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THERMOCHEMICAL CONVERSION OF AGROWASTE BIOMASS INTO BIOCHAR FUEL: A REVIEW ON PYROLYSIS AND TORREFACTION

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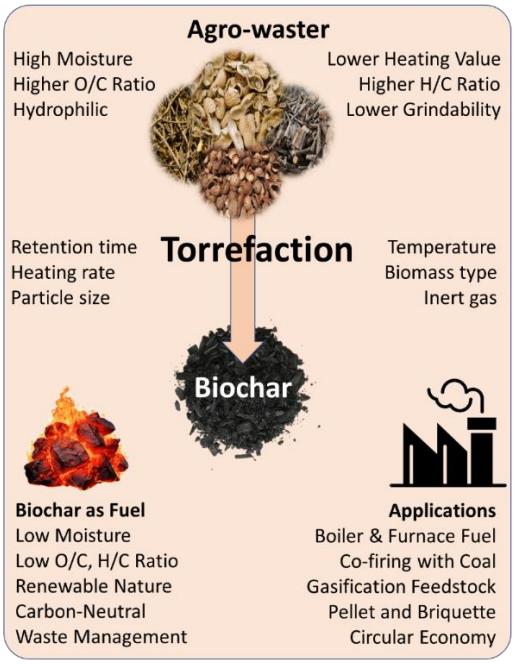
Graphical Abstract



Abstract
The continuous growth of the global population, urbanization and industrialization has led to a steep increase in worldwide energy demand, exerting immense pressure on conventional fossil fuel reserves. Fossil fuels currently dominate the global energy mix but are associated with severe environmental challenges such as greenhouse gas emissions, global warming and air pollution, highlighting the urgent need to explore sustainable and alternative energy sources. In response, renewable and sustainable energy resources have emerged as viable alternatives. Among these, biomass stands out as an abundant, carbon-neutral and renewable resource capable of producing valuable biofuels and bio-products. This review focuses on biomass availability, classification, composition, conversion pathways and the role of torrefaction and pyrolysis in producing energy-dense solid fuel biochar. The physicochemical characterization of biochar, its testing standards and its comparative performance with coal are discussed in detail. The paper further explores the applications of torrefied biomass, including its use as a co-firing agent in thermal power plants, feedstock for gasification and briquetting and a sustainable substitute for fossil coal in industrial and domestic heating. Moreover, the challenges and opportunities in biomass valorization are analyzed, emphasizing emerging opportunities in circular economy integration and decentralized energy systems. The study also identifies research gaps, particularly in optimizing process parameters for consistent biochar quality, developing cost-efficient torrefaction technologies and establishing standardized testing and classification methods. Overall, this review highlights the importance of optimizing thermochemical conversion processes to improve biochar yield and quality, contributing to clean, sustainable and circular bioenergy systems.

Keywords: Pyrolysis, Torrefaction, Biomass, Biochar, Biofuel, Sustainability.

1.0 INTRODUCTION

The rapid increase in agricultural waste generation poses significant environmental challenges, contributing to inefficient waste management and greenhouse gas emissions. Aligning with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), the thermochemical conversion of agrowaste into biochar offers a sustainable solution. Pyrolysis and torrefaction technologies enable the transformation of low-value biomass into high-energy-density biochar, promoting circular economy principles and reducing the dependence on fossil fuels.

1.1 Population

According to United Nations Population Division estimates, the global population in 2024 was approximately 8.2 billion and is expected to increase to 9.7 billion by the year 2050 [1]. Also is projected to peak around the year 2086 at approximately 10.4 billion people, based on the United Nations World Population Prospects 2022 and recent international forecasts. India, the most populous country, has approximate population of 1.46 billion, with a growth rate of 0.8% per year and is expected to peak at 1.7 billion by 2050. China follows with 1.42 billion people. The United States ranks third with 345 million people [1].

1.2 Energy Demand

As the global population increases, so does the demand for energy. Global energy supply is raising at an average annual rate of 2%, driven by demographic expansion, accelerated urbanization, industrial proliferation, particularly in emerging economies [2]. Energy is a crucial global commodity whose consumption is steadily rising and projected to grow by around 55% by 2040, based on current trends [3]. In India, energy supply is rising at a significant rate of 4.3% annually, fueled by rapid economic growth and expanding rural electrification [2].

1.3 Per-Capita Energy Consumption

Concurrently, per-capita primary energy consumption is increasing due to accelerated economic development, industrialization and urbanization, resulting in higher energy demand across residential, commercial and industrial sectors. India's per-capita primary energy consumption has grown by 2.8%, whereas the global per-capita primary energy consumption has increased by 0.9% [2]. Technological advancements, enhanced transportation systems and rising living standards further contribute to this growing energy demand.

1.4 Energy Mix

In 2024, fossil fuels dominated the global energy mix, with oil, natural gas and coal together making up 86.57% of total energy supply. Oil remains the largest contributor (33.61%), followed by coal (27.87%) and natural gas (25.09%). Non-fossil fuel sources, including nuclear energy, hydroelectric power and renewables, represent only 13.43% of the energy mix [2]. Petroleum-based fuel is currently used because of its high heating value (HHV), but it is neither environmentally friendly nor sustainable [4]. The growing dependence on fossil fuels for energy is a significant concern, both due to its potential impact on global climate through rising atmospheric carbon dioxide levels and because these resources are finite in the long run [5].

Figure 1 shows that fossil fuels dominate the energy mix, contributing the highest percentage among all energy sources. China and India rely heavily on fossil fuels, whereas the USA and Russia have a relatively higher share of nuclear and hydroelectric power. Although renewable energy sources (excluding hydroelectric) are present in all regions, their share remains relatively small compared to fossil fuels. The reason being, renewable energy faces challenges such as intermittency, lower energy density, high initial costs and limited storage infrastructure. Fossil fuels, in contrast, offer reliable, high-density energy with established infrastructure and lower short-term costs. Russia stands out with a significant proportion of hydroelectric energy, unlike China and India, which depend more on fossil fuels. Additionally, Japan has a noticeable share of nuclear energy, while other countries display varying levels of dependence on nuclear power.

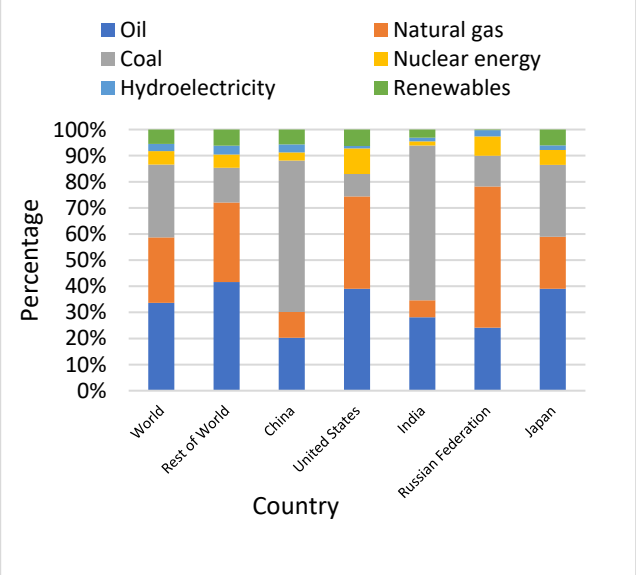


Figure 1 Percentage of electricity generated by top five countries source-wise in the year 2024 [2]

1.5 Environmental Impacts

On average, fossil fuels emit 2.5 kg CO_2, 10.4 g SO_2, 4.8 g NO_x, 3.0 g CO and 4.9 g particulate matter per kg of fuel, with additional trace pollutants. These emissions vary by fuel type, with coal and oil contributing most to sulphur and particulate pollution [6]. Energy demand in India is expected to grow thrice to four times over the next 25 years [7]. Therefore, the investigation of sustainable, cleaner, recyclable as well as environmentally friendly energy sources is need of an hour.

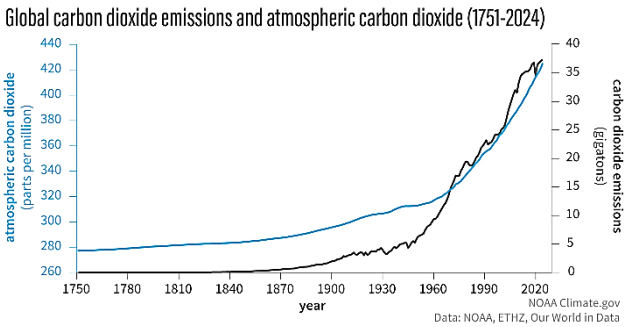


Figure 2 Global carbon dioxide emissions and atmospheric carbon dioxide from 1750 to 2024 [8], [9]

Figure 2 depicts that, in 1960s, atmospheric carbon dioxide increased by about 0.8 ppm per year on average. That growth rate doubled to an average of 1.6 ppm per year in the 1980s and 1.5 ppm per year in the 1990s. In the last decade (2015-2024), the annual increase has accelerated to 2.6 ppm per year. As a result, the annual rate of increase in atmospheric carbon dioxide over the past 60 years is 100-200 times faster than the increase that occurred at the end of the last ice age 11,000-17,000 years ago.

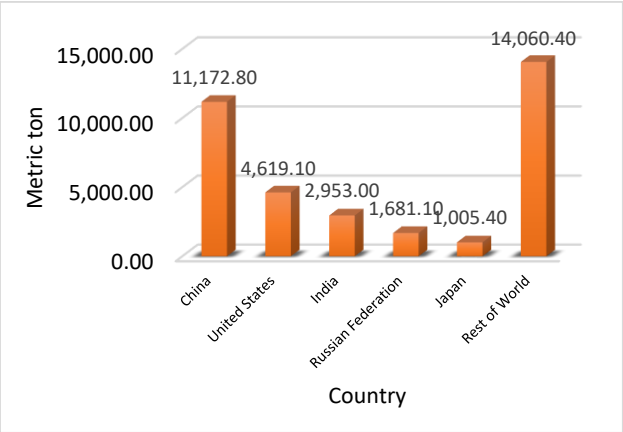


Figure 3 Country-wise carbon dioxide emissions from energy in metric ton in 2024 [2]

Figure 3 indicates that China contributes the highest carbon emissions, each exceeding 10,000 metric tons. The USA follows with emissions significantly lower than China but still substantial. India, Russia, Japan has comparatively lower emissions, with India emitting more than the latter two. The trend highlights the major role of industrialized and heavily populated nations in global carbon emissions.

1.6 Renewable Energy Sources – Biomass

The environmental impact of conventional energy sources necessitates a transition to renewable alternatives to ensure sustainability and mitigate climate change. Key renewable energy sources include solar energy, which utilizes photovoltaic cells or solar thermal systems; wind energy, generated through wind turbines; and hydropower, which harnesses flowing water. Geothermal energy taps into the Earth's subsurface heat. Biomass energy converts organic material through combustion or biochemical processes. Additionally, tidal and wave energy capture power from ocean movements and hydrogen energy, produced via fuel cells, offers a clean and efficient alternative for future energy needs.

Biomass refers to organic matter derived from plant-based sources, agricultural residues and other biological materials. These include wood and woody biomass, herbaceous plants, crop residues, aquatic vegetation and organic waste from animals and humans. Additionally, certain industrial and contaminated wastes, such as municipal solid waste, sewage sludge, demolition wood and other organic industrial by-products also qualify as biomass. In the current global energy landscape, biomass has gained significant recognition as a sustainable and eco-friendly renewable energy source [10], [11]. The utilization of non-edible biomass minimizes competition with food supplies while preserving fossil fuel reserves and its inherently low concentrations of sulphur and nitrogen reduce harmful emissions compared to coal [12]. Furthermore, biomass resources are abundant, cost-effective and versatile, enabling applications in biofuels, fertilizers while also contributing to the rehabilitation of degraded lands, enhancement of rural economies and strengthening of energy security. Despite challenges such as seasonal variability, inconsistent quality and inefficiencies in processing, biomass and biomass-derived fuels plays significant role in mitigating climate change and promoting a low-carbon economy. Biomass is increasingly acknowledged as a sustainable and eco-friendly renewable energy source in the modern energy sector [10], [11]. It serves as a key feedstock for energy through various processes, including direct combustion, gasification, fermentation, pyrolysis and anaerobic digestion. Due to its renewable nature, carbon neutrality and abundant availability, biomass emerges as a highly promising alternative energy option [13], [14], [15]. Its utilization not only lessens dependence on fossil fuels but also helps lower sulphur dioxide and carbon dioxide emissions [15], [16]. Biomass being carbon neutral, makes it a viable option for the present study.

1.7 Objectives And Scope Of Study

The present research focuses on the sustainable utilization of agricultural residues through thermochemical conversion techniques such as pyrolysis and torrefaction. It aims to enhance the energy recovery potential of agrowaste by producing high quality biochar as a renewable and eco-friendly substitute for conventional fossil fuels.

Objectives of the Study

1. To explore the thermochemical conversion of various agrowaste biomasses into biochar through pyrolysis and torrefaction for sustainable energy applications.
2. To analyze the availability, composition, and energy potential of biomass feedstocks for efficient energy recovery.
3. To evaluate the physicochemical, emission, and ash characteristics of biochar and compare them with conventional coal to determine its suitability as an alternative solid fuel.
4. To perform a comparative study of torrefied biomass from different agrowaste such as coconut shell, cotton stalk, tur stalk, rice husk, wheat straw, groundnut shell, and sugarcane bagasse with coal in terms of combustion behavior and environmental performance.
5. To assess the feasibility of co-firing biomass with coal to improve energy efficiency and reduce greenhouse gas emissions.
6. To examine the economic considerations, challenges, and opportunities associated with biomass valorization.

2.0 BIOMASS

Biomass is a complex and heterogeneous organic material of biological origin, mainly composed of carbon, hydrogen, oxygen and varying amounts of inorganic components. As a fuel, biomass contains more volatile matter, oxygen and reactive organic materials and usually less sulphur and ash than coal. This gives it several advantages such as being renewable, carbon-neutral and producing fewer pollutants, but also some challenges like lower energy content, higher moisture and variable ash composition during conversion processes [12], [17]. With a calorific value typically ranging between 14–22 MJ/kg, depending on its type, composition and moisture content, biomass provides significant energy potential, although generally lower than that of coal which is in the range 16.0–34.0 MJ/kg [12]. In most regions, open-field burning is the prevalent disposal practice adopted by farmers, leading to severe air and soil quality deterioration and substantial loss of valuable biomass resources [18], [19]. According to the Environmental Protection Agency (EPA), the burning of 1 ton of agricultural residue emits approximately 1400 kg of CO_2, 58 kg of CO, 11 kg of particulate matter, 4.9 kg of NO_x and 1.2 kg of SO_2 into the atmosphere, contributing to

global warming, smog formation, acid deposition and visual impairment [20]. Furthermore, residue burning results in nutrient depletion and degradation of soil fertility [21]. Hence, there is an urgent need to develop sustainable strategies for both effective disposal and energy recovery from agro-residues, ensuring environmental protection and energy security.

