. *Renewable and Sustainable Energy Reviews*, 183, 113520.
- Hameed, S., Sharma, A., Pareek, V., Wu, H., & Yu, Y.** (2019). A review on biomass pyrolysis models: Kinetic, network and mechanistic models. *Biomass and Bioenergy*, 2(8), 104–122.
- Hoang, A. T., Ong, H. C., Fattah, I. M. R., Chong, C. T., Cheng, C. K., Sakthivel, R., & Ok, Y. S.** (2021). Progress on the lignocellulosic biomass pyrolysis for biofuel production toward environmental sustainability. *Fuel Processing Technology*, 10(6997), 106997.
- Hossain, M. S., Therasme, O., Rajendran, K., Volk, T. A., Kumar, V., & Kumar, D.** (2024). Biochemical conversion of woody biomass to liquid biofuels. In *Sustainable Biorefining of Woody Biomass to Biofuels and Biochemicals* 81–101.
- How, B. S., Ngan, S. L., Hong, B. H., Lam, H. L., Ng, W. P. Q., Yusup, S., Ghani, W. A., Kansha, Y., Chan, Y. H., Cheah, K. W., Shahbaz, M., Singh, H. K. G., Yusuf, N. R., Shuhaili, A. F., & Rampli, J.** (2019). An outlook of Malaysian biomass industry commercialization: Perspectives and challenges. *Renewable and Sustainable Energy Reviews*, 113, 109277.
- Hryhoriv, Y., Butenko, Y., Kabanets, V., Filon, V., Kriuchko, L., Bondarieva, L., Mikulina, M., Yevtushenko, Y., Polyvanyi, A., & Kovalenko, V.** (2024). Prospectives of growing energy crops for the production of different types of biofuels. *Ecological Engineering & Environmental Technology*, 25(5), 191–197.
- Hu, W., Wang, J., Hu, J., Schuler, J., Grushecky, S., Jiang, C., Smith, W., Nan, N., & Sabolsky, E. M.** (2024). Combustion Behaviors, Kinetics, and Thermodynamics of Naturally Decomposed and Torrefied Northern Red Oak (*Quercus rubra*) Forest Logging Residue. *Energies*, 17(7), 1607.
- Ibitoye, S. E., Ajimotokan, H. A., Adeleke, A. A., & Loha, C.** (2023a). Effect of densification process parameters on the physico-mechanical properties of composite briquettes of corncob and rice husk. *Materials Today: Proceedings*.
- Ibitoye, S. E., Mahamood, R. M., Jen, T., Loha, C., & Akinlabi, E. T.** (2023b). An overview of biomass solid fuels: Biomass sources, processing methods, and morphological and microstructural properties. *Journal of Bioresources and Bioproducts*, 8(4), 333–360.
- Iglesias, C. A., Proupin, C. J., Rodríguez, A. J. A., Eimil, F. C., & Rodríguez, S. R.** (2023). Predicting the energy properties of torrefied debarked pine pellets from torrefaction temperature and residence time. *Renewable Energy*, 218, 119346.
- Ikegwu, U. M., Ozonoh, M., & Daramola, M. O.** (2021). Kinetic study of the isothermal degradation of pine sawdust during torrefaction process. *ACS Omega*, 6(16), 10759–10769.
- Irawan, A.** (2021). Potential and opportunity of co-firing power plant in Indonesia through torrefaction of empty fruit bunch - A review In *World Chemical Engineering Journal*, 5(1), 25–32.
- Ismail, R. I., Khor, C. Y., & Mohamed, A. R.** (2023). Pelletization temperature and pressure effects on the mechanical properties of *Khaya senegalensis* biomass energy pellets. *Sustainability*, 15(9), 7501.
- Javanmard, A., Abdul Patah, M. F., Zulhelmi, A., & Daud, W. M. A. W.** (2023). A comprehensive overview of the continuous torrefaction method: Operational characteristics, applications, and challenges. *Journal of the Energy Institute*, 108, 101199.

