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Review

Raw, Thermally Treated, and Densified Biomass for Solid-Fuel Combustion and Coal Co-Firing: A Critical Review

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Abstract

This review presents a comparative assessment of raw agricultural and wood-processing residues, thermally treated biomass, biochar, and densified fuels used alone or in coal blends. Drawing on 50 primary experimental and/or numerical studies and informed by previous reviews, it provides a comparative systematization of the advantages and disadvantages of biomass utilization routes in terms of fuel properties, combustion behavior, emissions, and practical application. Feedstocks included straw, husks, stalks, cobs, bagasse, sawdust, bark, leaves, and needles. The reported lower heating values ranged from 9 to 23 MJ kg^{-1} for raw biomass and from 23 to 32 MJ kg^{-1} for coal. The optimal biomass proportions were system-specific, depending on feedstock combinations and optimization criteria. In the studies reviewed, thermal treatment increased the heating values to as high as 31 MJ kg^{-1}. Densification was shown to improve fuel density, mechanical strength, storage, and handling. The effect of biomass addition on emissions was not uniform: reductions were reported for some fuel systems, whereas CO, CO_2, or other emissions increased in others. These outcomes depended on feedstock composition, blend ratio, pretreatment, and combustion conditions. Study heterogeneity and predominantly laboratory-scale evidence limit the transferability of these findings to pilot and industrial applications.

Keywords: biomass co-firing; torrefaction; biochar; briquetting; combustion emissions; solid biofuel

1. Introduction

The need to reduce the environmental impacts of coal-fired power generation and the pursuit of carbon neutrality motivate the development of alternative fuels and the use of renewable energy resources [1,2]. One of the key pathways identified for low-carbon development is the gradual replacement of coal with alternative renewable energy sources and the increased utilization of biofuels. The successful implementation of these measures requires extensive research and development activities, as well as the creation of innovative technologies aimed at the efficient utilization of green energy resources.

Biomass is among the renewable resources considered for partial coal substitution [1,3]. Unlike fossil fuels, biomass releases carbon that had previously been absorbed from the atmosphere by plants throughout their life cycle [4]. However, the carbon neutrality of biomass is not inherent and depends on feedstock origin, land-use change and regrowth,

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transport and pretreatment energy requirements, conversion efficiency, carbon debt, and the system boundaries applied in life-cycle assessment. The efficiency of biomass combustion was evaluated by numerical modeling of pulverized coconut shell combustion with a particle size of 100 μm in a laboratory reactor at a mass flow rate of 2.82 kg h^{-1} and an air velocity of 1.0 m s^{-1}. Combustion efficiency, defined as 100% minus heat losses due to incomplete combustion and unburned carbon, was calculated to be 92.94%, compared with the experimental result of 90.48% [4]. Coal–biomass co-firing is considered an approach to partially replacing fossil fuel with renewable biomass that may reduce environmental impacts and contribute to climate-change mitigation [3,5]. As one of the world's largest producers of palm oil, Indonesia generates substantial quantities of biomass residues from palm oil processing. Indonesian researchers have therefore proposed utilizing these residues as a supplementary fuel in coal-fired power generation systems [5]. Agricultural residues, particularly residue from straw, have also attracted considerable attention due to their relatively high calorific value and potential use as either a solid fuel or feedstock for the production of coke-like biomass and charcoal fuels [6]. According to Liu et al. [7], and as cited by Al-Haj Ibrahim [6], the combustion of approximately 400 million tonnes of straw generated annually in China could produce 291 TWh of electricity. On the basis of the respective fuel heating values, this electricity output would be equivalent to replacing up to 200 million tonnes of coal, thereby reducing CO_2 emissions by 193 million tonnes.

Munir [3] reviewed full-scale co-firing, showing that relatively low biomass shares can be used in some existing pulverized-coal boilers. However, the need for equipment modifications depended on the biomass properties, co-firing ratio, fuel-grinding and feeding systems, boiler design, and operating conditions. As of 2010, there were 234 commercial installations worldwide utilizing coal–biomass co-firing technology. These facilities are present in the greatest numbers in Finland (81), the United States (40), and Germany (27), followed by the United Kingdom (18), Sweden (15), Denmark (12), Australia (8), Italy and Canada (7 each), the Netherlands (6), and Austria (5), among others [3,8]. According to the cited historical sources, two coal–biomass co-firing plants were reported to be operating in Indonesia. Squire et al. [9], based on the Indonesian case, showed that incorporating existing biomass waste into coal-fired power plants can reduce carbon emissions without additional deforestation. However, the degree of achievable reduction is limited because the available waste biomass can satisfy the co-firing demand only at relatively low blending ratios. Increasing biomass co-firing beyond the available waste supply may create additional demand for purpose-grown biomass, potentially increasing pressure on land use and biomass markets and exports, ultimately contributing to deforestation and associated emissions. Economic analyses indicate that biomass co-firing may increase the levelized cost of electricity (LCOE), which accounts for investment, operation and maintenance, financing, and taxation costs, relative to conventional coal-fired generation. Xu et al. [10] reported that the LCOE calculated for a hypothetical coal–biomass indirect co-firing project in China, comprising a 20 MW biomass gasification system coupled with an existing 600 MW coal-fired unit and assuming prices of 500 yuan ton^{-1} for both corn straw and coal and a biomass blend proportion of 10%, rises by approximately 8% when biomass is co-fired with coal. The biomass was assumed to be transported to the power plant after crushing and pressing, with the pretreatment costs included in its procurement price; the transport distance and a separate transportation cost were not reported. The calculation assumed a 20-year plant life, an 8% discount rate, a 6% bank loan interest rate, and 5000 annual utilization hours. When biomass constitutes 15% of the fuel blend, the LCOE increases by 10.7%, while a 20% biomass share results in an LCOE increase of 19.1%. These changes are primarily attributed to biomass procurement costs, which vary significantly depending on the biomass type. For instance, the use of woodchips increases the LCOE by 5.71%, whereas rice husk may reduce it by 6.06%. In addition to feedstock price, the quantity of biomass required also affects electricity generation costs. Because biomass generally possesses a lower energy

density than coal, larger quantities of biomass are typically required to produce the same amount of energy, which inevitably influences the overall LCOE.