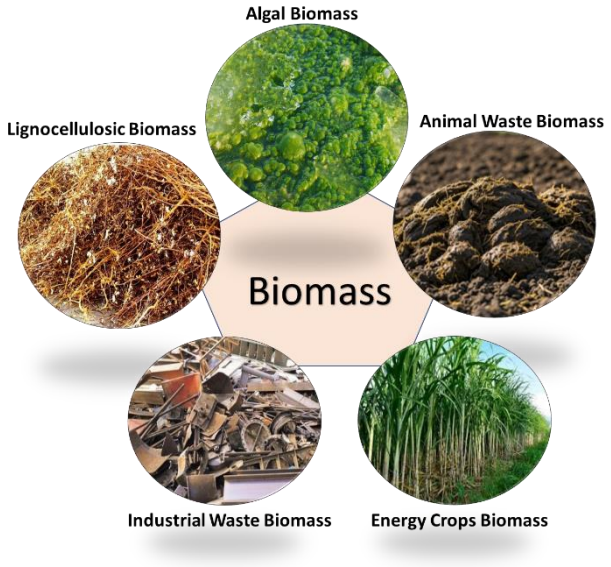


Figure 4 Source of Biomasses

Figure 4 shows source of biomasses. In many cases, different biomass types are blended to enhance their usability and efficiency in energy applications. The composition of biomass primarily includes carbon-rich compounds such as cellulose, hemicellulose and lignin. These components undergo thermochemical and biochemical conversion processes to produce biofuels. The effective utilization of biomass for energy production and biochemical synthesis requires a thorough understanding of its composition and properties. This knowledge can be leveraged to develop more efficient and sustainable conversion technologies [12]. Furthermore, mixed biomass, which consists of multiple biomass, such as the co-processing of agricultural and animal waste or the combination of municipal and industrial organic waste, can enhance process efficiency and energy output. The diverse characteristics of different biomass types influence their suitability for various applications, including biofuel and biochemical production, energy generation and soil fertility enhancement.

2.1 Global Availability Of Biomass

Forests act as significant carbon sinks, storing high-density biomass carbon that can be efficiently utilized for biofuel production from post-logging residues. The conversion of these residues into pellets or briquettes not only promotes renewable energy generation but also enhances carbon sequestration and supports global climate mitigation efforts [22]. As per the report by the Imperial College Centre for Energy Policy and Technology, the global land area is approximately 13 Gha (1 Gha = 10^9 hectares) [23]. Out of this, around 1.5 Gha is used for arable crop cultivation, 4 Gha is covered by forests and 3.5 Gha serves as pasture land, while the remaining land is designated for various other purposes [24]. India being a major agrarian economy, nearly 75% population depends directly or indirectly on agriculture for their livelihood [25]. A wide range of crops cultivated across the country's diverse agro-ecological zones generate substantial quantities of post-harvest crop residues, including straws, stalks, seed pods, husks, cobs and stubbles [26]. India produces approximately 656 million tons (Mt) of such residues annually, both on-farm and off-farm [27]. However, the effective management and utilization of these residues remain a significant challenge [28]. As per the analysis by Sukumaran et al., 2017, India has a total availability of 657 Mt of gross agro-residue [29]. According to a report by the Ministry of New and Renewable Energy (Government of India), India currently generates approximately 500 million metric tons of biomass annually (MNRE). Taking into account agricultural and forestry waste residues, the estimated surplus biomass available is around 120–150 million metric tons per year, with an energy potential of approximately 18,000 MW (MNRE). Among various biomass feedstocks, agricultural residues have emerged as a promising bioenergy resource, particularly in developing nations such as India [30], [31], [32], [33].

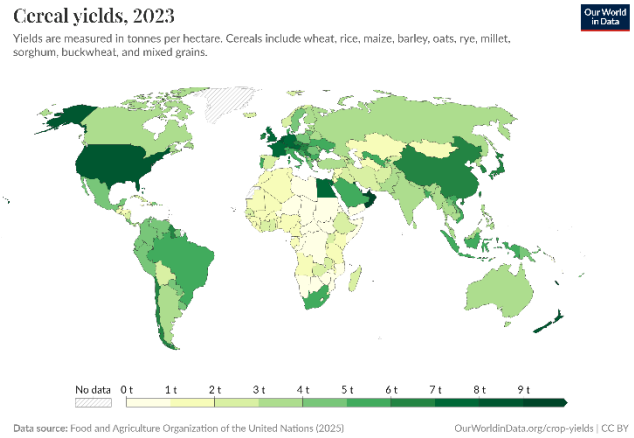


Figure 5 Global Cereal Production by Country in year 2023 [34]

Figure 5 illustrates global cereal production for the year 2023, showing that countries with high cereal output—such as China, India, the United States and Brazil dominate global grain production. Since agricultural residue generation is directly proportional to cereal production, these nations also produce substantial quantities of agro-waste. The large-scale cultivation of cereals results in considerable post-harvest biomass, which, if not managed effectively, can lead to waste accumulation and environmental issues. Conversely, this agro-residue represents a significant renewable resource that can be utilized for bioenergy generation, particularly through pyrolysis and torrefaction, contributing to sustainable waste management.

2.2 Potential In Biomass Energy Sector

Biomass has significant global potential for electricity generation. According to recent analyses, modern biomass could supply 3,000 terawatt-hours (TWh) per year of global electricity generation by 2050—equivalent to 10–20% of projected global power demand for that year if technology, supply chains and policies align favorably. This could also contribute to a reduction of 10–30 gigatons (Gt) of CO_2 emissions by 2050, depending on the extent of biomass deployment and decarbonization measures adopted [35]. Through renewable energy, estimated 11.6 million direct and indirect employment opportunities could be generated in the energy sector [36].

2.3 Classification Of Biomass

Biomass originates from organic feedstock like vegetation, agricultural byproducts and animal residues. Based on its origin biomass is broadly categorized into two types: natural and anthropogenic. Natural biomass originates from naturally occurring sources whereas anthropogenic biomass results from the processing of natural materials [17]. Based on its source and composition, biomass can be categorized into the following categories:

a. Lignocellulosic Biomass: Lignocellulosic biomass is mainly composed of three key structural components: cellulose, a polysaccharide providing mechanical strength; hemicellulose, a heterogeneous polymer that enhances flexibility; and lignin, a complex aromatic polymer that contributes to rigidity and resistance. Common examples include agricultural residues such as wheat straw and corn stalks, as well as forestry residues. Its widespread availability and cost-effectiveness make it a key focus in bioenergy research [37].

b. Algal Biomass: Microalgae and macroalgae effectively convert sunlight and carbon dioxide into biomass. Owing to their high lipid content and rapid growth rate, algal biomass is considered a promising feedstock for biofuel production [38].

c. Animal Waste Biomass: Animal manure and poultry litter, abundant in nutrients and organic matter, are extensively used for biogas generation via microbial decomposition in oxygen-free conditions [39].

d. Industrial and Municipal Waste Biomass: Industrial by-products such as sawdust and municipal solid waste such as food waste can be processed into bioenergy. These sources contribute to waste management while producing energy [40].

e. Dedicated Energy Crops: Crops like switchgrass, miscanthus and jatropha are grown specifically for energy production. They are high-yielding and require minimal agricultural inputs [41].

2.4 Classification Of Biofuels

Biofuels are classified into generations based on feedstock type and production technology: first-generation from edible food crops (e.g., corn ethanol, soy biodiesel); second-generation from non-food lignocellulosic biomass and wastes (e.g., crop residues, wood); third-generation from algae and microalgae; and fourth-generation from genetically engineered organisms with synthetic biology. Details about each are as follows:

2.4.1 First Generation

First-generation biofuels are produced from edible food crops such as corn, sugarcane, soybeans and vegetable oils through fermentation (for ethanol) or transesterification (for biodiesel). Common biofuel types include bioethanol, biodiesel, syngas and biogas [42], [43]. These biofuels offer advantages like compatibility with existing infrastructure and reduced greenhouse gas emissions compared to fossil fuels, but face criticism for the "food versus fuel" dilemma, potential deforestation, biodiversity loss and indirect land-use changes that can elevate overall emissions [44].

2.4.2 Second Generation

Unlike first-generation biofuels, second-generation biofuels derive from non-food feedstocks like energy crops, lignocellulosic plants, agricultural and forest residues, and wastes, using advanced fermentation and thermochemical processes [43]. These methods improve fuel yields, generate co-products, cut energy costs and waste, and boost economic viability through techniques such as membrane filtration, biorefinery integration, and mesophilic/thermophilic microbes in batch/continuous reactions for biofuels, organic acids and amino acids [43], [45]. Second-generation biofuels include cellulosic ethanol (from agricultural residues like corn stover or wheat straw), lignocellulosic butanol, Fischer-Tropsch diesel (from syngas via gasification), wood diesel (from woodchips) and bio-based kerosene or biodiesel from non-edible oils and wastes. Although these methods provide more sustainable alternatives, they are often intricate and costly to implement. Thus, researchers are paying attention on new alternate solution, which are economically feasible and simply accessible at greater extent.

2.4.3 Third Generation

Third-generation biofuels mainly use microalgae as feedstock, which can yield high amount of oil without needing arable land or competing with food crops [46]. Third-generation biofuels include biodiesel (via transesterification of algal oils), renewable diesel or green diesel (via hydrotreatment), bioethanol (from algal carbohydrates through fermentation), biogas (via anaerobic digestion) and bio-oil (via pyrolysis or hydrothermal liquefaction) [47]. These biofuels offer higher annual yields than first-generation crop-based fuels [48] , though challenges like high costs and scaling persist [49]. Grouped with second-generation as advanced biofuels, they also utilize non-food sources like waste cooking oil, animal fats, and fish oil, helping reduce water pollution and waste management burdens [48].

2.4.4 Fourth Generation

Fourth-generation biofuels focus on achieving a negative carbon footprint through the use of advanced genetic engineering and carbon capture technologies [50]. Biofuels, such as ethanol, butanol, isobutanol and modified fatty acids (for biodiesel) are produced from genetically engineered sources like cyanobacteria, oleaginous yeast (e.g., Yarrowia lipolytica), algae or bacteria using CO_2, sunlight, electricity or electrobiofuel processes [50]. These biofuels rely on genetically modified plants and microorganisms to produce fuels efficiently while sequestering atmospheric CO_2, contributing to sustainability and reduced greenhouse gas emissions [50], [51]. These biofuels promise superior GHG reductions through CO_2 sequestration, higher efficiency and versatility, but remain in R&D due to technical and economic hurdles.

Each successive generation of biofuels advances efficiency, sustainability and environmental performance by shifting from food-competing feedstocks to non-edible biomass, algae, and engineered microbes with CO_2 capture. First-generation offers basic GHG reductions but raises food security issues, while second- and third-generation improve yields and minimize land use through lignocellulosic and algal processes. Fourth-generation further excels with carbon-negative production via synthetic biology, achieving up to fourfold higher energy efficiency over earlier methods [52].

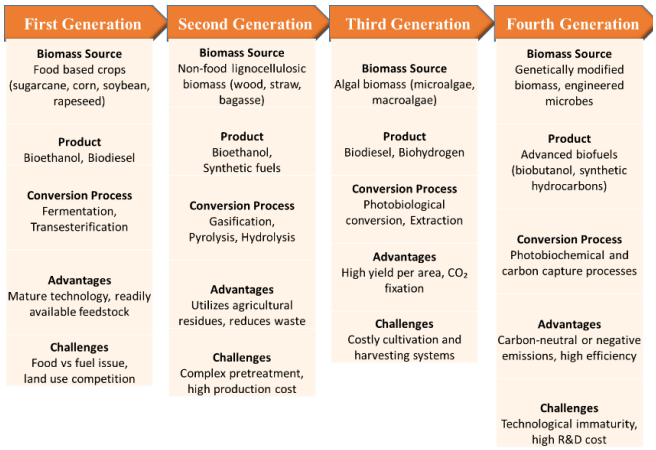


Figure 6 Generational classification of biofuels [43], [52]

Figure 6 shows the major distinctions between first, second, third and fourth generation biomass conversion technologies by feedstock type, product, process, advantages and challenges. This organizing framework provides a foundation for understanding advances and limitations in sustainable biofuel production.

2.5 Composition Of Biomass

Biomass comprises a heterogeneous composition of organic constituents along with trace amounts of inorganic compounds, encompassing multiple solid and fluid phases derived from diverse biological and environmental sources [53]. Biomass is predominantly composed of three fundamental biopolymeric constituent cellulose, hemicellulose and lignin supplemented by trace amounts of extractives and inorganic fractions, collectively contributing to its physicochemical properties. Cellulose, a linear polymer of glucose, typically constitutes 40–50% of biomass and serves as the primary structural component. Hemicellulose, a branched polymer of various sugars, accounts for 20–30% and contributes to the flexibility of plant cell walls. Lignin, a complex aromatic polymer, constitutes 15–30% of biomass, contributing to its structural rigidity and resistance to degradation. Its composition varies based on biomass type and source, which impacts its potential for bioenergy applications [54]. The first and most crucial step in analyzing and utilizing biomass as a solid fuel is identifying and characterizing its chemical and phase composition.