- Jekayinfa, S. O., Orisaleye, J. I., & Pecenka, R.** (2020). An assessment of potential resources for biomass energy in Nigeria. In *Resources* 9 (8), 1–43.
- Jha, S., Nanda, S., Acharya, B., & Dalai, A. K.** (2022a). A review of thermochemical conversion of waste biomass to biofuels. *Energies*, 15(17), 6352.
- Jha, S., Okolie, J. A., Nanda, S., & Dalai, A. K.** (2022b). A review of biomass resources and thermochemical conversion technologies. *Chemical Engineering & Technology*, 45(5), 791–799.
- Johnson, M. T., & Lee, R. S.** (2019). Energy conversion from biomass: Pathways and technologies. *Journal of Renewable Energy*, 45(3), 215–229.
- Khudayar, D., Mehrpooya, M., & Moosavian, S. M. A.** (2024). Hybrid biomass fast pyrolysis process and solar thermochemical energy storage system, investigation and process development. *Arabian Journal for Science and Engineering*, 49, 8341–8362.
- Kim, J. S., & Choi, G. G.** (2018). Pyrolysis of lignocellulosic biomass for biochemical production. *Waste Biorefinery: Potential and Perspectives*, 323–348.
- Kongto, P., Palamanit, A., Chaiprapat, S., Tippayawong, N., Khempila, J., & Ruangim, P.** (2024). Key fuel characteristics and techno-economic aspects of torrefied rubberwood biomass pellets produced by incorporating various cassava-based binders at varied doses. *Environmental Science and Pollution Research*, 31, 37663–3768.
- Kongto, P., Palamanit, A., Chaiprapat, S., Tippayawong, N., Khempila, J., Lam, S. S., Hayat, A., & Yuh Yek, P. N.** (2023). Physicochemical changes and energy properties of torrefied rubberwood biomass produced by different scale moving bed reactors. *Renewable Energy*, 219, 1–15.
- Kpalo, S. Y., Zainuddin, M. F., Manaf, L. A., & Roslan, A. M.** (2020). Production and characterization of hybrid briquettes from corncobs and oil palm trunk bark under a low-pressure densification technique. *Sustainability*, 12(6), 2468.
- Kumar, J. A., Sathish, S., Prabhu, D., Renita, A. A., Saravanan, A., Deivayanai, V. C., Anish, M., Jayaprabakar, J., Baigenzhenov, O., & Hosseini-Bandegharaei, A.** (2023). Agricultural waste biomass for sustainable bioenergy production: Feedstock, characterization and pre-treatment methodologies. *Chemosphere*, 331, 138680.
- Kumar, P., Subudhi, S., Bhatia, L., Saha, K., Mudgil, D., Prasad Shadangi, K., Srivastava, R. K., Pattnaik, B., & Arya, R. K.** (2022). Utilization of agricultural waste biomass and recycling toward circular bioeconomy. *Environmental Science and Pollution Research*, 30(4), 8526–8539.
- Laihonen, A., Aalto, S. L., Pihlatie, M., & Tirola, M.** (2024). Production of greenhouse gases by logging residue in boreal clear-cut forests. *European Journal of Forest Research*, 143, 1267–1281.
- Lavergne, S., Larsson, Sylvia. H., Da Silva Perez, D., Marchand, M., Campargue, M., & Dupont, C.** (2021). Effect of process parameters and biomass composition on flat-die pellet production from underexploited forest and agricultural biomass. *Fuel*, 12(302), 121076.