Other challenges associated with the utilization of biomass for co-firing with coal have also been reported in the literature [1,10–13]. These challenges include the low bulk density, brittleness, and fragility of biomass; greater grinding difficulty compared with coal; high moisture and volatile matter contents; significant differences in calorific value relative to coal; transportation, storage, and economic constraints; the wide diversity of biomass feedstocks; and the need for modifications to energy-generation facilities. Solutions have been proposed for some of these challenges, and research in this area is ongoing. For example, biomass shares of 10–15% have been reported to enable co-firing with coal without modifications to existing boilers under specific operating conditions [11,13]; however, the acceptable biomass proportion depends on the fuel characteristics and the design and operation of the combustion system. A particularly important issue that has received relatively little attention in the literature is the corrosion of pulverized-coal boilers during biomass co-firing [1,13]. Researchers attribute this phenomenon primarily to deposits formed on heat-transfer tubes. During the co-firing of coal and wood in a 150 MW pulverized-coal boiler, these deposits contained two to three times more potassium sulfate and sodium sulfate than those formed during coal combustion alone. The same study also reported a greater amount of unburned carbon on the furnace wall, indicating the presence of a strong reducing atmosphere.

Different approaches to overcoming the various drawbacks associated with biomass utilization have been proposed. For example, the preparation of blended fuels consisting of different types of biomass and low-grade solid fossil fuels has been suggested [14]. The use of sulfur-capturing agents has been recommended to reduce sulfur-containing emissions [15]. Among the most effective methods for increasing carbon content, reducing moisture and volatile matter contents, and enhancing the energy density of biomass is its pyrolysis or carbonization to produce biochar [12,16]. Biochar is widely known for its application as a reducing agent in metallurgical processes and as an adsorbent. However, it can also be utilized as a solid fuel. Carbonized biomass is considerably easier to grind than raw biomass, making it possible to achieve a more uniform particle size distribution, including particle sizes comparable to those of coal, with lower energy consumption and processing costs. As a substitute for conventional solid fuels, biochar is characterized by relatively high calorific value and good combustibility. However, its ash content depends on the feedstock and processing conditions and may increase during pyrolysis because of the concentration of mineral matter in the solid product. The production and utilization of biomass and biochar briquettes have been extensively reviewed by several authors [2,17,18]. Ngene et al. [2] noted that densified biochar briquettes offer several advantages over non-densified pyrolyzed biomass and are therefore expected to gain wider acceptance. Their superior performance is primarily attributed to improved mechanical strength and structural characteristics that positively influence the combustion process. Despite their numerous advantages, biochar briquettes are without limitations. Their production requires several preparatory operations, including pyrolysis, grinding, and briquetting. All of these processes incur additional costs and may have environmental impacts. Furthermore, some aspects of briquette production remain controversial. One such issue is the use of binders. Various binders are employed to improve briquette strength; however, depending on their type and chemical composition, they may adversely affect fuel properties. While enhancing mechanical performance, binders can increase the ash content and reduce calorific value. In addition, although pyrolysis improves the characteristics of the resulting fuel, the process itself may contribute to environmental pollution through the emission of gaseous pollutants [2]. Therefore, the development of biomass-

based fuels intended either as fuel additives or as substitutes for coal requires comprehensive evaluation from technical, environmental, and economic perspectives. Such studies are necessary to establish an effective policy framework for biomass–coal co-firing, taking into account the optimization of the physicomechanical and fuel properties of alternative fuels, as well as the performance characteristics of the co-combustion process itself [9,18].

In this context, the objective of this study was to analyze and synthesize the current state of research on the utilization of various types of biomass as solid fuels and in combination with coal. Previous reviews have addressed overlapping aspects of biomass utilization, with differing emphases on biomass–coal co-combustion [10], biochar briquetting [2], biomass briquette binders and mechanical properties [17], and experimental variables and optimization methods used in biomass briquette production [18]. Table 1 compares the scope and analytical focus of these and other related reviews discussed above with those of the present review. The specific contribution of the present review is a comparative systematization of the advantages and disadvantages of raw agricultural residues and wood-processing wastes, thermally treated biomass and biochar, and densified raw and carbonized biomass used either as standalone fuels or in combination with coal. The reviewed approaches are comparatively evaluated in terms of feedstock characteristics, pretreatment routes, fuel and combustion properties, environmental performance, and, where available, economic considerations. By examining these routes together, the review aims to help researchers make informed choices about methods for improving biomass fuel characteristics, taking into account feedstock properties, the requirements of the intended application, and the limitations of each method. Particular attention is given to identifying the advantages and limitations of each biomass utilization route, the technological solutions proposed to overcome the identified limitations, and the remaining knowledge gaps. This integrated assessment provides the basis for identifying future research directions toward biomass waste management strategies for energy production.

Table 1. Comparison of the present review with related review articles discussed in the Introduction [1].

Review	Fuel Options and Applications	Fuel Preparation	Main Analytical Focus	Evidence Scale and Type	Environmental Aspects	Economic Aspects
Liu et al. [1]	Raw and pretreated biomass and wastes of various origins, primarily for coal co-firing	Preparation for co-firing, including torrefaction, washing, and hydrothermal treatment	Coal–biomass property differences, component interactions, and effects of operating conditions on combustion, ash, and emissions	Laboratory experiments, numerical modeling, pilot-scale studies, and industrial trials	Gaseous emissions, ash, deposits, and corrosion	Retrofitting costs and differences between technological configurations
Ngene et al. [2]	Primarily biochar briquettes, including blends with raw biomass and coal, for domestic and industrial applications	Biochar production, briquetting, binders, and co-densification	Relationships between feedstock, production conditions, binders, and the thermal, mechanical, and environmental performance of briquettes	Experimental production and testing of briquettes. No uniform classification by evidence scale	Gaseous and particulate emissions and strategies to improve environmental performance	Qualitative discussion of binder costs, drying, and technology selection
Munir [3]	Various biomass feedstocks and agricultural residues, primarily for coal co-firing	Fuel preparation and feeding and co-firing configurations	Combustion efficiency, emissions, biomass proportion, and operational constraints, including air and fuel staging	Laboratory studies, TGA, test rigs, megawatt-scale facilities, and full-scale boilers	NO_x, SO_2, CO_2, ash properties, and corrosion risks	Qualitative discussion of implementation, supply, storage, and fuel handling
Al-Haj Ibrahim [6]	Raw, densified, and thermally treated fuels, primarily from straw, used alone or in blends	Size reduction, densification, torrefaction, pyrolysis/carbonization, and leaching	Straw-derived solid-fuel production, changes in fuel properties, and mitigation of ash-related problems	Laboratory and bench-scale studies, pilot-scale combustion tests, and full-scale boiler trials	Emissions, removal of alkali components, fouling, and bed agglomeration	Selected information on pretreatment energy requirements and densification benefits
Wang et al. [12]	Biochar for fuel and feedstock substitution in energy generation, cement production, and metallurgy	Pyrolysis, hydrothermal carbonization, and preparation for the intended application	Relationships between biochar properties and its functions in different technological processes	Property and process studies, modeling, and examples of engineering and commercial applications	Emissions, carbon-related effects, and published life-cycle assessments	Competitiveness and implementation barriers. Energy return and payback are identified as necessary assessment dimensions