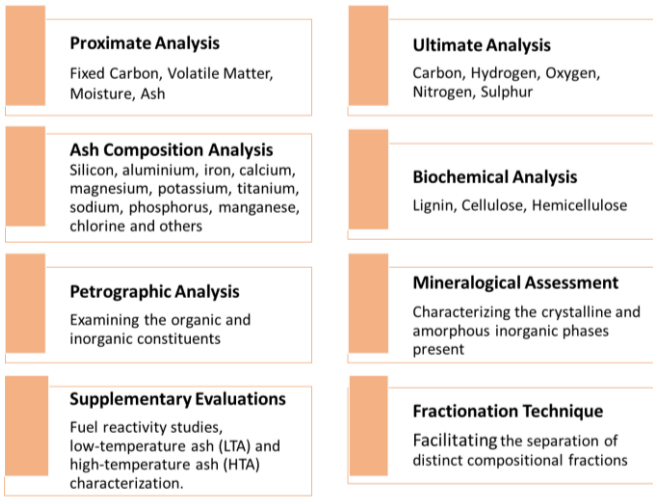


Figure 7 Analysis methods of biomass

Figure 7 shows composition and analysis methods of biomass. This composition serves as a distinct fundamental code that defines the fuel's properties, quality, potential applications and associated environmental impacts [53]. To facilitate comprehensive solid fuel characterization, a range of well-established analytical methodologies—encompassing physical, chemical, petrographic, mineralogical and geochemical techniques—have been employed. These approaches involve the assessment of:

(1) Proximate analysis, determining major physical components such as fixed carbon (FC), volatile matter (VM), ash content (A) and moisture(M);
(2) Ultimate analysis, quantifying elemental composition, including carbon (C), hydrogen (H), oxygen (O), sulphur (S) and nitrogen(N);
(3) Ash composition analysis, identifying major inorganic constituents such as silicon (Si), aluminium (Al), iron (Fe), calcium (Ca), sulphur (S), magnesium (Mg), potassium (K), titanium (Ti), sodium (Na), phosphorus (P) and trace elements including manganese (Mn), chlorine (Cl) and others;
(4) Petrographic analysis, examining the organic and inorganic constituents within the fuel matrix;
(5) Mineralogical assessment, characterizing the crystalline and amorphous inorganic phases present;
(6) Fractionation techniques, facilitating the separation of distinct compositional fractions; and
(7) Supplementary evaluations, such as fuel reactivity studies, low-temperature ash (LTA) and high-temperature ash (HTA) characterization.

Biomass conversion process is highly influenced by its chemical composition, as the quality and yield of the resulting products—whether biochar, bio-oil, or syngas—depend on both the inherent properties of the biomass and the operating parameters of the conversion process. Therefore, appropriate selection of biomass feedstock based on the desired end-use and process requirements is essential to achieve optimal conversion efficiency and product quality.

2.6 Factors Affecting The Selection Of Suitable Biomass For Fuel

Untreated biomass has several limitations, including high moisture content, low heating value, inhomogeneity, low bulk density and poor grindability. Additionally, its bulky nature and low energy density make it difficult to handle, store and transport compared to other fuels. However, the effectiveness of biomass utilization can be enhanced by processes such as demoisturization, drying, torrefaction, densification, pulverization for size reduction and palletization [55], [56]. Conversion can be done through biochemical methods like fermentation and thermochemical methods like pyrolysis and gasification. Processes like carbonization and torrefaction also help by turning biomass into cleaner, more convenient and useful energy rich products [7], [57], [58]. Biochemical conversion of biomass produces biofuel such as ethanol, whereas thermochemical processes yield three fuel products: bio-oil, bio-char and gases [59], [60]. Therefore, biomass is a renewable energy source that can be transformed into three different fuel forms: solid, liquid and gaseous. However, the efficiency and quality of the final fuel product depend significantly on the characteristics of the selected biomass. Following are the important factors affecting the selection of suitable biomass for good quality fuel.

2.6.1 Moisture Content

It refers to the amount of water present in a biomass. Moisture content greatly influences its thermal conversion efficiency, heating value and product quality during pyrolysis or torrefaction. High moisture reduces calorific value, causes energy losses and lowers biochar yield; hence, maintaining it below 10% ensures efficient and uniform heating. High moisture reduces energy efficiency and increases drying costs [61]. Fresh agricultural residues typically contain 64–78% moisture [62], whereas preserved or dried biomass intended for stable storage has a reduced moisture content of around 10% [63]. Sun drying, air drying, oven drying, rotary drum drying, belt drying, microwave drying, fluidized bed drying, infrared drying, superheated steam drying are some of the methods used for moving moisture before conversion.

Table 1 indicates that the moisture content of common agro-residues ranges between 6% and 14%, with coconut shell, cotton stalk and groundnut shell exhibiting relatively lower moisture levels. Consequently, these biomasses require less energy input and cost for drying, enhancing their suitability for thermal conversion processes. Specifically, coconut shell (6–8%) and groundnut shell (6–9%) possess low moisture content, making them ideal for direct combustion and pyrolysis due to reduced energy loss during drying. In contrast, cotton stalk (6–11%) and tur stalk (8–10%) exhibit moderate moisture levels, making them suitable for torrefaction and gasification applications. On the other hand, rice husk, wheat straw and sugarcane bagasse (8–14%) have higher moisture content, which necessitates pre-drying before undergoing thermochemical conversion.

2.6.2 Volatile Matter

Volatile matter refers to the fraction of a material that vaporizes upon heating, consisting of organic compounds such as hydrocarbons, tar and light gases, which significantly influence ignition and combustion behaviour. High volatile matter supports easier ignition, while low volatile matter may lead to incomplete combustion [24]. Balanced content ensures efficient burning however, low volatile matter contributes to higher fixed carbon retention in biochar.

Table 1 shows that cotton stalk, tur stalk, groundnut shell and sugarcane bagasse (70–76%) possess high volatile matter content, which enhances ignition characteristics and combustion efficiency during thermochemical conversion. In contrast, coconut shell (26–33%) exhibits a lower volatile fraction, favouring char formation with greater carbon stability and fixed carbon yield. Meanwhile, rice husk and wheat straw (65–80%) demonstrate high reactivity and volatile content, making them suitable feedstocks for bio-oil and syngas generation through pyrolysis and gasification processes.

2.6.3 Fixed Carbon

Fixed carbon in biomass refers to the solid fraction remaining after volatile matter is driven off by heating (usually above 600°C) in the absence of air. It is mostly carbon, with some mineral matter and does not include the volatile gases or the ash left after combustion. Fixed carbon represents the portion of biomass that contributes to char and coke formation during thermal processing. A higher fixed carbon percentage enhances biochar production, solid fuel quality and metallurgical applicability. It contributes to greater thermal stability, steady combustion and a higher calorific value, improving overall fuel performance [64]. Conversely, low fixed carbon results in lower energy yield, unstable combustion and limited suitability for processes aiming at maximum solid carbon recovery or activated carbon production. Thus, fixed carbon content serves as a key indicator of energy potential and char yield in biomass.

Table 1 shows the fixed carbon content of various biomass types. Coconut shell exhibits the highest fixed carbon content (60–68%), making it highly suitable for the production of high-calorific biochar and activated carbon. Cotton stalk, tur stalk and groundnut shell possess moderate fixed carbon levels (13–20%), rendering them appropriate for fuel-grade biochar applications. In contrast, rice husk (7–10%) and wheat straw (10–15%) have relatively low fixed carbon content, resulting in biochar with lower density.

Table 1 Proximate composition of various agro-residues [65] [66]

Biomass	Moisture (%)	Volatile Matter (%)	Ash (%)	Fixed Carbon (%)
Coconut shell	6 – 8	25 – 35	0.6 – 2	60 – 68
Cotton stalk	6 – 11	73 – 76	5 – 7	15 – 20
Tur stalk	8 – 10	70 – 76	4 – 8	17 – 19
Rice husk	8 – 12	65 – 75	15 – 20	7 – 10
Wheat straw	10 – 14	65 – 80	5 – 8	10 – 15
Groundnut shell	6 – 9	65-75	2 – 3	16 – 20
Sugarcane bagasse	10 – 14	70 – 75	1 – 3	15 – 18

2.6.4 Ash

Ash in biomass refers to the non-combustible mineral residue left after complete combustion of the organic material at high temperatures (usually above 750°C). The ash content is a measure of all inorganic minerals such as silica, alumina, potassium, calcium, magnesium, phosphorus and elements like chlorine, sodium, sulphur and trace heavy metals—originally present in the biomass or absorbed during growth or processing. [67]. Low-ash biomass improves energy density, process efficiency and equipment longevity, while ash-rich biomass can cause slagging, fouling, corrosion and increased maintenance costs. Certain biomass ashes may serve as soil amendments if heavy metals are minimal; however, high ash content reduces calorific value, increases handling and disposal costs and poses environmental risks due to toxic element leaching [67], [68]. Ash content in biomass indicates the total mineral fraction, affecting both fuel quality and thermal conversion processes such as combustion, gasification and pyrolysis [67].

Table 1 shows the ash content of different biomass types. Coconut shell (0.6–2%) and sugarcane bagasse (1–3%) exhibit low ash content, making them suitable for biochar production and co-firing with coal. Groundnut shell and cotton stalk have moderate ash levels (2–7%), which are acceptable for thermochemical conversion with minimal fouling concerns. In contrast, rice husk (15–20%) and wheat straw (5–8%) possess high ash content, potentially causing slagging and fouling in reactors.

2.6.5. Calorific Value

Calorific value (CV), also known as heating value, refers to the amount of energy released as heat when a specified amount of a fuel is completely combusted in oxygen. It is typically expressed in megajoules per kilogram (MJ/kg) or kilocalories per kilogram (kcal/kg) for solid fuels, including biomass. Fuels with higher carbon generally have higher calorific values. Higher hydrogen increases CV, while higher oxygen lowers it, as more energy is needed to combust the additional oxygen. Higher ash means lower CV, since ash is a non-combustible residue that does not contribute energy. High moisture absorbs heat during combustion (for vaporization), thus reducing the effective energy output [69], [70]. Thus, calorific value is a critical parameter that directly reflects the energy potential of the fuel.

Table 2 Calorific value of various agro-residues [65] [66]

Biomass	Calorific Value (MJ/kg)
Coconut shell	19 – 21
Cotton Stalk	16 – 16.5
Tur stalk	15.7 – 16
Rice husk	13 – 15
Wheat straw	15 – 16
Groundnut shell	17 – 18
Sugarcane bagasse	16 – 17

Table 2 shows the calorific values of various agro-residue commonly found in bulk. Coconut shell exhibits the highest calorific value, ranging from 19 to 21 MJ/kg, making it a superior fuel source. Groundnut shell and sugarcane bagasse follow with moderate energy content between 16 and 18 MJ/kg. Cotton stalk, tur stalk, wheat straw and rice husk display relatively lower calorific values, ranging from 13 to 16.5 MJ/kg, indicating their moderate energy potential for thermochemical conversion processes such as pyrolysis and torrefaction. These values are essential for assessing the fuel quality and energy efficiency of different biomass feedstocks.

2.6.6 Elemental composition

Elemental composition of biomass refers to the quantification of primary and trace chemical elements such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and mineral elements present in biomass feedstocks. This composition fundamentally determines the physicochemical properties and energy content of biomass and influences its suitability for bioenergy conversion processes [71]. Elemental composition of natural biomass varies due to multiple factors, including biomass type, plant species and specific plant parts. Growth processes regulate the selective uptake and deposition of compounds, while environmental conditions such as sunlight exposure, geographic location, climate, seasonal variations, soil composition, water availability, pH and nutrient levels also play a significant role. Additional influences include plant maturity, the use of fertilizers and pesticides, proximity to pollution sources such as highways, factories mines, as well as harvesting time and post-harvest handling, including transportation and storage. Furthermore, the presence of extraneous materials during harvesting, fluctuations in ash content and the blending of different biomass types contribute to variations in composition [53]. Biomass may contain toxic elements like lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), chromium (Cr) and others absorbed from contaminated soils or water [72]. Sulphur in biomass is a double-edged sword: while it is a vital nutrient in the biological context and generally low in biomass leading to cleaner combustion, its concentration must be monitored carefully for energy applications. Excess sulphur poses environmental and operational challenges, especially in thermal energy conversion systems, demanding strategies to minimize sulphur-related issues [73].

Table 3 shows the elemental composition of various biomass types used for bioenergy and biochar production. Coconut shell and groundnut shell have relatively high carbon content (44–49% and 44–46%, respectively), indicating good potential for char formation. Cotton stalk and tur stalk also show high carbon percentages (46–48% and 45–47%), with slightly higher hydrogen content, suggesting favorable energy content. Rice husk exhibits the lowest carbon content (36–38%) but moderate hydrogen levels, reflecting lower energy potential. Nitrogen and sulphur contents are minimal across all biomass types, indicating lower emissions of NO_x and SO_x during thermochemical conversion. Oxygen content varies between 35–49%, influencing the reactivity and thermal degradation behavior of the biomass during pyrolysis.

Table 3 Ultimate composition of various agro-residues

C (%)	H (%)	N (%)	S (%)	O (%)	Ref.
Coconut shell					
44 – 49	5.1 – 6	0.11 – 0.23	<0.1	44 – 49	[74]
Cotton stalk					
46 – 48	5.8 – 6.2	0.5 – 1	<0.2	43 – 45	[65]
Tur stalk					
45 – 47	5 – 6	1.2 – 1.5	<0.1	44 – 46	[65]
Rice husk					
36 – 38	5 – 6	0.3 – 0.6	<0.05	35 – 37	[65], [66]
Wheat straw					
38 – 41	5 – 6	0.5 – 0.8	<0.1	43 – 45	[65], [66]
Groundnut shell					
44 – 46	5.2 – 6	0.5 – 0.8	<0.01	40 – 42	[65], [66]
Sugarcane bagasse					
42 – 45	5 – 6	0.4 – 0.7	<0.08	43 – 48	[65], [66]

2.6.7 Lignocellulosic Composition

The proportion of lignin, cellulose and hemicellulose in biomass is called as Lignocellulosic composition. It affects its structural integrity, energy yield, combustion and conversion properties. Lignin contributes to higher energy density, while cellulose and hemicellulose influence pyrolysis and gasification behaviour [75]. Lignin-rich biomass usually offers higher CV compared to cellulose/hemicellulose-rich materials[76]. The proportions and structural properties affect biomass's calorific value, combustion behavior and conversion efficiency. High cellulose and hemicellulose typically improve energy yields, while lignin provides higher energy density but increases recalcitrance [77].

Table 4 shows the biochemical composition of different biomass types in terms of cellulose, hemicellulose and lignin content. Cotton stalk has the highest cellulose content (50–60%), indicating strong structural carbohydrates suitable for

biochar production with better structural strength and resistance to breakage during handling and use. Coconut shell and groundnut shell exhibit high lignin content (29–33% and 27–37%, respectively), which contributes to higher thermal stability and char yield during pyrolysis. Hemicellulose content is highest in sugarcane bagasse (25–30%) and wheat straw (24–28%), influencing the ease of thermal degradation and volatile release. These compositional differences are crucial for evaluating the suitability of biomass feedstocks for energy conversion and biochar quality optimization.