- Li, J., Xu, K., Yao, X., & Liu, J.** (2024). Investigation of biomass slow pyrolysis mechanisms based on the generation trends in pyrolysis products. *Process Safety and Environmental Protection*, 183, 327–338.
- Li, J., Li, Z., & Liu, M.** (2020). Progress in hydrogen production from biomass and waste materials: A review. *International Journal of Hydrogen Energy*, 45(52), 29288–29307.
- Ma, R., Yi, W., Liu, H., Sun, X., Zhang, Q., Sun, Z., Zhang, D., Wang, F., & Song, N.** (2024). Study on the flow characteristics of heterogeneous particles in three types of biomass fast pyrolysis down-tube reactors. *Powder Technology*, 11(440), 119736.
- Maitlo, G., Ali, I., Mangi, K. H., Ali, S., Maitlo, H. A., Unar, I. N., & Pirzada, A. M.** (2022). Thermochemical Conversion of Biomass for Syngas Production: Current Status and Future Trends. *Sustainability*, 14(5), 2596.
- Mamvura, T. A., & Danha, G.** (2020). Biomass torrefaction as an emerging technology to aid in energy production. *Heliyon* 6 (3), e03531.
- Mandefro, D., & Jabasingh, A.** (2021). A study on the torrefaction of rice husk as an attempt to enhance its energy content. *Journal of Scientific & Industrial Research* 80, 87–90.
- Marques, J. de A. O., Alves, J. L. F., de Oliveira, G. P., Melo, D. M. de A., de Melo Viana, G. A. C., & Braga, R. M.** (2024). Catalytic flash pyrolysis of *Scenedesmus* sp. post-extraction residue using low-cost HZSM-5 catalyst with the perspective to produce renewable aromatic hydrocarbons. *Environmental Science and Pollution Research*, 31(12), 18785–18796.
- Mekonen, A. G., Berhe, G. G., Desta, M. B., Belete, F. A., & Gebremariam, A. F.** (2024). Production and characterization of briquettes from sugarcane bagasse of Wonji Sugar Factory, Oromia, Ethiopia. *Materials for Renewable and Sustainable Energy*, 13, 27–43.
- Mellalou, A., Silva, W. O., Soutrenon, M., Girault, H. H., Outzourhit, A., Alami, J., & Ghamouss, F.** (2024). Biomass screening for syngas production by flash photopyrolysis. *RSC Advances*, 14(17), 11706–11714.
- Miller, J. B., Thomas, E. R., & Zhang, W.** (2021). Thermochemical processes for biofuel production. *BioEnergy Review*, 38(2), 98–115.
- Mishra, R. K., Jaya Prasanna Kumar, D., Sankannavar, R., Binnal, P., & Mohanty, K.** (2024). Hydro-deoxygenation of pyrolytic oil derived from pyrolysis of lignocellulosic biomass: A review. *Fuel*, 360, 130473.
- Molino, A., Chianese, S., & Musmarra, D.** (2016). Biomass gasification technology: The state-of-the-art overview. *Journal of Energy Chemistry*, 25(1), 10–25.
- Nour, M., Amer, M., Elwardany, A., Attia, A., Li, X., & Nada, S.** (2021). Pyrolysis, kinetics, and structural analyses of agricultural residues in Egypt: For future assessment of their energy potential. *Cleaner Engineering and Technology*, 2, 100080.