Ibitoye et al. [16]	Biochar for iron and steel production, including coal and coke substitution	Various biomass thermochemical conversion techniques	Selection of production methods and biochar properties for metallurgical applications	Laboratory studies, technical-scale results, and biochar production at different scales. Pilot integration is also proposed as a future task	Greenhouse gas emissions, waste utilization, and impacts of fossil-carbon substitution	Capital and operating costs, transport, equipment, carbon payments, and financial support
Obi et al. [17]	Briquettes from various biomass feedstocks, with emphasis on binders and densified-fuel quality	Briquetting with organic, inorganic, and composite binders	Mechanical properties, handling resistance, and quality-assessment methods	Laboratory quality tests and references to pilot-scale fuel-preparation studies. Industrial adoption is discussed separately	Environmental factors in feedstock and binder selection. Combustion and emission quality factors are outside the main assessment scope	Feedstock and binder costs and availability, supply chains, energy requirements, and market barriers
Marreiro et al. [18]	Briquettes from various biomass feedstocks and blends, including selected thermally treated materials	Feedstock preparation, thermal pretreatment, and briquetting	Effects of production variables on energetic and mechanical properties, experimental design, and optimization	Laboratory presses, manual and mechanized densification, and examples of industrial briquette production	Environmental motivation, ash content, and selected factors affecting emissions	Qualitative discussion of preparation, densification, transport, storage, and maintenance costs
Present review	Joint assessment of raw biomass, thermally treated biomass and biochar, and densified fuels from raw and treated feedstocks. Diverse agricultural and wood-processing residues used alone or in coal blends	Torrefaction, hydrothermal treatment, pyrolysis/carbonization, pelletization, and briquetting	Comparative systematization of advantages, disadvantages, and trade-offs between improvements in fuel and mechanical properties, combustion behavior, emissions, and application constraints	50 primary experimental and/or numerical studies. Predominantly laboratory evidence, including TGA, with selected pilot-scale fuel-preparation studies and industrial application trials	Measured gaseous emissions, ash-related risks, and published life-cycle assessments, considering conditions and comparison limitations	Comparison of published economic assessments and cost drivers where available. No original techno-economic model

[1] The table describes the principal scope of the reviews rather than the absence of related topics. Fuel-production scale is distinguished from the scale of fuel-use trials. An intended industrial application is not treated as evidence of industrial testing. Qualitative cost discussion is distinguished from quantitative economic assessment. TGA: thermogravimetric analysis.

2. Review Methodology

The process of source identification and analysis included four consecutive stages.

Initial bibliographic search: Publications were searched in the international scientometric database Web of Science between 10 and 20 December 2025 using a basic keyword search in the All Fields field. The publication period considered was 2010–2025. Each keyword or phrase was entered as a separate query, without restrictions on language or document type. The search terms included coal burning, agrowaste, wood waste, torrefaction, biochar, biomass, co-firing, combustion, fuel additive, and greenhouse gas emission. Multiword search terms were entered without quotation marks. For example, coal burning was entered without quotation marks in the All Fields field and searched as a separate query. The retrieved bibliographic records were exported to EndNote using the Full Record option and organized into thematic groups. Based on a screening of abstracts for relevance to biomass combustion, coal–biomass co-firing, and fuel preparation, an initial set of 25 representative articles was selected. This initial set served as the starting point for the subsequent expansion and verification of the literature, which resulted in the final set of 50 primary studies included in the comparative analysis.

Expansion of the source set with AI assistance. To identify additional relevant sources, the author responsible for literature screening used ChatGPT (OpenAI, San Francisco, CA, USA, GPT-5.1/5.2, ChatGPT Plus) in December 2025. The model was provided with the list of selected publications and prompted to identify similar academic studies. Each publication suggested by AI was verified by the same author by checking its title, authors, publication year, and DOI, where available, against the publisher's record and assessing its relevance to the scope of the review. All verified publications were then read in full by the same author. Qualitative assessment involved checking consistency between the text, tables, and figures and whether the conclusions were supported by the reported data. Studies with contradictory data or conclusions not supported by the reported results were excluded from the main dataset. The final decision on the inclusion of each publication was made by the same author independently of the AI recommendations. AI-suggested publications that met the same relevance and quality criteria as sources identified through the database search were included among the 50 primary studies. Every included source was independently verified by the author responsible for screening. The numbers of AI-suggested references, duplicates, and references excluded or retained after verification were not recorded separately. Separate tracking of sources by identification route was not an objective of this critical review. These counts cannot be reliably reconstructed retrospectively, which limits the retrospective assessment of search completeness.

Systematization, qualitative analysis, and technical verification of references: The final set of sources was manually classified by the same author. The articles were grouped according to the thematic sections of the study. The primary studies were classified by biomass type, pretreatment state, and physical fuel form, distinguishing standalone combustion from coal co-firing. Within these groups, the reported fuel properties, combustion behavior, emissions, and, where available, environmental and economic assessments were compared qualitatively, taking into account blend composition, experimental conditions, and evidence scale. After revising the manuscript and finalizing the reference list, AI tools were used as an auxiliary means of citation placement, for sequential renumbering of references throughout the text, tables, and Supplementary Materials, and replacement of citation numbers after sources were added or removed. Textual analysis, scientific interpretation, critical evaluation, synthesis of theoretical concepts, and formulation of conclusions were performed entirely by the authors.

Linguistic adaptation: Generative artificial intelligence tools (ChatGPT, OpenAI, GPT-5.1/5.2, 5.5, and ChatGPT Plus) were used to assist translating the manuscript into English, followed by manual editing.

Following relevance screening and thematic classification, 50 primary studies encompassing experimental investigations, numerical modeling, life-cycle assessments, and techno-economic analyses were included in the comparative analysis of raw, thermally treated, and densified biomass fuels. Additional review articles, official documents, and supporting publications were used to establish the broader scientific, policy, and theoretical context of the study.