Table 4 Biochemical composition of various agro-residues

Biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ref.
Coconut shell	26 – 30	23 – 27	29 – 33	[78]
Cotton stalk	50 – 60	20 – 25	14 – 19	[65]
Tur stalk	36 – 45	18 – 23	15 – 19	[65]
Rice husk	28 – 35	15 – 21	19 – 24	[65], [66]
Wheat straw	35 – 45	24 – 28	13 – 19	[65], [66]
Groundnut shell	34 – 40	18 – 22	27 – 37	[65], [66]
Sugarcane bagasse	38 – 45	25 – 30	13 – 18	[65], [66]

2.6.8 Size

Biomass size typically refers to the particle size of biomass feedstock used in thermochemical processes such as combustion, pyrolysis, gasification and torrefaction. Particle size can vary from micro-scale powders to larger chips or chunks, often controlled by milling or grinding processes before conversion. Smaller particle sizes increase the surface area exposed to heat and reactants, improving reaction rates and heat transfer efficiency in thermochemical processes. This promotes better conversion efficiency and higher yields of desired biofuels [79]. Finer biomass particles heat more uniformly and rapidly, reducing incomplete conversion or char leftover and improving energy recovery [80]. Particle size influences volatile matter release and char formation, with smaller particles releasing volatiles faster, affecting the product composition and quality [81]. Very fine particles may cause handling issues like dust explosion risk, while very large particles may cause non-uniform conversion [82]. Optimizing particle size reduces residence time and energy consumption during gasification or pyrolysis, improving process economics [80]. Thus, particle size has a significant effect on the thermochemical conversion of biomass, influencing reaction rates, product yields, heat and mass transfer and ultimately the efficiency of processes like pyrolysis, gasification and combustion.

2.6.9 Bulk Density

Bulk density is the mass of biomass per unit volume, including the space between particles, typically expressed in kilograms per cubic meter (kg/m³). It reflects how much biomass can be packed or stored in a given volume and is influenced by particle size, shape, moisture content and compaction [83]. It significantly affects the thermochemical conversion of biomass by influencing the fuel's energy density, feeding and handling properties, heat and mass transfer and overall conversion efficiency. High bulk density biomass is preferred for ease of transportation, storage and better energy packing density [84]. Increased bulk density enhances packing density in reactors, potentially reducing void spaces and improving reactor thermal gradients, which can improve conversion kinetics. Studies show that densification increases volumetric heating value and reduces particulate emissions during combustion, indicating cleaner and more efficient biomass utilization [85].

Table 5 Bulk density of various agro-residues [86], [87]

Biomass	Bulk Density (kg/m³)
Coconut shell	350 – 500
Cotton stalk	80 – 120
Tur stalk	90 – 120
Rice husk	90 – 150
Wheat straw	80 – 120
Groundnut shell	180 – 220
Sugarcane bagasse	80 – 120 (loose), 180 – 225 (compressed)

Table 5 shows the bulk density of various biomass types, which is an important parameter affecting storage, handling and reactor feeding during thermochemical conversion. Coconut shell has the highest bulk density, making it more compact and efficient for transport and energy storage. Groundnut shell and sugarcane bagasse exhibit moderate bulk densities while cotton stalk, tur stalk, rice husk and wheat straw have low bulk densities, indicating their lightweight and porous nature. These variations in bulk density influence reactor design, feeding mechanisms and overall process efficiency in biochar and bioenergy production.

2.6.10 Contaminants

Contaminants are the unwanted substances, such as heavy metals, sand, dirt, or plastics, chlorine, sulphur that may affect the efficiency, product quality and environmental impact of biomass utilization. Biomass with minimal contaminants, such as heavy metals or inorganic impurities, is preferred to avoid operational issues and environmental concerns during fuel conversion processes [88]. Elements like chlorine and sulphur in biomass lead to the formation of corrosive compounds and toxic emissions (e.g., dioxins, SOx, HCl) during combustion or pyrolysis, requiring advanced emission control technologies. Biomass contamination may also influence product composition, reducing the yield and quality of bio–oil, syngas, or char by promoting undesirable side reactions or forming refractory residues [89]. Pre–treatment steps (washing, drying, sorting) can reduce contaminant levels and improve thermochemical conversion outcomes.

2.6.11 Sustainability and Availability

It is the ability of a resource to be utilized without depletion or environmental impact while being accessible in sufficient quantity and quality for practical applications. Readily available and sustainably sourced biomass ensures a consistent supply, reducing operational disruptions and promoting environmental sustainability [24].

Table 6 Agrowaste availability in India

Biomass	Approximate availability (Mt/year) [90], [91], [92]	Approximate Share (%) [92], [93]
Coconut shell	2.2	1.5
Cotton stalk	13.4	3.5
Tur stalk	2.5	<1
Rice husk	23 – 28	25 – 30
Wheat straw	30 – 35	30 – 35
Groundnut shell	4.5	2.5
Sugarcane bagasse	70 – 75	20 – 25

Table 6 shows the approximate annual availability different biomass residues generated in India. Wheat straw exhibits the highest availability, ranging from 98 Mt/year and contributing about 30–35% of the total biomass share, followed by sugarcane bagasse with 70 Mt/year (20–25%). Rice husk also represents a significant portion, contributing around 25–30% with an annual generation of 24 Mt. Cotton stalk, groundnut shell and coconut shell have moderate availability (2–13 Mt/year), while tur stalk contributes less than 1% of the total biomass potential. These data highlight the abundant and diverse biomass resources available for sustainable energy and biochar production through thermochemical processes.

2.7 Composition Testing Of Biomass For Conversion

Standard methods of proximate and ultimate analysis of biomass are crucial for ensuring accurate, reliable and reproducible results in biomass characterization. Proximate analysis offers critical information on the combustion characteristics and thermal degradation kinetics of biomass, while ultimate analysis determines its elemental composition, facilitating a deeper understanding of the fuel's intrinsic chemical properties and reactivity. These standard methods facilitate comparison across studies, ensure consistency in research and industrial applications and are vital for optimizing processes like pyrolysis, torrefaction and combustion to achieve sustainable energy solutions. Table 7 presents the standardized testing methods along with their corresponding codes utilized for the characterization and analysis of biomass samples.

Table 7 Standard biomass testing methods

Parameter	ASTM Standard	Description / Purpose	Ref.
Proximate Analysis			
Moisture Content	ASTM E871–82 (Reapproved 2019)	Determines moisture by oven drying; essential for combustion efficiency	[66], [94], [95]
Volatile Matter	ASTM E872–82 (Reapproved 2019)	Measures volatile matter released at high temperature without oxygen	[96], [97], [98]
Ash Content	ASTM D1102–84 (Reapproved 2021)	Determines inorganic residue after combustion	[66], [97]
Fixed Carbon (by difference)	ASTM E870–82 (section 9)	Computed from total of proximate analysis values	[94], [96]
Ultimate Analysis			
Carbon, Hydrogen, Nitrogen, Sulphur, Oxygen	ASTM D5373–16 / ASTM D4239–18e2	Elemental composition using CHNS analyzers or high–temperature combustion techniques	[66], [99], [100]
Calorific Value / Energy Testing			
Higher Heating Value (HHV)	ASTM E711–87 (Reapproved 2023)	Determines gross calorific value by bomb calorimeter	[94], [101], [102]
Bulk Density Measurement			
Density of Biomass	ASTM E873–82 (Reapproved 2019)	Establishes procedures for estimating bulk density of solid biofuels	[66], [101]
Particle Size / Sieve Analysis			
Biomass particle distribution	ASTM E828–19	Determines size distribution for combustion, densification and handling quality	[66], [103]
Ash Fusion Temperature (AFT)			
Thermal behavior of ash residues	ASTM D1857–04 (Reapproved 2020)	Estimates melting and deformation behavior of ash during thermal conversion processes	[66], [103]
Thermogravimetric Analysis (TGA)			
Thermal degradation characteristics	ASTM E1641–16	Standard practice for decomposition and kinetic study via thermogravimetric analysis	[104], [105], [106]
Lignocellulosic Composition			
Cellulose, Hemicellulose and Lignin Content	ASTM E1721–01 (Reapproved 2018)	Quantifies structural carbohydrates and lignin using acid hydrolysis	[99], [107], [108]

3.0 BIOMASS CONVERSION PROCESSES

Biomass utilization is crucial for advancing sustainable energy solutions and optimizing waste management. It involves transforming organic materials into valuable energy products. This conversion occurs through various processes, including pyrolysis, gasification and fermentation. As a renewable substitute for fossil fuels, biomass contributes to lowering greenhouse gas emissions and decreasing dependence on finite natural resources. Moreover, byproducts like biochar enhance soil fertility and aid in carbon sequestration. Table 8 presents a comparative analysis of different biomass utilization techniques, outlining their processes, benefits and limitations.

Table 8 Different methods of biomass utilization

Process	Advantages	Disadvantages
Direct combustion [109] [110], [111]		
Biomass is burned to produce heat and energy, often for cooking, heating and electricity generation	Simple and cost effective, suitable for small–scale applications	Inefficient if not optimized, can release pollutants without emission controls
Gasification [110], [112], [113]		
Converts biomass into syngas (H_2, CO, CH_4) via heat in a low–oxygen environment for electricity or fuel	Higher efficiency than combustion Produces cleaner energy with reduced emissions	Requires advanced technology and infrastructure
Pyrolysis [114]		
Biomass heated without oxygen to produce bio–oil, syngas for further processing and biochar for fuel.	Flexible end products, biochar improves soil fertility and sequesters carbon	High initial cost
Anaerobic Digestion [115]		
Microorganisms decompose wet organic waste in an oxygen–free environment to produce biogas and digestate	Converts waste into energy, reduces GHG emissions and provides fertilizer	Limited to organic and wet biomass
Fermentation [116]		
Microbial action converts sugars/starches (ex., corn, sugarcane) into ethanol and other biofuels	Reduces fossil fuel dependency, established global adoption	Competes with food production
Torrefaction (slow pyrolysis) [117]		
Biomass heated at 200–300°C without oxygen, producing dry, energy–dense material similar to coal	Improves energy density and transportability, long–term storage	Requires additional processing infrastructure
Transesterification [118]		
Biomass oils are chemically converted into biodiesel, usable as diesel substitute or blend	Renewable, reduces carbon emissions, compatible with diesel engines	Competes with food production

3.1 Pyrolysis

Pyrolysis is a thermochemical conversion process that breaks down organic materials at elevated temperatures (typically 300–700°C) in low oxygen environment. This process yields three primary products: biochar (solid), bio–oil (liquid) and syngas (gas) as shown in figure 8. The physicochemical properties and yield of these products are governed by the intrinsic characteristics of the feedstock and critical process variables, such as thermal decomposition temperature, pyrolysis kinetics, residence duration, reactor configuration etc. [114]. Following are the factors affecting pyrolysis process.

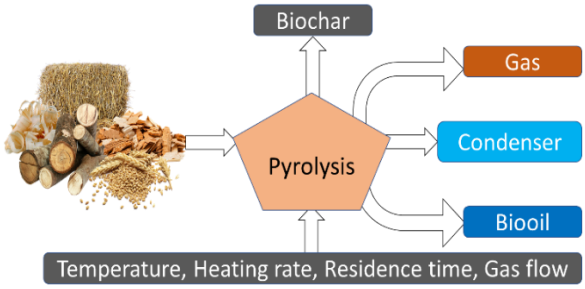


Figure 8 Product of pyrolysis [119]

3.1.1 Temperature

The thermal properties of the biochar depend on raw material characteristics and the temperature during pyrolysis [120]. Lower temperatures (300–500°C) favor biochar production, while higher temperatures (500–700°C) enhance bio–oil and gas yields [121]. Temperatures exceeding 300°C lead to significant devolatilization and polymer carbonization, both of which are unfavorable for the process [117]. Additionally, lignin degradation in biomass becomes dominant beyond this temperature, potentially hindering the pelletization of torrefied products. Moreover, rapid thermal breaking of cellulose, resulting in tar formation, typically begins between 300°C and 320°C [122]. These factors establish 300°C as the upper temperature limit for effective torrefaction.

3.1.2 Residence Time

The retention duration of biomass within the reactor significantly impacts its thermochemical decomposition kinetics and overall conversion efficiency. Torrefaction is characterized by a slow heating rate, distinguishing it from the fast–heating nature of pyrolysis. Typically, the heating rate in torrefaction is below 50°C/min. Due to this, the residence time of biomass in a torrefaction reactor extends to several minutes. A longer residence time results in a lower mass yield but enhances the energy density of the final product [121]. The influence of residence time is often significantly impacted by factors such as temperature, heating rate and other operational parameters, making it difficult to provide a clear and direct understanding of its role in biochar production [123]

3.1.3 Particle Size

Particle size is a critical parameter in the pyrolysis process, as it significantly influences the rate of heat transfer to the biomass feedstock. Biomass particle size had a significant impact on product yields in the lower temperature region [124]. Larger particle sizes increase the distance between the biomass surface and its core, thereby impeding the efficient flow of heat from the hotter exterior to the cooler interior. This results in a pronounced temperature gradient within the particle, which is known to enhance char yield due to uneven thermal decomposition dynamics [125]. Smaller particles increase surface area, improving heat transfer and accelerating pyrolysis [126]. An experimental study was conducted on Paulownia wood using particle sizes ranging from 12 mm to less than 0.3 mm. The samples were torrefied at temperatures of 260°C and 290°C in a fixed–bed reactor for

durations between 30 and 90 minutes. The results indicated that smaller particle sizes generally produced slightly lower energy yields compared to larger ones. It was also observed that an increase in particle size led to a corresponding increase in the higher heating value of the biomass [127].

3.1.4 Heating Rate

The heating rate is a key factor in biomass pyrolysis, as it significantly affects the characteristics and composition of the final product. Lower heating rates help reduce or prevent secondary pyrolysis reactions. Additionally, low heating rates prevent thermal cracking of the biomass, leading to a higher biochar yield. On the other hand, high heating rates promote the fragmentation of the biomass, increasing the yield of gaseous and liquid products while reducing the potential for biochar formation. Moderate heating rates favor char formation by allowing sufficient time for thermal decomposition. Rapid heating can lead to incomplete devolatilization, affecting char quality [126]. A study on the pyrolysis of safflower seeds reported a decrease in biochar yield with an increase in the heating rate from 30 to 50 °C/min, indicating that higher heating rates favor the formation of more volatile products over solid char [128].

3.1.5 Feedstock Composition

Lignocellulosic composition (cellulose, hemicellulose, lignin) influences char yield and properties as they decompose at different temperature ranges [129]. Lignin–rich biomass tends to produce higher char yields due to its thermal recalcitrance. High moisture reduces reaction temperature efficiency due to energy consumption for vaporizing water, lowering bio–oil yield [130].