- Nwabunwanne, N., Vuyokazi, T., Olagoke, A., Mike, O., Patrick, M., & Anthony, O. (2021). Torrefaction Characteristics of Blended Ratio of Sewage Sludge and Sugarcane Bagasse for Energy Production. *Applied Sciences*, 11(6), 2654.
- Odejobi, O. J., Ajala, O. O., & Osuolale, F. N. (2024). Review on potential of using agricultural, municipal solid and industrial wastes as substrates for biogas production in Nigeria. *Biomass Conversion and Biorefinery*, 14(2), 1567–1579.
- Okafor, C. C., Nzekwe, C. A., Ajaero, C. C., Ibekwe, J. C., & Otunomo, F. A. (2022). Biomass utilization for energy production in Nigeria: A review. *Cleaner Energy Systems*, 3, 100043.
- Oladosu, K. O., Babalola, S. A., Kareem, M. W., Ajimotokan, H. A., Kolawole, M. Y., Issa, W. A., Olawore, A. S., & Ponle, E. A. (2023). Optimization of fuel briquette made from bi-composite biomass for domestic heating applications. *Scientific African*, 21, e01824.
- Omosewo, E. O., Olaoye, J. O., Ajibola, T. B., & Ajimotokan, H. A. (2017). Conservation of conventional and renewable energy sources and their conversion techniques. In: Egbewole W. O., Abdul Raheem AMO, eds. *History and Philosophy of Science*, Ilorin, Nigeria: General Studies Division, University of Ilorin, p. 46–70.
- Pandey, S., & Erbaugh, J. T. (2024). Driving sustainable uptake: a systematic review of global literature on policies governing woody biomass for energy. *Discover Sustainability*, 5(1), 28.
- Papari, S., & Hawboldt, K. (2015). A review on the pyrolysis of woody biomass to bio-oil: Focus on kinetic models. *Renewable and Sustainable Energy Reviews*, 52, 1580–1595.
- Pędzik, M., Tomczak, K., Janiszewska-Latterini, D., Tomczak, A., & Rogoziński, T. (2022). Management of Forest Residues as a Raw Material for the Production of Particleboards. *Forests*, 13(11), 1933.
- Phang, F. J. F., Tiong, S. I. X., Wang, Y. S., Soh, M., Chew, J. J., Khaerudini, D. S., Thangalazhy-Gopakumar, S., How, B. S., Loh, S. K., Yusup, S., & Sunarso, J. (2024). Hydrochars derived via wet torrefaction of empty fruit bunches: Effect of temperature and time, comparison to oil palm trunks counterpart, and their pyrolysis behavior. *Journal of Analytical and Applied Pyrolysis*, 179, 106441.
- Picchio, R., Latterini, F., Venanzi, R., Stefanoni, W., Suardi, A., Tocci, D., & Pari, L. (2020). Pellet Production from Woody and Non-Woody Feedstocks: A Review on Biomass Quality Evaluation. *Energies*, 13(11), 2937.
- Pietraccini, M., Badu, P., Tait, T., Glaude, P.-A., Dufour, A., & Dufaud, O. (2023). Study of flash pyrolysis and combustion of biomass powders using the Godbert-Greenwald furnace: An essential step to better understand organic dust explosions. *Process Safety and Environmental Protection*, 169, 458–471.
- Pradhan, P., Mahajani, S. M., & Arora, A. (2021). Pilot scale production of fuel pellets from waste biomass leaves: Effect of milling size on pelletization process and pellet quality. *Fuel*, 285, 119145.
- Rabiu, A. B., Lasode, O. A., Popoola, O. T., Babatunde, O. P., & Ajimotokan, H. A. (2019). Densification of tropical wood residues for the development of solid fuels. *The IAFOR International Conference on Sustainability, Energy & the Environment, Hawaii 2019*, 1–11.
- Ribeiro, G. F., & Junior, A. B. (2023). The global energy matrix and use of agricultural residues for bioenergy production: A review with inspiring insights that aim to contribute to deliver solutions for society and industrial sectors through suggestions for future research. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 41(8), 1283–1304.
- Román-Figueroa, C., Montenegro, N., & Paneque, M. (2017). Bioenergy potential from crop residue biomass in Araucania Region of Chile. *Renewable Energy*, 102, 170–177.
- Ross, J. R. H. (2019). Catalysis in biomass conversion. *Contemporary Catalysis*, 343–364.
- Sadh, P. K., Chawla, P., Kumar, S., Das, A., Kumar, R., Bains, A., Sridhar, K., Duhan, J. S., & Sharma, M. (2023). Recovery of agricultural waste biomass: A path for circular bioeconomy. *Science of the Total Environment*, 870, 161904.
- Sahoo, G., Sharma, A., & Chandra Dash, A. (2022). Biomass from trees for bioenergy and biofuels – A briefing paper. *Materials Today: Proceedings*, 65, 461–467.
- Saidu, N. S., Aladodo, M. A., & Ajimotokan, H. A. (2022). The effects of particle size, compaction pressure, and torrefaction on quality and thermal properties of pelletized corncob residues. In *Southern Brazilian Journal of Chemistry: 2021 Virtual Conference* (pp. 1–4).
- Saravanakumar, A., Vijayakumar, P., Hoang, A. T., Kwon, E. E., & Chen, W. H. (2023). Thermochemical conversion of large-size woody biomass for carbon neutrality: Principles, applications, and issues. *Bioresource Technology*, 370, 128562.
- Saravanan, A., Yaashikaa, P. R., Senthil Kumar, P., Vickram, A. S., Karishma, S., Kamalesh, R., & Rangasamy, G. (2023). Techno-economic and environmental sustainability prospects on biochemical conversion of agricultural and algal biomass to biofuels. *Journal of Cleaner Production*, 414, 137749.
- Sarc, R., & Viczek, S. A. (2024). Co-processing of solid recovered fuels from mixed municipal and commercial waste in the cement industry – A pathway to a circular economy. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 42(3), 260–272.
- Sarker, T. R., Nanda, S., Meda, V., & Dalai, A. K. (2023). Densification of waste biomass for manufacturing solid biofuel pellets: a review. *Environmental Chemistry Letters*, 21(1), 231–264.
- Sarker, T. R., Azargohar, R., Stobbs, J., Karunakaran, C., Meda, V., & Dalai, A. K. (2022). Complementary effects of torrefaction and pelletization for the production of fuel pellets from agricultural residues: A