Different types of publications were considered according to their evidential role and were not treated as equivalent evidence. Primary research articles reporting experimental and/or numerical data were used as the principal evidence base for the comparative assessment and for drawing the main conclusions of this review. Review articles were primarily used to establish the state of the art, identify general research trends and knowledge gaps, and contextualize this review relative to previous syntheses. Conference proceedings were considered when they contained relevant experimental or technical data. An official technical report was used to contextualize technical constraints and biomass pretreatment, while regulatory requirements were discussed as reported in the cited research articles. The book and other supporting sources were used to interpret fundamental physicochemical and thermochemical aspects in the Discussion. Non-English-language sources were included only when they were directly relevant to the scope of the review and the reported information could be reliably interpreted.

The experimental scale and methodology of the reviewed studies were taken into account when interpreting their results. The evidence scale was determined from the description of the installation and the process investigated in each source. TGA and experiments in laboratory installations were classified as laboratory-scale evidence. Pilot-scale designations were applied to the relevant process, such as briquetting or thermal treatment, when explicitly reported in the original source. Tests conducted at operating power plants and other industrial facilities were classified as industrial-scale evidence. Demonstration activities were discussed with reference to the installation and test conditions reported in the original sources, without assigning them to another evidence-scale category. Results from numerical modeling, life-cycle assessment, and techno-economic calculations were distinguished from direct experimental measurements. Findings obtained from thermogravimetric analysis (TGA) and other laboratory-scale experiments were considered within the conditions of the respective studies and were not directly extrapolated to pilot-scale or industrial boiler performance. Pilot-scale and industrial-scale evidence was considered separately where such data were available.

3. Raw Agricultural Residues and Wood Processing Waste

3.1. Straw and Other Cereal Residues

Proszak-Miąsik et al. [19] investigated the fuel properties of oat straw (OS1), fossil coal from Lower Silesia, Poland (CLS), and their blends at OS1–CLS ratios of 10/90, 20/80, and 30/70. The calorific value of oat straw was substantially lower than that of coal (15.52 and 27.73 MJ kg^{-1}, respectively), and increasing the proportion of oat straw therefore increased the calculated fuel consumption. For an assumed boiler efficiency of 70% and thermal outputs of 5–25 kW, the calculated consumption of pure oat straw in 2018 ranged from 1.657 to 8.286 kg h^{-1}. Among the mixtures investigated, the OS1–CLS 30/70 blend was identified by the authors as the most favorable from environmental and economic perspectives. For this blend, the corresponding calculated fuel consumption was 1.069 kg h^{-1} at 5 kW and 5.343 kg h^{-1} at 25 kW. The properties of the individual fuels and their blends, including lower and higher heating values (LHV and HHV, respectively), are presented in Table 2. The emission results obtained by Proszak-Miąsik et al. [19] illustrate the trade-offs associated with oat-straw utilization. Emission measurements were conducted during separate combustion of compressed oat straw and coal in a boiler rated at 20 kW. Fuel blends were not tested for emissions. Compared with coal combustion, the reported

NO and NO_x emissions decreased by approximately 1.8 times and SO_2 emissions by 4.3 times, whereas CO emissions increased by an average of 1.8 times (Table S1). The mean measured flue-gas oxygen contents were 11.63% for straw and 11.03% for coal. Methane emissions remained nearly unchanged, amounting to 23.68 mg m^{-3} for oat straw and 24.22 mg m^{-3} for coal. The average ash content of oat straw was approximately 1.5 times lower than that of coal. However, the authors emphasized that the composition and energy characteristics of the oat straw varied between harvesting years because of differences in weathering and aging. Coal properties also varied, although less markedly: its ash content was 8.22%, 8.46%, and 8.08% in 2018, 2019, and 2020, respectively. The average ash content calculated from these annual values is reported in Table 2.

The combustion behavior of rice residues is strongly influenced by their ash composition. Tsai et al. [20] reported calorific values of 16.94 MJ kg^{-1} for rice straw (RS) and 16.05 MJ kg^{-1} for rice husk (RH1), as shown in Table 2. Despite its higher ash content, rice husk was considered more suitable for energy utilization because SiO_2 constituted 91.17% of its ash compared with 34.45% for rice straw. Accordingly, rice husk exhibited lower base-to-acid, fouling, and slagging indices (0.08, 0.06, and 0.003, respectively) than rice straw (1.29, 0.76, and 0.09). Rice husk ash also contained lower quantities of potassium and sulfur oxides at 5.99% and 0.73%, respectively, compared with 35.54% and 10.52% in rice straw ash. These compositional differences indicate lower predicted slagging and sulfur-related emission risks for rice husk under the conditions considered by the authors.

In addition to ash composition, the reactivity of rice husk depends on whether it is used untreated or after carbonization. Zakaria et al. [21] compared the pyrolysis and combustion behavior of untreated rice husk (RH3), rice husk char (RHC), and their blends with Mukah Balingian and Blair Athol low-rank coals (MB and BA) and Silantek medium-rank coal (SL). The proximate and ultimate characteristics of the investigated fuels are summarized in Tables 2 and S2. Untreated rice husk exhibited higher reactivity than the investigated coals, which the authors attributed primarily to its volatile matter content of up to 68 wt.% compared with up to 45 wt.% for the coals (Table 2). The coal–rice husk blends consequently showed limited interaction between their components during pyrolysis and combustion. The carbonized rice husk behaved differently. The MB–RHC and BA–RHC blends acted as single fuels during combustion, as indicated by synergistic effects in their DTG profiles [21]. The interaction was less favorable when RHC was blended with the higher-quality SL. The authors related this difference to the carbon contents of RHC and SL, which were 48.1% and 78.4%, respectively (Table S2). Based on these results, Zakaria et al. [21] suggested that rice husk char could improve the combustion behavior of low-rank coals. This conclusion was based on laboratory TGA; its applicability to fixed-bed pulverized boilers requires further validation.

Table 2. Basic properties of untreated biomass, coal, and their blends [1].