3.1.6 Inert Gas

Carrier gas flow rate significantly affects the distribution of pyrolysis products. During biomass pyrolysis, moderate to high amounts of vapors are generated and if not purged, they can participate in secondary reactions, altering the nature and composition of the products. Efficient mass and heat transfer due to gas flow leads to more uniform heating of biomass particles, which is critical for consistent pyrolysis reactions [131]. High gas flow rates tend to sweep pyrolysis vapors out quickly, favoring liquid (bio–oil) and gas yields by minimizing the contact time of volatiles with hot surfaces that promote secondary char–forming reactions. Low gas flow rates tend to increase char yield, as vapors have more time in the reactor and can undergo secondary reactions, increasing the fixed carbon content in biochar. Too high inert flow, however, can cool the reactor and lower process efficiency; thus, optimizing gas flow is essential for both yield and energy efficiency [132].

Table 9 shows the effect of gas flow rate on the distribution of pyrolysis products, indicating that lower flow rates favor char formation, moderate rates optimize bio–oil yield and higher rates enhance gas production due to rapid vapor removal.

Table 9 Effect of gas flow rate on product distribution during biomass pyrolysis [133]

N_2 Flow Rate (L/min)	Bio-oil Yield (wt.%)	Char Yield (wt.%)	Gas Yield (wt.%)	Key Observation
0-5	Low (~40-50)	High	High	Slow sweep leads to long vapor residence time, promoting repolymerization and secondary char/gas formation.
10-20	Moderate (~55)	Moderate	Moderate	Transitional; partial secondary reactions occur.
25 (optimum)	High (63.2)	Low	Low	Short vapor residence (<2 s) maximizes bio-oil by minimizing cracking.
>25	Decreasing (~50-60)	Stable	Increasing	Excess flow entrains vapors, reducing bio-oil recovery.

However, in industrial-scale pyrolysis plants, inert gases are often omitted to avoid elevated operational costs associated with gas supply, compression and recycling systems. Vacuum pyrolysis, for instance, operates without carrier gases by reducing pressure to facilitate rapid vapor evacuation, enabling efficient heat transfer for larger biomass particles while minimizing secondary reactions. Self-sustaining designs using partial oxidative pyrolysis or syngas recycling further eliminate external inert gas needs, enhancing economic feasibility for commercial biochar and bio-oil production [134], [135].

3.1.7 Additives

Catalysts play a vital role in improving biomass pyrolysis by altering reaction pathways, accelerating decomposition and enhancing product quality and yield. Catalysts enhance char quality by increasing fixed carbon content and surface area, useful for soil amendment or as a solid fuel [136]. Extensive research on biomass thermochemical conversion has confirmed the positive impacts of catalysts, highlighting the critical role of their selectivity in optimizing product distribution [137]. Torrefaction assisted by alkali and alkaline earth metal (AAEM) catalysts has been shown to improve both the yield and quality of biochar [138]. The release of AAEMs during torrefaction enhances the energy density, heating value, grindability and thermal degradation characteristics of the resulting product [139], [140], AAEM catalysts are particularly effective in increasing biochar yield [141], [142], while zeolite–based catalysts in pyrolysis have been demonstrated to enhance the yield and quality of bio–oil [143].

Table 10 Catalytic effects on biochar during torrefaction [144], [145], [146], [147]

Chemical Role During Torrefaction	Effect on Biochar Yield	Effect on Biochar Quality	Example & Mechanism
$CaCl_2$			
Promotes dehydration and cross-linking of biomass polymers	Increases biochar yield by promoting carbonization reactions	Enhances biochar stability, surface functional groups, and porosity	$CaCl_2$ acts as a dehydrating agent that facilitates aromatic carbon formation and increases fixed carbon content
Ni-based catalysts			
Catalyzes reforming and cracking of volatiles	May reduce char yield slightly by enhancing volatile conversion to gases	Improves syngas quality and biochar catalytic activity	Nickel doped biochar catalyzes steam reforming reactions, increasing hydrogen and CO content
KOH			
Increases alkaline environment promotes gasification-like reactions	Can increase biochar yield by inhibiting tar formation	Enhances surface area and porosity, increases alkalinity	KOH activates carbon surface, increasing microporosity
Acidic catalysts (e.g., H_3PO_4)			
Catalyzes dehydration and polymerization of biomass components	Increases char yield through enhanced cross-linking	Improves thermal stability and generates oxygen-containing surface groups	Phosphoric acid catalyzes polycondensation reactions forming stable biochar with acidic surface groups
Zeolites			
Provide acidic and shape-selective sites for cracking volatiles	Can modulate biochar formation by promoting secondary reactions	Increases carbon crystallinity and surface acidity	Zeolite's acidity promotes secondary cracking of volatiles leading to biochar with tailored porosity and functionality

Table 10 show different catalysts influence chemical pathways such as dehydration, cross-linking, reforming and cracking during torrefaction. These pathways affect biochar yield by either promoting carbon retention or enhancing volatile conversions, while improving quality through increased surface functionality, stability, porosity and catalytic properties.

Pyrolysis process has attracted considerable attention as a sustainable technology owing to its potential for effective waste management, renewable energy generation and long–term carbon sequestration. Biochar produced during pyrolysis is rich in carbon and can be used as a soil amendment to improve fertility and store carbon in the soil, thereby mitigating climate change [148]. Bio–oil, with its high energy density, can be upgraded into transportation fuels, while syngas serves as a clean energy source [24]. Recent advancements in reactor designs such as fluidized beds and microwave–assisted systems have enhanced the efficiency and scalability of pyrolysis. These innovations aim to optimize product yield and quality, particularly for biochar and bio–oil, making pyrolysis a key component of sustainable energy systems [149].

The pyrolysis process is classified on the basis of operating temperature (low, medium, high), heating rate (slow, fast, flash), atmosphere (inert, non–inert), feedstock type (biomass, plastic, rubber, mixed waste), end products (char, oil, gas–dominant), reactor type (fixed–bed, fluidized–bed, rotary kiln, microwave, solar) and scale (laboratory, pilot, commercial). Figure 9 provides a comparative analysis of different types of pyrolysis based on their operating conditions and product distribution. Slow pyrolysis, characterized by low heating rates and long residence times, maximizes biochar yield while producing lower amounts of bio–oil and syngas. In contrast, fast and flash pyrolysis operate at significantly higher temperatures and heating rates, favoring bio–oil production while reducing biochar yield. Intermediate pyrolysis offers a balanced approach, yielding moderate quantities of biochar, bio–oil and syngas. These variations highlight how process parameters influence product composition, making the selection of pyrolysis type crucial for specific applications.

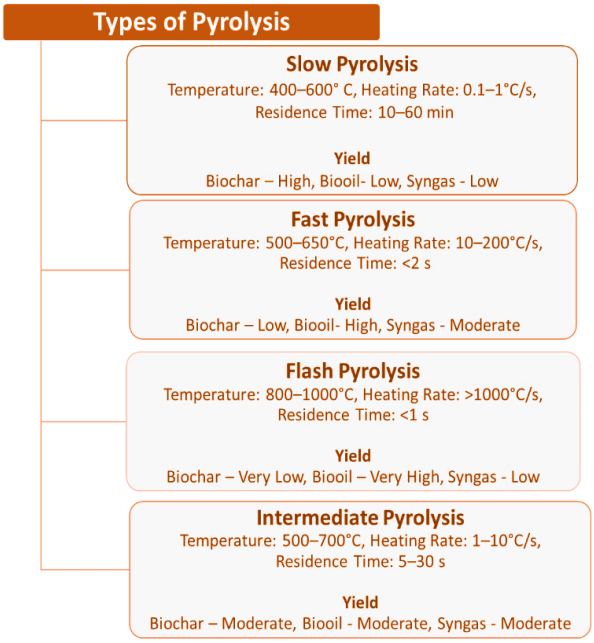


Figure 9 Types of pyrolysis [150]

3.2 Torrefaction

Torrefaction is a thermochemical treatment technique wherein biomass undergoes controlled heating in an inert or oxygen–deficient environment, resulting in enhanced energy densification by elevating its higher heating value (HHV) and improving its hydrophobic characteristics [151], [152]. Biomass torrefaction process begins with feedstock supply and pre–treatment operations such as size reduction, drying and sieving. The core torrefaction stage involves controlled heating in an inert atmosphere (N_2 or CO_2) within a temperature range of 200–300°C, governed by parameters like residence time and heating rate. The process concludes with post–treatment steps, including cooling, screening, densification and packaging, to produce a stable and energy–dense solid biofuel as represented in figure 10. The process involves breakdown of hemicellulose and the partial depolymerization of cellulose and lignin, yielding a carbon–rich solid residue termed torrefied biomass or biochar,

accompanied by the release of gaseous and liquid by–products [61], [153], [154], [155]

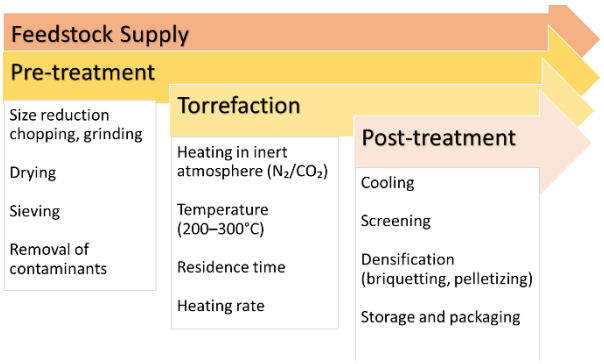


Figure 10 Process flow of biomass torrefaction: pre–treatment, torrefaction and post–treatment stages

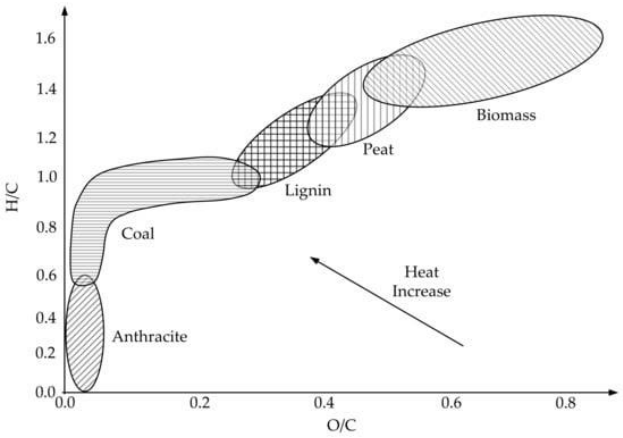


Figure 11 van Krevelen diagram[156], [157], [158]

Chemically, torrefaction operates through the preferential elimination of oxygen (O) as well as hydrogen (H) from biomass, leading to the formation of a carbon–enriched solid product characterized by lower oxygen–to–carbon (O/C) and hydrogen–to–carbon (H/C) atomic ratios. The van Krevelen diagram (figure 11) serves as a useful tool for understanding the chemical structure of biomass and its conversion products, particularly during processes like pyrolysis, gasification and combustion. It plots the H/C (hydrogen to carbon) ratio against the O/C (oxygen to carbon) ratio, helping to assess the fuel quality and the degree of maturity of the biomass. Biomass with a high O/C ratio and low H/C ratio is more oxygen–rich and less energy–dense, while fuels with low O/C and H/C ratios, such as biochar or coal are more carbon–rich and energy–dense. The diagram provides insights into how the biomass behaves under thermal treatment, aiding in the optimization of the pyrolysis process for desired product outcomes like bio–oil, syngas and biochar.

The dry torrefaction process progresses through multiple sequential stages, including heating, drying, torrefaction and cooling [159]. According to Bergman et al. (2005), the drying phase can be further subdivided into two distinct stages, thereby classifying torrefaction as a five–stage thermochemical conversion process as described in table 11 and represented on graph in figure 12.

Table 11 Characterization of the distinct phases involved in the torrefaction process [117]

Phase	Description
1. Heating	Biomass is subjected to thermal exposure until it attains the drying temperature, initiating the phase where its inherent moisture content undergoes evaporation.
2. Pre–drying	At approximately 100°C, the free moisture present in the biomass undergoes phase transition, evaporating at a steady temperature.
3. Post–drying	As the temperature rises to 200°C, the remaining water bound within the biomass structure is fully released, leading to mass reduction.
4. Torrefaction	The primary phase of torrefaction occurs at around 200°C, where substantial mass reduction is observed. The torrefaction temperature denotes the highest stable temperature maintained during the process.
5. Cooling	The resulting torrefied product is cooled to below 200°C to mitigate the risk of auto–ignition before being exposed to ambient air and subsequently brought down to ambient temperature.

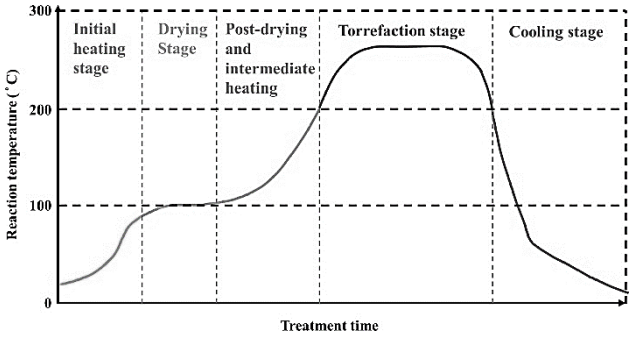


Figure 12 Schematic of different stages during dry torrefaction [117]

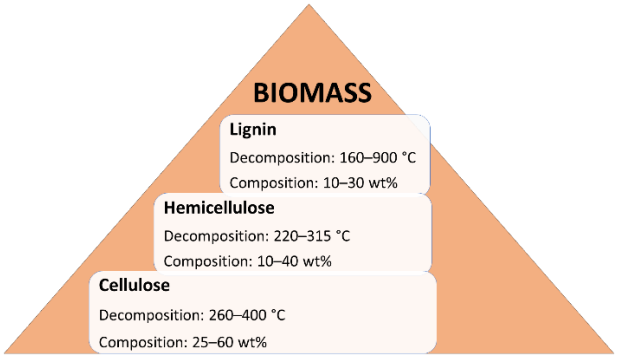


Figure 13 Contents and reaction of biomass components at different torrefaction temperatures [160]

Figure 13 illustrates thermal decomposition behavior of the primary biomass components different torrefaction temperatures. Hemicellulose decomposes at lower temperatures (200–300°C), undergoing drying, depolymerization and significant devolatilization. Lignin exhibits a broader decomposition range, softening early and degrading gradually up to 300°C. Cellulose undergoes limited devolatilization at moderate temperatures and extensive

carbonization beyond 250°C. The torrefaction process primarily affects hemicellulose and cellulose, enhancing biochar quality while making biomass more energy–dense and hydrophobic. Understanding these reactions helps optimize torrefaction parameters for improved fuel properties.