comparative study. *Industrial Crops and Products*, 181, 114740.

Sarker, T. R., Azargohar, R., Dalai, A. K., & Meda, V. (2021). Characteristics of torrefied fuel pellets obtained from co-pelletization of agriculture residues with pyrolysis oil. *Biomass and Bioenergy*, 150, 106139.

Sarker, T. R., Azargohar, R., Dalai, A. K., & Venkatesh, M. (2020). Physicochemical and fuel characteristics of torrefied agricultural residues for sustainable fuel production. *Energy and Fuels*, 34(11), 14169–14181.

Shahabuddin, M., Alam, M. T., Krishna, B. B., Bhaskar, T., & Perkins, G. (2020). A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes. *Bioresource Technology*, 312, 123596.

Sharma, A., Singh, S., & Gupta, R. (2023). The role of machine learning in optimizing biomass conversion technologies. *Energy Advances*, 5(1), 99–112.

Siwal, S. S., Zhang, Q., Devi, N., Saini, A. K., Saini, V., Pareek, B., Gaidukovs, S., & Thakur, V. K. (2021). Recovery processes of sustainable energy using different biomass and wastes. *Renewable and Sustainable Energy Reviews*, 150, 111483.

Smith, A. B. (2020). Introduction to biofuels and biomass energy systems. *Renewable Energy Resources*, 62(4), 221–235.

Song, B., & Hall, P. (2020). Densification of biomass and waste plastic blends as a solid fuel: Hazards, Advantages, and Perspectives. *Frontiers in Energy Research*, 8, 58.

Stelte, W., Sanadi, A. R., Shang, L., Holm, J. K., Ahrenfeldt, J., & Henriksen, U. B. (2012a). Recent developments in biomass pelletization – A review. *BioResources*, 7(3), 4451–4490.

Stelte, W., Holm, J. K., Sanadi, A. R., Barsberg, S., Ahrenfeldt, J., & Henriksen, U. B. (2012b). A study of bonding and failure mechanisms in fuel pellets from different biomass resources. *Biomass and Bioenergy*, 35(2), 910–918.

Sui, H., Chen, J., Cheng, W., Zhu, Y., Zhang, W., Hu, J., Jiang, H., Shao, J., & Chen, H. (2024). Effect of oxidative torrefaction on fuel and pelletizing properties of agricultural biomass in comparison with non-oxidative torrefaction. *Renewable Energy*, 226, 120423.

Tamelová, B., Malat'ák, J., Velebil, J., Gendek, A., & Aniszewska, M. (2021). Energy utilization of torrefied residue from wine production. *Materials*, 14(7), 1610.

Tekin, K., Karagöz, S., & Bektaş, S. (2014). A review of hydrothermal biomass processing. *Renewable and Sustainable Energy Reviews*, 40, 673–687.

Thengane, S. K., Kung, K. S., Gomez-Barea, A., & Ghoniem, A. F. (2022). Advances in biomass torrefaction: Parameters, models, reactors, applications, deployment, and market. *Progress in Energy and Combustion Science*, 93, 101040.

Toor, S. S., Rosendahl, L., & Rudolf, A. (2011). Hydrothermal liquefaction of biomass: A review of subcritical water technologies. *Energy*, 36(5), 2328–2342.

Trejo-Pech, C. O., Yu, T. E., Lanning, D. N., Dooley, J. H., Larson, J. A., & English, B. C. (2024). A techno-economic analysis comparing a hammermill and a rotary shear system to process woody biomass for biofuel production. *Energies*, 17(4), 886.

Tun, J., Win, T. & Puchor (2019). Biomass Energy: An overview of biomass sources, energy potential, and management in Southeast Asian Countries. *Resources*, 8(2), 81.

Ugwu, C. O., Ozor, P. A., Ozoegwu, C. G., Ndukwe, A., & Mbohwa, C. (2022). Biomass resources in Nigeria and the conversion pathways. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, 1–11.

Vaish, S., Sharma, N. K., & Kaur, G. (2022). A review on various types of densification/briquetting technologies of biomass residues. *IOP Conference Series: Materials Science and Engineering*, 1228(1), 012019.

Van Geem, K. (2019). Kinetic modeling of the pyrolysis chemistry of fossil and alternative feedstocks. *Computer Aided Chemical Engineering*, 45, 295–362.