Fuel	Composition [2]	Moisture [3], %	Ash [3], %	Volatile Matter [3], %	Fixed Carbon [3], %	LHV [3], MJ kg^{-1}	HHV [3], MJ kg^{-1}	References
Straw and Other Cereal Residues								
CLS	100	5.54	8.25	N/R [4]	N/R	27.73	28.49	[19]
OS1	100	8.62	5.43	N/R	N/R	15.52	16.75	[19]
OS1–CLS	30/70 [5]	6.46	7.41	N/R	N/R	24.08	24.97	[19]
RS	N/R	N/R	9.5	74.29	12.07	N/R	16.94	[20]
RH1	N/R	N/R	12.1	71.35	8.13	N/R	16.05	[20]
MB	100	N/R	3.7	43.0	53.3	N/R	25.2	[21]
BA	100	N/R	6.4	25.1	68.5	N/R	32.0	[21]
SL	100	N/R	9.3	45.4	45.3	N/R	28.7	[21]
RH3	100	N/R	15.0	68.0	17.0	N/R	16.2	[21]
RHC	100	N/R	38.8	9.9	51.3	N/R	20.0	[21]

LtC	100	8.97	5.45	53.54	32.04	N/R	23.77	[22]
RH4	100	7.98	17.78	54.96	19.29	N/R	14.29	[22]
RH2	100	5.4	18.00	58.46	18.14	N/R	15.17	[23]
SHC	100	N/R	10.27	32.32	57.41	N/R	N/R	[24]
SHCC	100	N/R	14.93	6.45	78.62	N/R	N/R	[24]
ST1	100	N/R	10.75	75.9	13.35	N/R	N/R	[24]
CMEP	100	6.61	37.0	3.72	52.67	21.9	22.6	[25]
CS	100	5.50	7.47	69.18	17.85	16.2	17.04	[25]
W	100	5.81	4.99	54.45	34.75	16.2	17.05	[25]
BR	100	9.95	27.28	43.13	19.64	15.1	15.91	[25]
CYLPT	100	4.30	19.12	29.58	47.00	20.28	N/R	[26]
PM	100	1.36	3.5	77.2	18.00	9.81	N/R	[26]
ST2	100	15.68	16.74	56.7	10.90	15.93	N/R	[26]
Woody Biomass Residues								
HC	100	N/R	22.93	23.1	53.97	N/R	N/R	[27,28]
PS	100	N/R	3.7	80.68	15.62	N/R	N/R	[27,28]
HC–PS	80/20 [5]	N/R	21.83	31.82	46.35	N/R	N/R	[27,28]
CC	100	4.1	11.8	44.0	N/R	N/R	31.00	[29]
CCN	100	3.7	3.4	79.5	N/R	N/R	23.42	[29]
CC–CCN	50/50 [5]	N/R	N/R	N/R	N/R	N/R	26.66	[29]
LC	100	15.00	7.02	43.38	34.60	N/R	23.38	[23]
PopS	100	4.76	4.72	80.95	9.57	N/R	12.81	[23]
CI	100	35.59	5.82	32.14	26.45	16.54	16.59	[30]
AWB	100	48.15	8.36	35.79	7.71	8.54	8.59	[30]
CI–AWB	97/3	34.77	5.92	33.60	25.70	16.61	16.66	[30]
SNI	N/R	<35	<4.5	N/R	<12	N/R	>12.56	[30]
Other Agricultural and Biomass Residues								
R	100	9.05	6.94	75.07	8.94	N/R	16.94	[22]
PKS1	100	7.62	6.61	72.25	13.52	N/R	21.25	[22]
PNS	100	5.97	5.61	56.76	31.66	N/R	19.33	[23]
SFR	100	3.86	17.64	71.84	6.66	N/R	13.73	[23]
MBm	N/R	10.1	6.2	78.2	15.6	N/R	22.9	[31]
BC	N/R	0.8	31.1	8.2	60.7	N/R	24.3	[31]

[1] Evidence scale, particle size, and test conditions: Ref. [19]—laboratory fuel characterization and separate combustion of compressed straw and coal in a domestic boiler rated at 20 kW. Straw blocks measured approximately 20 × 10 × 15 cm. Fuel consumption for blends at 5–25 kW was calculated assuming 70% boiler efficiency. Ref. [20]—laboratory fuel and ash characterization after drying at approximately 100 °C for 24 h. Ref. [21]—laboratory TGA using approximately 20 mg samples at 25–900 °C, a heating rate of 20 °C min^{-1}, and an air flow of 100 mL min^{-1}. Ref. [22]—laboratory TGA of particles < 250 μm, using 5–10 mg samples at approximately 40–700 °C and an air flow of 60 mL min^{-1}. Heating rates were 5, 10, 20, and 40 °C min^{-1}. Ref. [23]—laboratory tube-furnace tests using samples passing a 60-mesh sieve. Each blend sample weighed 1 g, and emissions were recorded at 50 °C intervals from 100 to 950 °C. Ref. [24]—laboratory TGA using 10 mg samples at 50–800 °C and 20 °C min^{-1}, with 21, 30, or 40 vol.% O_2 in CO_2 at a total gas flow of 100 mL min^{-1}. The coal used to prepare semi-char had a particle size of 75–150 μm. Ref. [25]—laboratory TGA of 100–150 μm particles, using approximately 10 mg samples at 30–1000 °C, heating rates of 10–50 °C min^{-1}, and a dry-air flow of 50 mL min^{-1}. Ref. [26]—laboratory TGA using 3.50 ± 0.10 mg samples in 21% O_2/79% N_2 at 0.67 mL s^{-1}. Samples were heated to approximately 1200 °C at 10.2 °C min^{-1} and held for 30 min. Refs. [27,28]—laboratory TGA of 180–250 μm particles, using approximately 10 mg samples at 25–915 °C and heating rates of 5, 12.5, and 20 °C min^{-1}. Ref. [29]—laboratory TGA and ignition/combustion tests of 100–400 μm particles, with ignition tests conducted in heated air at 500–800 °C. Ref. [30]—industrial CFB boiler tests with 3 wt.% acacia wood bark. The fuel had a broad particle-size distribution, with 47.64% below 4.75 mm after crushing. Ref. [31]—laboratory TG–DSC of 105–210 μm particles, using 15 ± 1 mg samples heated to approximately 927 °C at 6, 12, 24, and 30 °C min^{-1}

under an air flow of 100 mL min^{-1}. Particle sizes were not explicitly specified in [20,21,26]. The SNI row presents fuel-quality requirements rather than experimental results. [2] Composition ratios are given on a mass basis, with the components listed in the same order as in the "Fuel" column. [3] Analytical basis: Ref. [19]; dry basis: Refs. [20,24,27,28]; for Ref. [21], proximate-analysis values were reported on a dry basis, whereas the basis of the calorific values was not explicitly specified. For Ref. [22], biomass samples were naturally dried for 3–5 days, but the analytical basis of the tabulated values was not explicitly specified. For Ref. [23], the analytical basis was not explicitly specified. For [26], proximate-analysis values were reported on an air-dried basis, whereas LHV was reported on an as-received basis. As analyzed after oven drying at 55 °C for two days: Ref. [25]. For Ref. [31], moisture was measured at equilibrium under storeroom conditions, whereas ash, volatile matter, fixed carbon, and HHV were reported on a dry basis. For Ref. [29], moisture, ash, and volatile matter were reported on air-dried, dry, and dry ash-free bases, respectively. The HHV of the CC–CCN 50/50 blend was estimated from the coal HHV and the approximately 14% reduction reported in Ref. [29], rather than taken from a directly reported measurement. For Ref. [30], the analytical basis was not explicitly specified. [4] N/R—not reported in the original source; hereafter, N/R is used without the superscript. [5] Composition identified by the original authors as optimal or favorable under the investigated conditions.