4.0 PHYSICOCHEMICAL CHARACTERISTICS OF BIOCHAR

Torrefaction induces substantial modifications in the physicochemical characteristics of biomass, resulting in improved fuel properties compared to untreated feedstock [155]. The process leads to a significant reduction in moisture content and volatile matter, accompanied by an increase in fixed carbon, calorific value and overall energy density. These enhancements make torrefied biochar a superior solid biofuel with better storage stability, hydrophobicity and grindability as represented in figure 14. As a result, torrefied biomass exhibits improved handling and transportation characteristics, facilitating more efficient thermochemical conversion processes. Moreover, the alterations in sphericity and heating value further enhance combustion efficiency and energy utilization potential [151], [161], [162] The changes in the characteristics of biomass are discussed as follows.

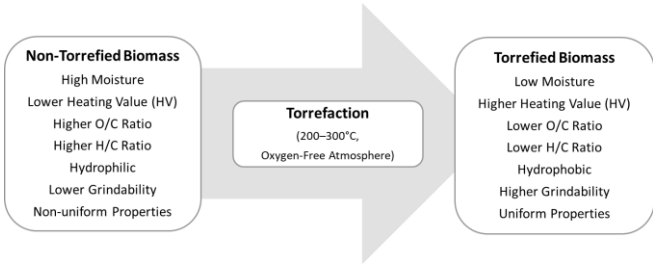


Figure 14 Diagrammatic comparison of biomass properties with torrefied biomass properties

4.1 Moisture Content

During torrefaction, dehydration eliminates hydroxyl groups in wood, restricting hydrogen bond formation and making the biomass hydrophobic [163]. Thus, there is reduction in moisture content in torrefied product. This reduction plays a crucial role in enhancing energy efficiency and optimizing the quality of the final product, as excessive moisture content contributes to energy losses during combustion [151].

Table 12 shows that moisture content of all biomass shows a significant decline after torrefaction, indicating improved fuel stability and storability. For instance, coconut shell and groundnut shell biochar exhibit the lowest moisture values (<5% and 3–6%, respectively), demonstrating excellent hydrophobic properties suitable for long–term storage and energy applications. Cotton stalk and tur stalk also show marked reductions (from 6–11% and 8–10% to 5–7% and 2–6%), reflecting efficient dehydration during the thermal process. Similarly, rice husk, wheat straw and sugarcane bagasse biochar retain lower moisture levels (3–8%), confirming the effectiveness of torrefaction in driving off bound water.

Table 12: Comparison of proximate composition of raw biomass and corresponding biochar samples [164], [165], [166], [167], [168]

Parameter	Raw Biomass Value	Biochar Value	Remarks / Effect of Torrefaction or Pyrolysis
Coconut Shell			
Moisture (%)	6 – 8	<5	Decreased moisture; increased stability
Volatile Matter (%)	25 – 35	10 – 18	Reduced volatiles, more fixed carbon
Ash (%)	0.6 – 2	2 – 5	Ash content may increase slightly
Fixed Carbon (%)	60 – 68	70 – 85	Enhanced fixed carbon and calorific value
Calorific Value (MJ/kg)	18 – 21	25 – 30	Significant increase after pyrolysis
Cotton Stalk			
Moisture (%)	6 – 11	5 – 7	Moisture reduced by pyrolysis
Volatile Matter (%)	70 – 75	20 – 30	Reduction due to pyrolysis
Ash (%)	5 – 7	5 – 8	Slight ash content change
Fixed Carbon (%)	15 – 20	50 – 65	Increased fixed carbon
Calorific Value (MJ/kg)	15 – 17	24 – 28	Calorific value improves after biochar formation
Tur Stalk			
Moisture (%)	8 – 10	2 – 6	Decreased moisture
Volatile Matter (%)	70 – 76	18 – 29	Reduced volatiles
Ash (%)	4 – 7	4 – 8	Ash mostly stable
Fixed Carbon (%)	17 – 19	55 – 70	Higher carbon concentration
Calorific Value (MJ/kg)	15 – 16	22 – 27	Calorific value improved
Rice Husk			
Moisture (%)	8 – 12	3 – 7	Moisture reduced
Volatile Matter (%)	65 – 75	25 – 35	Pyrolysis reduces volatile content
Ash (%)	15 – 20	20 – 25	Ash content slightly increased
Fixed Carbon (%)	7 – 10	50 – 60	Higher fixed carbon due to carbonization
Calorific Value (MJ/kg)	13 – 15	24 – 28	Significant improvement in calorific value
Wheat Straw			
Moisture (%)	10 – 14	4 – 8	Decreased moisture
Volatile Matter (%)	65 – 80	20 – 35	Volatile matter reduced
Ash (%)	5 – 9	7 – 12	Ash content modest increase
Fixed Carbon (%)	10 – 15	50 – 68	Higher fixed carbon
Calorific Value (MJ/kg)	15 – 16	23 – 29	Improved calorific value
Groundnut Shell			
Moisture (%)	6 – 9	3 – 6	Lower moisture after pyrolysis

Volatile Matter (%)	70 – 75	18 – 34	Reduced volatiles
Ash (%)	2 – 5	3 – 7	Ash increased mildly
Fixed Carbon (%)	13 – 18	55 – 70	Increased fixed carbon content
Calorific Value (MJ/kg)	17 – 18	24 – 30	Calorific value enhanced
Sugarcane Bagasse			
Moisture (%)	10 – 14	4 – 8	Significant moisture reduction
Volatile Matter (%)	70 – 75	20 – 35	Dropped volatile matter
Ash (%)	1 – 3	3 – 6	Slight ash increase
Fixed Carbon (%)	15 – 18	52 – 68	Higher fixed carbon content
Calorific Value (MJ/kg)	16 – 17	24 – 29	Calorific value significantly improved

4.2 Fixed Carbon and Volatile Matter

Torrefaction significantly alters the proximate composition of biomass, especially the fixed carbon and volatile matter content, affecting the fuel properties of the resulting biochar. Torrefaction enhances the fixed carbon content of biomass by removing moisture and decomposing hemicellulose, leading to higher energy density and carbon stability. Simultaneously, volatile matter decreases sharply from about 70% to 20 – 25% as light organics and gases are released during heating[169]. These changes result from dehydration and deoxygenation reactions between 200°C and 300°C, forming stable aromatic carbon structures characteristic of high–quality biochar [170]. The table 12 shows that torrefaction and pyrolysis significantly alter the volatile matter and fixed carbon content across all biomass types, enhancing the solid fuel characteristics of the resulting biochar. In all cases, volatile matter decreases sharply, indicating the release of thermally labile compounds such as CO, CO_2, CH_4 and tars during thermal decomposition. Conversely, fixed carbon content increases, reflecting carbon enrichment and higher energy density in the biochar. Specifically, coconut shell shows a reduction in volatile matter from 25–35% to 10–18% and an increase in fixed carbon from 60–68% to 70–85%, demonstrating high thermal stability and superior fuel quality. Cotton stalk and tur stalk exhibit similar trends, with volatile matter decreasing from 70–76% to below 30% and fixed carbon rising to 65–70%, suggesting effective devolatilization and carbon retention. Rice husk biochar records a substantial rise in fixed carbon (from 7–10% to 50–60%), despite its high ash content, indicating efficient carbonization. Wheat straw, groundnut shell and sugarcane bagasse also follow the same pattern, with fixed carbon increasing by more than threefold compared to raw biomass.

4.3 Bulk Density

Torrefaction affects the bulk density of biochar by reducing moisture and volatiles, causing structural shrinkage and carbon concentration that can either slightly decrease or increase density depending on porosity. This is due to thermal decomposition of hemicellulose, moisture and volatile release causing structural compaction and reduced particle size enhancing packing density. Studies have shown that torrefaction increases bulk density through material densification, as observed in Goldenrod, White Spruce sawdust and agricultural residues like sugarcane bagasse, which exhibit improved grindability, pellet stability and heating value despite increased microporosity [170], [171], [172]. The bulk density of torrefied biomass generally falls within the range of 180–350 kg/m³, depending on the initial density of the raw biomass [151].

4.4 Calorific Value

Torrefaction enhances the calorific value of biomass by removing moisture and volatile organics, thereby enriching the carbon concentration and energy density [156]. The calorific value typically increases by 10–30%, depending on torrefaction temperature and residence time. This improvement results from the breakdown of hemicellulose, release of oxygen–rich volatiles and formation of stable aromatic carbon compounds. Reduced moisture also minimizes energy loss during combustion, making torrefied biochar more coal–like in energy content.

Table 12 shows that the calorific value of all biomass types increases substantially after torrefaction or pyrolysis, confirming a significant improvement in the energy density and fuel quality of the resulting biochar. This enhancement is attributed to the loss of moisture and volatiles and the enrichment of fixed carbon content, which collectively make biochar a more efficient and stable solid fuel. Specifically, coconut shell biochar exhibits a notable rise in calorific value from 18–21 MJ/kg to 25–30 MJ/kg, reflecting high carbon retention and excellent energy potential. Similarly, cotton stalk and tur stalk show improvements from 15–17 MJ/kg and 15–16 MJ/kg to 24–28 MJ/kg and 22–27 MJ/kg, respectively, indicating effective thermochemical upgrading. Rice husk demonstrates one of the most significant gains, from 13–15 MJ/kg to 24–28 MJ/kg, despite its high ash content, suggesting efficient conversion to carbon–rich material. Wheat straw, groundnut shell and sugarcane bagasse follow similar trends, with calorific values rising by approximately 50–70%, confirming improved combustion efficiency and reduced ignition losses.

4.5 Grindability

Raw biomass exhibits a highly fibrous structure with significant mechanical toughness. Torrefaction weakens this structure by degrading the hemicellulose matrix and depolymerizing cellulose [151], reducing fiber length without significantly altering particle diameter. This enhances grindability and facilitates better handling and transport [162]. Furthermore, torrefaction enhances the generation of small size particles under identical processing conditions [173], [174], while the energy required for grinding torrefied biomass chips is reduced by approximately 90% compared to untreated wood chips [175]

Table 13 Comparison of grindability of different biomass samples before and after pyrolysis [164], [165], [166], [167], [168]

Biomass	Raw Biomass Value	Biochar Value
Coconut Shell	Moderate	Improved
Cotton Stalk	Less brittle	More brittle
Tur Stalk	Less brittle	Higher
Rice Husk	Hard	Moderate
Wheat Straw	Moderate	Easy
Groundnut Shell	Moderate	Improved
Sugarcane Bagasse	Moderate	Easy

Table 13 shows that torrefaction and pyrolysis enhance the grindability of all biomass types, making biochar more brittle, friable and easier to mill compared to their raw forms. Biomass such as rice husk, wheat straw and sugarcane bagasse exhibit the most noticeable improvement due to structural weakening and carbonization.

4.6 Ultimate Analysis (C, H, O)

Torrefaction primarily targets hemicellulose and some cellulose, releasing oxygen–rich and hydrogen–rich volatile components as gases. These devolatilization reactions concentrate carbon and reduce oxygen/hydrogen content. The process increases carbon concentration (typically from ~45% to 65 – 75%) due to devolatilization and moisture removal, thereby enhancing fixed carbon and energy density [176]. Hydrogen and oxygen contents decline substantially through dehydration and decarboxylation reactions, improving calorific value and fuel stability [176], [177]. Overall, torrefaction produces a carbon–rich, hydrophobic and thermally stable biochar with coal–like characteristics suitable for energy applications.

Figure 15 shows that biochar derived from all biomass types exhibits a significant improvement in fuel properties compared to their raw forms. The carbon content increases substantially (by 20 – 40%), while the hydrogen and oxygen contents decrease sharply, indicating enhanced carbonization and higher energy density. For example, coconut shell and groundnut shell biochar show the highest fixed carbon values (up to 85% and 75%, respectively), suggesting superior calorific potential and thermal stability. In contrast, rice husk and sugarcane bagasse biochar, though improved, show relatively lower carbon enrichment due to their higher initial ash and volatile contents. The marked reduction in hydrogen and oxygen across all samples (typically from 5 – 6% to 1 – 4% and 40 – 48% to 5 – 18%) confirms efficient devolatilization during pyrolysis or torrefaction, which enhances combustion efficiency and hydrophobicity.

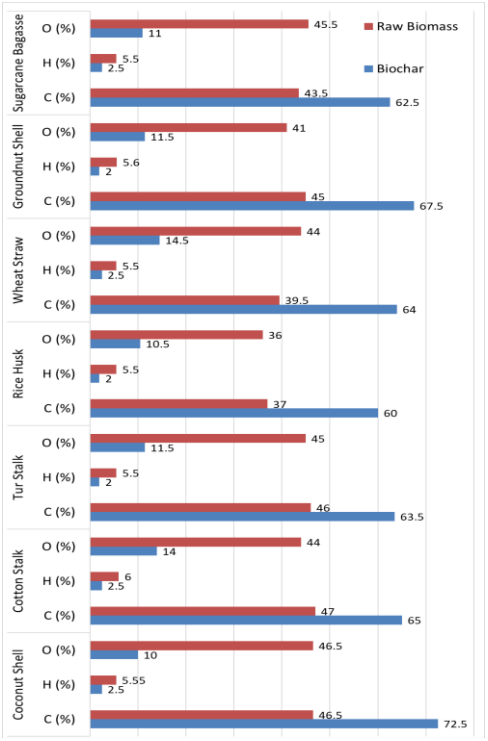


Figure 15 Comparison of elemental composition (C, H, O) of raw biomass and corresponding biochar samples [65]

4.7 Ultimate Analysis (N, S)

Nitrogen content shows minor reductions, potentially lowering NO_x emissions during combustion. Sulphur content slightly decreases or remains stable, minimizing SO_x emission potential [178]. Figure 16 shows Nitrogen and sulphur contents remain low in all biochar, minimizing the risk of NOx and SOx emissions. Overall, the conversion of raw biomass to biochar significantly improves its fuel quality, energy content and environmental performance, making it a more stable and sustainable solid fuel.