Velázquez-Martí, B., Gaibor-Chávez, J., Niño-Ruiz, Z., & Cortés-Rojas, E. (2018). Development of biomass fast proximate analysis by thermogravimetric scale. *Renewable Energy*, 126, 954–959.

Wang, K., Pan, J., Gao, Y., Wu, G., Lin, G., Ding, K., Hu, X., Zhang, S., & Huang, Y. (2024). Effects of various pretreatments on fast pyrolysis of biomass to bio-oil: A case study of levoglucosan. *Journal of Analytical and Applied Pyrolysis*, 177, 106300.

Wang, X., Hu, M., Hu, W., Chen, Z., Liu, S., Hu, Z., & Xiao, B. (2016). Thermogravimetric kinetic study of agricultural residue biomass pyrolysis based on combined kinetics. *Bioresource Technology*, 219, 510–520.

Williams, G. D., & Clark, D. A. (2022). Modeling and optimizing biomass fuel formulations for improved efficiency. *Renewable and Sustainable Energy Reviews*, 51(6), 1082–1095.

World Bioenergy Association (2021). The global role of bioenergy in energy transition.

Wu, C., Yuan, X., Yang, G., Ning, D., Zhang, Y., Liu, Y., & Wang, G. G. (2024). How does position affect the decomposition of fine woody debris in subtropical forest? *Forest Ecology and Management*, 560, 121829.

Wu, T., Dang, Q., Wu, Y., Lei, T., & Yu, J. (2023). Catalytic hydro pyrolysis of biomass over NiMo bimetallic carbon-based catalysts. *Journal of Environmental Chemical Engineering*, 11(3), 110024.

Xiu, S., & Shahbazi, A. (2012). Biomass gasification for hydrogen production: A review. *Renewable and Sustainable Energy Reviews*, 16(6), 3437–3448.

Yan, P., Nur Azreena, I., Peng, H., Rabiee, H., Ahmed, M., Weng, Y., Zhu, Z., Kennedy, E. M., & Stockenhuber, M. (2023). Catalytic hydropyrolysis of biomass using natural zeolite-based catalysts. *Chemical Engineering Journal*, 476, 146630.

Yana, S., Nizar, M., Irhamni, & Mulyati, D. (2022). Biomass waste as a renewable energy in developing bio-

based economies in Indonesia: A review. *Renewable and Sustainable Energy Reviews*, 160, 112268.

Yang, W., Lv, L., Han, Y., Li, Y., Liu, H., Zhu, Y., Zhang, W., & Yang, H. (2022). Effect of densification on biomass combustion and particulate matter emission characteristics. *Atmosphere*, 13(10), 1582.

Yang, H., Yan, R., & Chen, H. (2014). Effect of CO₂ on the production of hydrogen during biomass gasification. *Energy Conversion and Management*, 76, 76-84.

Yu, J., Chen, S., Yu, Y., Zhang, C., & Jin, M. (2024). Influence of feedstock selection on cellulosic ethanol production based on densified biomass with calcium hydroxide and regular steam pretreatment. *Renewable Energy*, 227, 120561.

Yub H. N., Parvez, A., & Afzal, M. (2018). Process and energy analysis of pelleting agricultural and woody biomass blends. *Sustainability*, 10(6), 1770.

Zha, Z., Wu, K., Ge, Z., Ma, Y., Zeng, M., Wu, Y., Tao, Y., & Zhang, H. (2023). Effect of oxygen on thermal behaviors and kinetic characteristics of biomass during slow and flash pyrolysis processes. *Combustion and Flame*, 247, 112481.

Zhang, Z., Zhu, M., & Zhang, D. (2018). A thermogravimetric study of the characteristics of pyrolysis of cellulose isolated from selected biomass. *Applied Energy*, 220, 87–93.

Zhao, Z., Xu, X., & Liu, X. (2017). Effects of steam and CO₂ on hydrogen production in biomass gasification. *Energy*, 139, 156-164.

Zhu, L., Cai, W., Li, J., Chen, D., & Ma, Z. (2024). Highly selective production of light aromatics from co-catalytic fast pyrolysis of pre-deoxygenated biomass and hydrogen-rich polyethylene using a dual-catalyst system. *Energy*, 296, 131241.