The biomass proportion is another factor determining the performance of coal–rice-husk blends. Bampenrat et al. [22] reported an average activation energy of 121.84 kJ mol^{-1} for the LtC–RH4 blend at the recommended coal/biomass ratio of 75/25. Kanwal et al. [23] obtained the most favorable reported emission characteristics for an LC–RH2 blend containing 30% rice husk, corresponding to a coal/biomass ratio of 70/30 (Table S1). At this ratio, the unburned carbon content in the ash decreased from 8.3% for coal to 5.18% for the blend, indicating improved burnout under the investigated conditions. The different proportions recommended in these studies show that the rice-husk content associated with favorable performance depends on the fuel system and experimental conditions.

The environmental performance of rice residues was also evaluated using a broader system boundary. Sofán-Germán et al. [32] compared the combustion and co-combustion of bituminous coal with rice husk and coconut residues. For the rice-husk-only scenario, the authors reported a global warming potential of 300 kg CO_2 eq., a eutrophication potential of 4.742 kg PO_4 eq., and a photochemical smog formation potential of 0.012 kg C_2H_4 eq. The study specified a functional unit of 1 MJ of thermal energy and considered fuel extraction and transport, processing and blending, co-firing, gaseous emissions, and ash. These life-cycle impact indicators should not be interpreted as direct combustion emissions or explained solely by the fuel properties in Table 2, since they also reflect the included supply and processing stages and the assumptions adopted in the assessment.

Straw addition may also improve the combustion of carbonaceous fuels with poor ignition characteristics. Li et al. [24] investigated the co-firing of Shenhua coal semi-char (SHCC), a low-temperature pyrolysis product characterized by poor ignitability and burnout, with straw (ST1) under oxy-fuel O_2/CO_2 conditions. The characteristics of SHCC and ST1 are presented in Tables 2 and S2. Thermogravimetric analysis showed that the stage-specific activation energies associated with volatile matter combustion at 250–350 °C and fixed-carbon combustion at 350–450 °C changed as the straw proportion increased. At the same time, the overall activation energy decreased substantially when straw was introduced into the semi-char, declining from 91.51 kJ mol^{-1} for pure SHCC to 56.43 kJ mol^{-1} for the SHCC–ST1 75/25 blend. Further increases in the straw content produced smaller changes, with activation energies of 47.44, 42.38, and 46.18 kJ mol^{-1} for blends containing 50%, 75%, and 100% ST1, respectively. The authors attributed the reduction in overall activation energy and ignition temperature to synergistic interactions between the fuel components.

The importance of cereal-residue type was further demonstrated by Wang et al. [25], who compared wheat straw (W), corn straw (CS), beet residues (BRs), and their blends with coal from the Maasvlakte energy plant (CMEP). In this study, coal was added to biomass to improve its combustion performance. The properties of the investigated feedstocks are summarized in Tables 2 and S2. Among the examined mixtures, the CMEP–CS blend showed the most favorable combustion characteristics. Compared with pure corn straw, coal addition slightly increased the ignition temperature from 243 to 249 °C and the temperature corresponding to the maximum mass-loss rate from 264 to 271 °C. The combustion temperature increased more substantially from 299 to 390 °C. These values were obtained at a heating rate of 10 °C min^{-1}, which was also identified as favorable for the CMEP–W blend. The authors attributed the resulting combustion behavior to synergistic interactions between the fuel components.

A direct comparison with another agricultural residue confirmed that biomass type can be as important as its proportion in the blend. Shen et al. [26] compared the effects of straw (ST2) and pig manure (PM) on the combustion behavior of coal (CYLPT). Their proximate and ultimate characteristics and calorific values are presented in Tables 2 and S2. The CYLPT–PM blends exhibited higher reactivity than the CYLPT–ST2 blends. The activation energies of blends containing 15% and 20% pig manure were 64.98 and 64.75 kJ mol^{-1}, respectively, whereas the corresponding values for the straw-containing blends were 70.38 and 78.40 kJ mol^{-1}. Increasing the pig manure proportion from 5% to 30% reduced the ignition temperature from 423 to 402 °C [26]. However, the combustion temperature, flammability index, and comprehensive combustion characteristic index did not change monotonically with biomass content. The maximum synergistic effect, determined from the difference between the experimental and calculated mass-loss values, occurred at a pig manure content of 5%, whereas the minimum was observed at 10%. Based on the combined combustion characteristics, the authors identified 15% pig manure as the most favorable addition. Although these results concern a non-cereal residue, their comparison with straw demonstrates that trends observed for one biomass type cannot be transferred directly to another.

3.2. Woody Biomass Residues

Using blends of Hwange bituminous coal (HC) and untreated pine sawdust (PS) as a case study, Marangwanda et al. [27,28] demonstrated not only that the addition of biomass resulted in a lower ignition temperature and a higher maximum mass loss rate during combustion but also that a synergistic effect could be achieved when the fuels were co-fired. Using thermogravimetric analysis (TGA), the authors showed that proper optimization of the blend composition is essential for maximizing this synergistic behavior. Bituminous coal combusted at approximately 565 **°C**, whereas pine sawdust burned at around 446 **°C**. The addition of 10, 20, and 30% PS shifted the mass-loss profiles of the fuel blends toward lower temperatures. According to the authors of [27], this behavior is associated with the substantially higher volatile matter content of pine biomass (80 wt.%) compared with coal (23 wt.%, Table 2). The combustion of volatiles occurs at lower temperatures, while the highly porous char structure formed during PS combustion facilitates the release of volatile products from the combustion zone. However, the synergistic effect at this stage was not observed for all blends and became evident only when the PS content reached at least 20%. An increase in the heating rate from 5 to 20 **°C** min^{-1} reduced the ignition temperature by approximately 34% while increasing the combustion temperature by about 35%. The influence of the heating rate became less pronounced as the particle size decreased. As shown in [28], the kinetic parameters did not exhibit a linear dependence on the PS content in the blend. Nevertheless, increasing the amount of volatile matter released during biomass degradation (Table 2) hindered oxygen access to carbon particles. As a result, a higher activation energy was required to ignite the residual char. On average,

the activation energy increased from 93 to 106 kJ mol^{-1} during the homogeneous combustion stage of volatile matter and from 53 to 104 kJ mol^{-1} during the heterogeneous char combustion stage as the biomass content increased from 0 to 30%. Based on the combined analysis of combustion and kinetic parameters, the authors concluded that the blend containing 20% PS was the most favorable. The volatile matter, fixed-carbon, and ash contents of this blend were comparable to those of coal (Table 2).