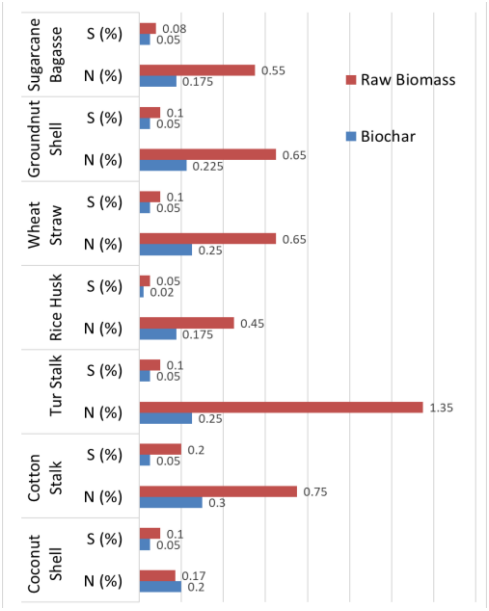


Figure 16 Comparison of elemental composition (N, S) of raw biomass and corresponding biochar samples [65]

4.8 Ash Content

Torrefaction generally increases the ash content of biochar on a dry weight basis, as volatile organics and moisture are expelled while inorganic minerals remain concentrated in the solid residue. Thus, ash becomes a higher percentage of the total biochar mass, even though the absolute amount of mineral matter stays roughly the same [170], [179]. This relative enrichment occurs because thermal decomposition of cellulose, hemicellulose and lignin releases gaseous products (CO_2, CO, H_2O), reducing organic mass. Consequently, the proportion of ash in the remaining biochar increases substantially, with some biomasses (e.g., rice husk) showing ash content rising from ~7% to over 38% at higher torrefaction temperatures [169]. The effect magnitude depends on biomass composition and the intensity of torrefaction conditions, mainly governed by temperature, heating rate and retention time.

Experimental investigations shows that that biochar generally exhibits a slight to moderate increase in ash content compared to raw biomass, with high – ash residues like rice husk showing the most significant rise [164], [165], [166], [167], [168]. From a fuel properties perspective, this indicates that while energy density may improve due to carbon enrichment, feedstocks with initially high ash could pose challenges such as slagging or fouling during combustion.

5.0 COMPARISONS OF CHARACTERISTICS OF TORREFIED BIOMASS WITH COAL

Torrefied biomass exhibits physicochemical properties that closely resemble those of conventional coal, making it a promising renewable substitute for fossil – based solid fuels. Comparative analysis of parameters highlights the enhanced fuel characteristics of torrefied biomass for co – firing and energy applications.

Biochar can be evaluated based on two key parameters: Physicochemical Characteristics and Emission and Ash Characteristics. These parameters provide a comprehensive understanding of its fuel quality, combustion behavior and environmental impact compared to conventional solid fuels.

5.1 Physicochemical Characteristics

Physicochemical characteristics of biochar include parameters such as carbon content, hydrogen – to – carbon ratio, volatile matter, fixed carbon and calorific value. These properties determine the energy density, stability and combustion performance of the fuel. Understanding physicochemical characteristics is essential for assessing the suitability of biochar as a substitute for coal and optimizing process parameters during pyrolysis or torrefaction to achieve desired fuel quality.

Table 14 Comparative analyses of physicochemical characteristics of raw biomass, torrefied biomass [180], [181]

Parameter	Raw Biomass	Torrefied Biomass	Notes / Implications
Volatile Matter (VM) (%)	65 - 80	40 - 50	Decreases after torrefaction; affects ignition
Fixed Carbon (FC) (%)	10 - 20	40 - 50	Fixed carbon increases with torrefaction
Carbon Composition (%)	45 - 50	55 - 65	Carbon content increases, approaching coal
Oxygen Composition (%)	40 - 45	20 - 30	Oxygen content reduced during torrefaction
Atomic O/C Ratio	~0.7	~0.3	Indicator of fuel quality improvement
Atomic H/C Ratio	~1.5	~1.0	Decreasing H/C ratio shows enhanced fuel stability
Sulphur	0.1–0.3	0.1–0.3	typically decreases due to volatilization of sulphur-containing compounds
Volumetric Energy Density (GJ/m³)	5 - 8	10 - 14	Doubling after torrefaction improves storage
Handling and Logistics	Difficult (fragile, bulky)	Easier (hydrophobic, dense)	Torrefaction improves handling and storage
CO_2 Emissions (kg/MJ)	~0.08 (biogenic carbon)	~0.07 (biogenic carbon)	Biomass considered carbon-neutral
Co-Firing Feasibility with Coal	Poor (due to high moisture, low energy density)	Good (similar to coal)	Torrefied biomass ideal for co-firing
Heating Value (MJ/kg)	14 - 18	18 - 24	Increased after torrefaction
Dust Explosibility	High (fine particles ignite easily)	Reduced (due to hydrophobicity and density)	Torrefied biomass safer to handle
Hygroscopic Behavior	High (absorbs moisture easily)	Low (hydrophobic surface)	Torrefaction improves moisture resistance
Biological Degradation	High (susceptible to microbes)	Low (resistant)	Torrefied biomass more stable for storage
Transportation Cost	High (low energy density, bulky)	Lower (dense, higher energy content)	Torrefied biomass reduces transportation cost

Table 14 gives the comparative analyses of physicochemical characteristics of raw biomass, torrefied biomass. Table shows that Torrefied biomass exhibits several properties that make it a promising and sustainable substitute for coal in energy applications. Its heating value, ranging from 18 to 24 MJ/kg, closely approaches that of bituminous coal (24 – 30 MJ/kg), indicating a significant improvement in fuel quality suitable for co – firing. The elemental composition of torrefied biomass, characterized by reduced O/C and H/C ratios (~0.3 and ~1.0), resembles that of coal, enhancing its thermal stability and combustion efficiency. Environmentally, torrefied biomass offers clear advantages with its biogenic carbon and low sulphur content (0.05 – 0.3%), resulting in lower CO_2 and SO_2 emissions compared to fossil coal. Furthermore, its hydrophobic, dense and biologically stable nature improves storage, transportation and handling characteristics, overcoming the limitations of raw biomass. Overall, torrefied biomass provides a renewable, carbon – neutral and cleaner alternative to coal, contributing significantly toward sustainable and low – carbon energy transitions. Unlike raw biomass, torrefied briquettes exhibit hydrophobic properties and resistance to biological degradation, making them easier to store. Moreover, torrefied biomass exhibits compatibility for co – firing with coal at ratios of up to 50%, establishing it as a viable renewable energy alternative for industrial applications.

Table 15 Properties of natural coal [182]

Lignite (Low Rank)	Sub – bituminous	Bituminous	Anthracite (High Rank)
Moisture Content (%)			
30–60	15–30	5–15	2–8
Volatile Matter (%)			
35–45	30–40	20–35	5–15
Fixed Carbon (%)			
25–35	35–45	45–60	80–95
Ash Content (%)			
5–15	5–15	5–15	5–15
Carbon Content (%)			
60–70	70–75	75–85	85–95
Hydrogen Content (%)			
4–5	4–5	3–4	2–3
Oxygen Content (%)			
20–30	15–20	5–15	1–5
Sulphur Content (%)			
0.2–1.0	1–2	1–3	1–4
Gross Calorific Value (MJ/kg)			
15–20	20–26	25–30	28–32
Porosity (%)			
High (~40–50)	Moderate (~30–40)	Lower (~10–30)	Very low (~5–10)
Rank Indicator (Ro %)			
<0.5	0.5–1.0	1.0–2.0	>2.0

Table 15 presents fuel-quality characteristics across the major coal ranks —lignite, sub-bituminous, bituminous, and anthracite. Following torrefaction, biomass is converted into

biochar, whose fuel suitability is evaluated through proximate analysis, ultimate analysis and heating value. These properties are compared with benchmark coal characteristics to assess energy quality. Based on similarity with different coal ranks, the biochar can be appropriately graded for suitable energy applications.

5.2 Emission And Ash Characteristics

Emission and ash characteristics describe the gaseous emissions (CO_2, CO, NO_x, SO_x) and the quantity and composition of ash generated during combustion. These factors are critical in evaluating the environmental impact and operational behavior of biochar – based fuels. Low emission levels and favorable ash properties, such as low slagging and fouling potential, are vital for ensuring cleaner energy production and sustainable utilization of biomass resources.

Table 16 shows that biomass – based biofuels offer a cleaner and more sustainable alternative to coal from both environmental and operational perspectives. Firstly, CO_2 emissions from biomass are significantly lower (0 – 1500 g/kg) and often considered carbon – neutral, supporting global carbon reduction goals. Secondly, SO_2 emissions are drastically reduced (10 – 200 mg/Nm³) compared to coal (500 – 2000 mg/Nm³), owing to the naturally low sulphur content in biomass. Thirdly, NO_x emissions are also lower for biomass (50 – 400 mg/Nm³), which helps in reducing smog formation and improving air quality. Fourthly, particulate matter emissions from biomass combustion are considerably less (20 – 150 mg/Nm³), reflecting improved combustion efficiency and reduced particulate pollution. Lastly, ash content and composition in biomass (1 – 20%) are more favorable, containing beneficial minerals like K, Ca and P with lower sulphur, thus minimizing slagging issues and offering potential reuse in soil amendment. Overall, biomass emerges as a cleaner, low – emission and sustainable energy substitute for coal.

Table 16 Comparative emission and ash characteristics of coal and biofuels

Parameter	Coal	Biofuel (Biomass)	Reference
CO_2 Emissions (kg/kg fuel)	2.0 – 2.5	0 (Carbon neutral) to 1500	[183], [184]
SO_2 Emissions (mg/Nm³)	500 – 2000	10 – 200	[185], [186]
NOx Emissions (mg/Nm³)	300 – 1500	50 – 400	[185], [186]
Particulate Matter (mg/Nm³)	50 – 400	20 – 150	[185], [186]
Ash Content (%)	5 – 30	1 – 20	[187], [188]
Ash Composition (Major Elements)	Si, Al, Fe, Ca, Mg, S	K, Ca, Mg, Si, P, low S	[187], [188]

6.0 CO – FIRING BEHAVIOR OF COAL WITH BIOMASS

Co – firing of coal with biomass has emerged as a promising approach to enhance the sustainability of power generation while reducing greenhouse gas and pollutant emissions. Although both fuels share common constituents such as carbon, hydrogen, oxygen, nitrogen and sulphur, their combustion behaviors differ significantly. Biomass typically exhibits a lower calorific value and higher volatile matter compared to coal, resulting in less heat release but easier ignition and lower ignition temperatures [189]. Importantly, when coal and biomass are combusted together, the combustion process is not merely an additive effect of the two fuels. Instead, complex physicochemical interactions occur, influencing ignition, flame stability, heat release and ash behavior. These interactions form the basis of the co – firing mechanism, co – firing indices and synergistic effects, which are critical for optimizing fuel blends and ensuring stable, efficient and environmentally friendly operation of coal – fired power plants [190].

Combustion performance is commonly evaluated using thermogravimetric (TG) and derivative thermogravimetric (DTG) analyses. Among the various indices proposed, ignition temperature, burnout temperature and maximum combustion rate temperature are the most representative, as they characterize the initial, final and intermediate stages of fuel combustion[190]. These indices are critical for assessing the impact of biomass addition on the combustion behavior of coal during co – firing.

6.1 Ignition and Burnout Temperature

Ignition temperature represents the threshold of self – sustaining combustion, while burnout temperature marks the near – complete conversion of fuel to ash. Biomass addition generally lowers both ignition and burnout temperatures compared to coal, mainly due to its high volatile content and low fixed carbon fraction [191], [192], [193]. Studies show that blending 20% biomass with coal can reduce ignition temperature by 100 – 170 °C, making co – firing advantageous for ignition and overall combustion efficiency. The type of biomass is critical, as higher volatile matter (e.g., beetroot, corn straw, corncob) contributes to lower ignition temperatures and improved burnout performance, while biomass with high lignin (e.g., hardwood) exhibits higher ignition temperatures due to thermal stability [194], [195]. Operational parameters such as particle size, heating rate and oxygen concentration further influence ignition and burnout characteristics, with larger particles and CO_2 atmospheres raising ignition temperature, while higher oxygen promotes faster burnout [196], [197].

6.2 Maximum Combustion Rate Temperature

The maximum combustion rate temperature (Tmax) indicates the point at which combustion rate peaks. A lower Tmax implies higher reactivity. Co – firing studies reveal that the addition of biomass often increases Tmax due to rapid volatilization of light hydrocarbons during the initial stage, leaving less reactive char for the later combustion phase [198]. For example, co – firing pine sawdust with coal lowered ignition temperature but raised Tmax. Similarly, co – firing high – alkali coal with municipal sludge increased Tmax because of the low reactivity of stable inorganic components in sludge [199].

6.3 Improvement Strategies

Combustion indices are strongly influenced by the organic and inorganic composition of biomass. Higher cellulose and hemicellulose contents enhance ignition due to rapid

volatilization, while lignin increases char reactivity and accelerates burnout [200]. Biomass minerals also affect combustion: certain minerals (e.g., Ca, K_2O, Cl) act as catalysts for char oxidation, while others (e.g., in rosewood) inhibit volatilization and delay ignition[201]. Pretreatment methods such as washing and hydrothermal carbonization further improve combustion indices by reducing Tmax and increasing combustion rates, as demonstrated with wheat straw blends [202]. Thus, careful biomass selection, blending strategies and pretreatment can significantly enhance co – firing efficiency.

6.4 Ash Agglomeration, Fouling And Slagging Behaviors

The addition of biomass to coal alters ash properties, often lowering ash fusion temperatures and increasing the risks of agglomeration, fouling and slagging. Ash agglomeration occurs when particles begin to melt and fuse at the initial deformation temperature, fouling results from deposit accumulation on boiler surfaces and slagging produces hard, glassy deposits at high temperatures. Studies have shown that biomass generally exhibits lower ash melting temperatures than coal, increasing agglomeration severity as the biomass ratio rises. For example, low – rank coal co – fired with sewage sludge and sawdust showed nearly twice the agglomeration degree compared to coal alone, although sludge minerals (Al, Ca, Fe) could mitigate the effect by reacting with alkali metals in wood ash [203]. At low blending ratios, woody biomass had little impact due to its low ash content, but higher ratios increased fouling and slagging risks [204]. Biomass type also plays a key role: palm kernel shell and bark promoted fouling through the formation of low – melting Ca – Fe – Al – Si compounds, whereas Japanese cedar showed minimal effect [205]. Hazelnut shell addition reduced initial deformation temperature by nearly 50% due to CaO enrichment, while rice husk had a weaker influence, making it a better option for reducing ash – related issues [206]. Overall, biomass selection and use of inhibitors are crucial to minimizing ash – related challenges during co – firing.