Yankovsky et al. [33] further examined the effects of particle size and fuel preparation on the spraying and combustion characteristics of coal–wood mixtures. Their analysis focused on the influence of fuel grinding and blend composition on combustion efficiency. The study demonstrated that the co-grinding of coal and pine sawdust resulted in a uniform particle size distribution. The resulting particles, with sizes below 80 μm, promoted rapid ignition of the fuel blend, a broad flame angle, and efficient combustion. The most favorable combustion characteristics were achieved at a coal-to-pine sawdust ratio of 50/50 and a burner supply pressure of 3 bar.

A deterioration in the combustion characteristics of both coal (Chernogorskiy coal, CC) and biomass (chopped cedar needles, CCNs) with increasing particle size (from 100 to 200 μm to 300–400 μm) was also reported in [29]. Specifically, the mass loss rate decreased and the combustion index deteriorated. The temperature corresponding to the maximum decomposition rate increased for biomass, whereas it decreased for coal. The ignition temperatures (Ti) of the char residue for coal and biomass with particle sizes of 100–200 μm were 368 and 260 °C, respectively. For the corresponding fuels with particle sizes of 300–400 μm, these temperatures increased to 390 and 267 °C. The burnout temperatures (Tbs) of coal and biomass were 733 and 542 °C, respectively, for particles of 100–200 μm, and 788 and 642 °C for particles of 300–400 μm. Glushkov et al. [29] attributed these observations to the formation of significant temperature gradients within larger particles. The addition of biomass in the form of cedar needles to coal at a blending ratio of 50/50 reduced the ignition temperature of the char residue to 276 and 343 °C for the 100–200 and 300–400 μm fractions, respectively. At the same time, the burnout temperature decreased to 597 and 622 °C for the corresponding particle-size fractions. In contrast, the mass loss rate increased, reaching 3.24% min^{-1} instead of 2.81% min^{-1} for the finer particles and 3.20% min^{-1} instead of 2.43% min^{-1} for the coarser particles. The temperature corresponding to the maximum mass loss rate for the 100–200 μm fraction (462 °C) was comparable to that observed for fine biomass particles. However, for the 300–400 μm fraction, this temperature reached 547 °C, exceeding the values determined for both coal (488 °C) and biomass (472 °C). The addition of biomass to coal enhanced the reactivity of the fuel blend, as evidenced by a reduction in the activation energy of the combustion process from 60.3 to 42.5 kJ mol^{-1}, in contrast to the results reported in [28]. Furthermore, the smaller the particle size of the biomass additive, the shorter the ignition time and the greater the degree of burnout of the fuel mixture. However, increasing the biomass content in the fuel blend beyond 50% is undesirable because it results in a reduction in the higher heating value (HHV). As shown in Table 2, the HHV of the fuel blend containing 50% CCN was approximately 14% lower than that of the original coal.

In the case of poplar sawdust (PopS), the lowest emissions of carbon oxides and sulfur oxides relative to coal combustion were achieved using a coal-to-biomass ratio of 50/50 [23]. Under these conditions, emissions of carbon oxides and sulfur oxides were reduced by 38% and 99%, respectively (Table S1). The unburned carbon content in the ash, used in [23] as an indicator of burnout, was 7.11% for this blend, compared with 8.3% for coal.

Cahyo et al. [30] conducted a techno-economic and environmental analysis of the co-firing of a coal (CI)–acacia wood bark (AWB) blend in circulating fluidized bed boilers (the characteristics of CI, AWB, and their blend, together with the requirements of the Indonesian National Standard (SNI), are summarized in Tables 2 and S2). The results

demonstrated that the investigated biomass did not satisfy several requirements of the Indonesian National Standard. In particular, its calorific value (8.59 MJ kg^{-1}) was below the specified minimum limit (12.59 MJ kg^{-1}), whereas its ash content (8.36%) and moisture content (48.15%) exceeded the allowable values of <4.5% and <35%, respectively (Table 2). The addition of 3% biomass increased the cost of the fuel blend by 0.26% relative to coal alone. At the same time, the lower energy content of the blend resulted in increased fuel consumption. The use of acacia bark reduced sulfur dioxide emissions but promoted an increase in nitrogen oxide emissions. Nevertheless, the overall emissions of sulfur dioxide and nitrogen oxides generated during the co-combustion of coal with a 3% biomass addition remained below the applicable regulatory limits. However, the effects of the particle size of both fuel components on the co-combustion process were not examined in detail. Further studies are therefore required to assess the suitability of acacia bark at higher co-firing ratios and under other industrial operating conditions.

3.3. Other Agricultural and Biomass Residues

Bampenrat et al. [22] investigated lignite coal (LtC) and biomass co-combustion using thermogravimetric analysis. Using cassava root (R) and palm kernel shell (PKS1) biomass products (Table 2), as well as different coal-to-biomass blending ratios (75/25, 50/50, and 25/75), the authors demonstrated that the thermal decomposition of biomass proceeds through three to four stages. These stages include moisture evaporation and the release of light volatile compounds (up to 190 °C), oxidation of part of the volatile matter (150–390 °C), char combustion (390–550 °C), and oxidation of inorganic compounds (530–680 °C). In contrast, lignite combustion was characterized by only two major stages, namely moisture removal (up to 160 °C) and the release and oxidation of volatile matter (160–560 °C). For the combustion of coal–biomass blends, biomass addition reduced the ignition temperature as a result of enhanced coal devolatilization. However, the reduction in ignition temperature was not accompanied by improvements in the combustion index, combustion reactivity, or calorific value (Table 2). Based on the combined combustion characteristics reported in that study, the authors identified the coal-to-biomass ratio of 75/25 (wt.%/wt.%) as the most favorable among the investigated blends. The calculated average activation energies for the LtC–R and LtC–PKS1 fuel blends at the recommended coal-to-biomass ratio of 75/25 were 105.25 and 179.66 kJ mol^{-1}, respectively [22].

Among the other biomass residues investigated by Kanwal et al. [23], pine nut shells (PNSs) and sunflower residues (SFRs) showed the most favorable emission characteristics at biomass contents of 30% and 40%, respectively, corresponding to coal-to-biomass ratios of 70/30 and 60/40 (Table S1). The unburned carbon contents of these blends were 7.20% and 0.45%, respectively, compared with 8.3% for coal.