6.5 Gaseous Pollutant Emissions Of Coal And Biomass Combustion

Co – firing biomass with coal influences gaseous emissions such as SO_2, NOx, CO and CO_2. Generally, biomass tends to reduce SO_2 and NOx emissions due to its low sulphur and nitrogen content and the catalytic role of biomass char in sulfation reactions. For instance, cedar nut shell blended with bituminous coal significantly reduced SO_2 and H_2S emissions, while lignite blends showed weaker effects because of mismatched combustion timing [207]. Industrial boiler studies confirm that co – firing wood chips with hard coal lowered SO_2, VOCs and HCl, although CO_2 and NOx increased [208]. Similarly, anthracite co – fired with wood pellets reduced SO_2 and NO, but increased CO emissions due to incomplete pellet combustion [209]. In lignite blends, higher char fractions in biomass promoted NO reduction to N_2, further lowering NOx despite higher biomass – N content [210]. However, certain biomass types like distillery sludge increased SO_2 emissions because of their high sulphur content, though NOx emissions decreased due to stable fuel – N compounds [211]. Temperature also strongly affects gaseous pollutants: higher temperatures reduce CO through better combustion but have complex effects on SO_2 due to competing sulfation and sulfate decomposition reactions [212]. Similar temperature – dependent effects were observed for rice husk co – firing. Overall, biomass type, blending ratio and operating conditions determine pollutant emission trends, highlighting the need for careful optimization.

7.0 ECONOMIC CONSIDERATIONS IN BIOMASS – TO – BIOCHAR CONVERSION

The economics of biomass – to – biochar conversion depend on several key cost components, including feedstock procurement, capital investment, energy consumption, labor and maintenance. Additional influencing factors include process efficiency, emission control systems, by – product management, logistics, certification, compliance and ongoing research and development (R&D) efforts. Table 17 highlights how each major cost component of the process is linked to circular economy benefits, ensuring both economic feasibility and environmental sustainability.

Thermochemical processing of biomass fulfills the circularity principle by converting waste materials into valuable and reusable products while minimizing resource loss and emissions. In this process, agricultural and organic residues (otherwise considered waste) are transformed through pyrolysis, gasification or torrefaction into useful outputs such as biochar, bio – oil and syngas. Biochar can be reused as a soil amendment, improving fertility, carbon sequestration and crop yield, while bio – oil and syngas can serve as renewable energy sources, reducing dependence on fossil fuels. The nutrient – rich ash generated can be recycled back into the soil, closing the nutrient loop. Additionally, the use of local biomass residues promotes waste valorization, energy recovery and carbon recycling, ensuring that materials remain in productive use for as long as possible. Thus, thermochemical biomass conversion aligns with the circular economy by integrating resource efficiency, emission reduction and by – product utilization into a sustainable, closed – loop system.

Table 17 Integration of cost components with circular economy benefits in biomass – to – biochar conversion [213], [214], [215], [216], [217], [218], [219], [220], [221]

Cost Component	Description	Circular Economy Benefit
Feedstock procurement	Collection, drying, storage of agricultural/ forestry/ municipal residues	Valorizes local biomass waste, reduces landfill burden and creates resource recovery loops
Capital investment	Reactor type, automation, infrastructure	Enables scalable systems designed for multiproduct recovery (biochar, syngas, bio – oil)
Energy consumption	Heating methods and insulation	Use of syngas/biomass for self – sustaining energy, lowering fossil fuel dependency
Labor and maintenance	Skilled/unskilled manpower, routine servicing	Generates local green jobs, supports sustainable

		industrial ecosystems
Process efficiency	Retention time, throughput, continuous operation	Higher yields with reduced waste, improving resource productivity
Emission control systems	Cyclones, scrubbers, biofilters	Minimizes environmental footprint and reintegrates captured particulates
By – product management	Utilization of syngas, bio – oil and heat	Converts waste streams into value – added products, ensuring resource circularity
Logistics and distribution	Packaging, centralized vs. decentralized delivery models	Promotes localized use of biochar, lowering transport costs and supporting local economies
Certification & compliance	Standards, safety, regulations	Strengthens market trust, enabling sustainable adoption in agriculture and energy sectors
Research and Development (R&D)	Process optimization, advanced reactors, parameter control	Enhances multiproduct utilization and long – term sustainability in line with circular models

However, the cost of biomass – to – biochar conversion can be reduced by using low – cost or waste feedstocks such as agricultural residues, optimizing process parameters like temperature and retention time and recovering energy from syngas or bio – oil generated during pyrolysis. Large – scale or modular units, integration of solar or industrial waste heat and automation can further lower operational costs. Additionally, co – producing value – added products and leveraging government incentives or carbon credits can enhance economic viability.

8.0 APPLICATIONS OF TORREFIED BIOMASS

Torrefied biomass, due to its improved energy density, hydrophobicity and stable carbon structure, has diverse applications across energy, industry, environment and agriculture. Its utilization not only enhances process efficiency but also contributes to decarbonization and sustainability. Table 18 summarizes the key applications of torrefied biomass along with their specific benefits.

Table 18 Applications of Torrefied Biomass [222], [223], [224], [225], [226]

Application Area	Description / Use	Reason for Suitability
Co – firing with Coal in Power Plants	Used as a renewable substitute or supplement for coal in thermal power generation.	Torrefied biomass has similar grindability, higher energy density, and lower moisture, enabling smooth combustion without major burner modifications.
Gasification Feedstock	Acts as a superior input for gasification to produce syngas for fuels and chemicals.	Enhanced carbon content, lower volatile matter, and reduced tar formation due to improved structural uniformity after torrefaction.
Pellet Production / Solid Biofuels	Used to make high – density, hydrophobic pellets for convenient storage and transport.	Torrefaction upgrades mechanical durability, increases hydrophobicity, and stabilizes composition for long – term storage.
Metallurgical Reducing Agent	Serves as a cleaner alternative to coke or charcoal in metal processing industries.	High fixed carbon and lower ash content support reduction reactions while minimizing CO_2 emissions.
Feedstock for Bio – Oil and Biochar Production	Intermediate for liquid biofuel and activated carbon generation through pyrolysis.	Pretreated biomass improves yield, carbon stability, and quality of subsequent pyrolysis products.
Soil Amendment and Carbon Sequestration	Used to produce biochar – like material for improving soil fertility and long – term carbon storage.	Stable carbon structure prevents rapid decomposition and enhances nutrient retention.
Adsorbent and Filtration Media	Applied in water purification and pollutant adsorption.	Enhanced porosity and surface reactivity from torrefaction increase adsorption performance.
Composite and Polymer Filler	Added to strengthen bio – based plastics and composites.	Increased aromatic carbon structure provides mechanical reinforcement and thermal stability.
Battery and Electrochemical Applications	Source for hard carbon anodes in sodium – ion and lithium – ion batteries.	Torrefied biomass – derived carbon structures have high surface area and stable electrochemical behavior.
Hydrogen and Power – to – X Systems	Sustainable carbon source for producing synthetic fuels through gasification and power – to – X technologies.	High carbon purity and low oxygen ratio enable efficient CO_2 utilization and hydrogen integration.

Biomass – to – biochar conversion offers multiple societal benefits by transforming agricultural and organic waste into a valuable resource. It provides an effective method for waste

management, reducing environmental pollution and mitigating open – field burning of residues. By sequestering carbon, biochar helps combat climate change and reduces greenhouse gas emissions. It also generates renewable energy during pyrolysis, contributing to energy security and reducing reliance on fossil fuels. Economically, biochar production creates new income streams for farmers and entrepreneurs, fostering rural development. Integration with circular economy principles ensures optimal use of resources and minimizes waste. Additionally, biochar can be used in coal co – firing, promoting cleaner power generation and lowering industrial emissions. Overall, biomass – to – biochar conversion supports environmental sustainability, economic growth and social well – being.

9.0 CHALLENGES AND OPPORTUNITIES IN BIOMASS VALORIZATION

The large-scale adoption of biomass – to – biochar conversion technologies encounter multiple challenges spanning feedstock availability, supply chain logistics, technological limitations, policy frameworks and economic feasibility. Shell recently decided to cancel its large – scale renewable fuel project at Rotterdam, Netherlands, which was expected to produce about 820,000 tons per year of advanced biofuels, including sustainable aviation fuel [227], [228]. The company cited high construction and feedstock costs, weak market conditions and poor commercial competitiveness as key reasons for withdrawal. Despite beginning in 2022, the project faced escalating expenses, technical challenges and limited policy support for biofuel demand in Europe. Shell expects a financial loss of around US $600 million from the decision. The move highlights major problems in large – scale biofuel ventures—rising capital costs, uncertain policy incentives and limited availability of affordable waste – based feedstocks—making such projects less economically viable under current market conditions.

However, these challenges also present opportunities for innovation and sustainable integration when addressed through appropriate strategies. Table 19 outlines the major challenges, corresponding opportunities and potential solutions that can strengthen the role of pyrolysis in biomass valorization.

Table 19 Challenges, Opportunities and Possible Solutions in Biomass Valorization

Challenge Area	Key Challenges	Opportunities	Possible Solutions
Feedstock Availability [229], [230], [231]	Uncertainty in agro – residue availability due to competing uses and inconsistent data	Improved resource mapping and optimized residue utilization	Develop region – specific biomass inventory using remote sensing, GIS and machine learning tools
Supply Chain & Logistics [232], [233], [234]	Seasonal availability, high moisture, low bulk density, high transport/storage cost	Strengthened local supply chains and improved biomass handling	Establish decentralized collection/pre – processing centers; adopt pelletization and torrefaction
Feedstock Variability [235], [236]	Heterogeneous chemical and physical properties affecting pyrolysis performance	Standardized feedstock quality for improved conversion yields	Pre – processing (drying, size reduction, densification) and blending strategies
Pretreatment Process [237], [238]	High energy demand, cost and generation of inhibitory compounds in chemical pretreatment methods.	Development of eco – friendly and cost – effective pretreatment methods (enzymatic, biological, ultrasound – assisted).	Use microwave – assisted, ionic liquid, or biological pretreatments to improve lignin removal and reduce chemical usage.
Reactor Design & Operation [239], [240], [241]	High energy input, inefficient heat distribution, difficulty in parameter control	Advanced reactor systems with improved efficiency and scalability	Adoption of autothermal, microwave – assisted and solar – assisted pyrolysis; deployment of fluidized/auger reactors
Conversion Efficiency [242], [243]	Low yield and degradation of value – added products due to complex lignocellulosic structure.	Consolidated bioprocessing and integrated biorefineries improve conversion efficiency and product yield.	Apply advanced catalysts, genetic enzyme engineering and hybrid biochemical – thermochemical routes to increase product yield and reduce energy losses.
Product Quality [241], [244]	High oxygen content and variable composition of biochar/bio – oil	Process control and real – time monitoring allow optimization for consistent product yield and superior properties.	Incorporation of in – line monitoring sensors, catalytic upgrading units and standardization of quality parameters
Policy & Regulation [245], [246]	Lack of clear frameworks for adoption, commercialization and carbon credits	Institutional support and recognition of biochar in climate strategies	Define policies, provide incentives, certification standards and integrate biochar into carbon trading systems
Technology Cost [230], [244]	Capital – intensive operations and scalability constraints in biorefinery systems.	Process intensification, automation and bio – catalyst engineering reduce cost and increase efficiency.	Support through subsidies, tax benefits, public – private partnerships and deployment of modular, decentralized units
Environmental Impact [244], [246]	Potential emissions and wastewater concerns during thermochemical conversion.	Valorization replaces fossil carbon sources, reducing greenhouse gas emissions and supporting circular economy models.	Integrate CO_2 capture, biochar utilization and closed – loop wastewater recycling in biorefineries for low – emission and sustainable operation.

Addressing these challenges holistically through technological innovation, robust supply chains, supportive policies and circular economy practices will enable the scalable and sustainable implementation of pyrolysis technologies. Such integrated approaches not only enhance economic feasibility but also unlock significant opportunities for rural development, renewable energy generation and environmental sustainability.

10.0 RESEARCH GAPS AND FUTURE SCOPE

Despite significant advancements in biomass conversion research, several critical gaps remain unaddressed. Optimization of torrefaction and pyrolysis parameters for maximizing both biochar yield and quality requires further systematic investigation. The potential of unconventional feedstocks, such as aquatic biomass, for torrefaction remains largely unexplored. Long – term studies on the performance, stability and environmental impact of co – firing torrefied biomass with coal are still limited. Research on fourth – generation biofuels integrating biochar technologies is in its infancy. Moreover, the absence of standardized testing protocols for biochar characterization hampers consistent comparison across studies. Variations in biochar properties derived from multiple biomass sources also necessitate comprehensive correlation studies. Additionally, the pretreatment of biomass—such as drying, pelletization, or chemical treatment using acids, alkalis, or solvents (e.g., NaOH or H_2SO_4)—needs deeper exploration to enhance conversion efficiency and product uniformity. The use of catalysts like zeolites, calcium oxide (CaO), or nickel – based materials can significantly improve reaction rates, selectivity and bio – oil quality, yet remains underutilized in torrefaction and pyrolysis systems. The combination of different biomass types (e.g., mixing coconut shell with groundnut shell or bagasse) offers potential for synergistic effects on biochar yield and quality but requires systematic evaluation. Finally, dedicated R&D efforts toward advanced reactor designs, such as continuous or hybrid torrefaction – pyrolysis systems with precise temperature and residence time control, are crucial for achieving scalability, process uniformity and commercial viability.

Thus, addressing these multi – dimensional gaps through advanced experimental, analytical and modeling approaches is essential for positioning biomass – derived biochar and next – generation biofuels as reliable, economically viable and environmentally sound alternatives to conventional fossil fuels.

11.0 CONCLUSION

The study establishes that biomass based thermochemical conversion through pyrolysis and torrefaction presents a sustainable alternative to fossil fuels. Optimized conversion parameters enhance the physicochemical and combustion characteristics of biochar, making it suitable for co – firing and energy applications. Feedstock analysis identifies coconut and groundnut shells as superior for high – quality biochar, while cotton stalk, tur stalk, bagasse and rice husk exhibit potential for diversified bioenergy use. Despite higher initial costs, the long – term advantages such as emission reduction, waste valorization and energy recovery ensure environmental and economic sustainability. Integrating biomass utilization within a circular economy framework promotes rural employment, resource efficiency and supports Sustainable Development Goals (SDGs) on clean energy, climate action and sustainable industrial growth.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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