Coimbra et al. [31] assessed the co-combustion behavior of bituminous coal (BC, Tables 2 and S2), microalgae biomass derived from wastewater treatment (MBm, Tables 2 and S2), and their blend (MBm–BC) using simultaneous thermogravimetric analysis and differential scanning calorimetry (DSC). The authors demonstrated that, unlike many other biomass types reported in the literature, MBm has a relatively high HHV (22.9 MJ kg^{-1}), close to that of bituminous coal (24.3 MJ kg^{-1}; Table 2). Such similarity in calorific value is advantageous for the co-combustion of MBm and BC. The apparent activation energy of combustion for the MBm–BC blend (approximately 98.5 kJ mol^{-1} on average) was found to be much closer to that of bituminous coal (approximately 84 kJ mol^{-1}) than to that of microalgae biomass alone (approximately 196.5 kJ mol^{-1}). The apparent activation energy of wastewater-derived microalgae biomass was more than twice as high as that of pure bituminous coal. The ignition temperature of the fuel blend decreased, whereas its combustion temperature remained close to that of pure coal.

4. Thermally Treated Biomass and Biochar

4.1. Biochar and Semi-Coke

Softwood sawdust from larch (L), pine (P), and cedar (C), together with the corresponding semi-cokes (SCL, SCP, and SCC), was examined using thermogravimetric analysis [34–36]. The investigated fuels included the individual biomass samples and semi-cokes, their mixtures with each other, blends of SCL and SCP with Borodino lignite coal (BLC–SCL and BLC–SCP), and mixtures of cedar biomass with semi-coke derived from brown coal. Blending biomass with semi-coke produced either from the same biomass or from brown coal extended the combustion interval and increased the temperature at which complete burnout was achieved [34]. Furthermore, increasing the biomass content from 25% to 75% in blends with brown coal semi-coke increased the combustion index [36]. However, the ignition temperatures of the individual softwood-derived carbonizates were more than 100 °C higher than those of lignite [35]. In contrast, blends of carbonizates and lignite at a ratio of 50/50 exhibited ignition temperatures that were nearly identical to those of lignite and substantially lower than those of the individual wood-derived carbonizates. The burnout temperatures of these blends exceeded those of lignite alone while remaining close to the burnout temperatures of the corresponding carbonizates. The LHV values of the BLC–SCL and BLC–SCP blends were approximately 1.5 times the LHV of lignite alone (Table 3). Consistent with the findings of Marangwanda et al. [27,28] for coal–pine sawdust blends, Zhuikov et al. [34,35] identified volatile matter content as a key factor governing the combustion behavior of semi-coke-containing fuel blends. Synergistic interactions between the fuel components were observed in the low-temperature region through volatile matter combustion and in the high-temperature region through char burnout. At the same time, the combustion behavior of the fuel blends did not follow the principle of additivity [35].

Table 3. Basic properties of thermally treated biomass, coal, and their blends [1].

Fuel	Composition [2]	Moisture [3], %	Ash [3], %	Volatile Matter [3], %	Fixed Carbon [3], %	LHV [3], MJ kg^{-1}	HHV [3], MJ kg^{-1}	References
Biochar and Semi-Coke								
BLC	100	11.6	9.2	47.3	N/R [4]	16.1	N/R	[35]
SCL	100	1.7	4.1	4.7	N/R	32.6	N/R	[35]
SCP	100	4.7	3.7	3.4	N/R	31.6	N/R	[35]
BLC–SCL	50/50 [5]	6.7	6.7	26.0	N/R	24.4	N/R	[35]
BLC–SCP	50/50 [5]	8.2	6.5	25.4	N/R	23.9	N/R	[35]
ClC	100	5.8	8.1	36.7	55.2	21.5	N/R	[37]
BMT	100	5.6	4.8	76.0	19.2	14.8	N/R	[37]
BMTC	100	3.4	19.1	26.4	54.5	21.8	N/R	[37]
ASC	100	0.7	21.4	1.7	N/R	26.2	N/R	[38]
PSSC	100	1.8	2.8	8.0	N/R	33.0	N/R	[38]
Hydrothermally Treated Biomass [6]								
CII	100	31.43	2.50	33.76	32.31	N/R	18.64	[39]
HT-FRD	100	5.81	2.09	77.81	14.29	N/R	16.50	[39]
Torrefied Biomass								
CIII	100	23.57	5.31	38.11	33.01	N/R	18.68	[40]
Twig	100	6.36	28.67	26.89	38.08	N/R	13.77	[40]
Trunk	100	6.39	3.58	26.62	63.41	N/R	26.83	[40]
Weed	100	5.93	59.59	18.73	15.75	N/R	5.21	[40]
CIII–Twig	75/25	19.27	11.15	35.31	34.28	N/R	17.45	[40]
CIII–Trunk	25/75 [5]	10.69	4.01	29.49	55.81	N/R	24.79	[40]
CIII–Weed	75/25	19.16	18.88	33.26	28.70	N/R	15.31	[40]
EC	100	2.25	14	31	55	27.205	28.134	[41]
BW	100	5.41	1.16	82	16.84	17.374	19.429	[41]
LTTBW	100	3.00	1.12	77.88	21	19.690	21.058	[41]

MTTBW	100	2.38	1.15	71.85	27	20.352	21.698	[41]
AS	100	8.64	1.60	77.67	20.73	20.71	22.79	[42]
AS-300	100	1.26	4.07	22.30	73.63	29.11	30.60	[42]
KFP	100	10.87	1.32	79.14	19.54	17.07	19.33	[42]
KFP-300	100	2.98	5.03	26.40	68.57	27.07	28.50	[42]
VP	100	10.84	2.89	77.06	20.04	16.58	18.84	[42]
VP-300	100	2.68	7.98	28.46	63.57	26.19	27.69	[42]
OP	100	3.51	1.31	79.85	18.84	21.22	23.92	[42]
OP-300	100	2.26	4.56	21.66	73.78	29.91	31.36	[42]
PWC	100	2.61	0.27	81.91	17.82	17.57	19.89	[42]
PWC-300	100	1.87	0.94	26.08	72.98	29.37	30.92	[42]
EWC	100	6.98	0.67	82.02	17.30	20.82	23.13	[42]
EWC-300	100	2.89	1.67	29.76	68.67	23.08	25.15	[42]
OS2	100	7.8	5.0	77.8	N/R	N/R	17.74	[43]
OS2-257.5	100	3.8	5.54	64.8	N/R	N/R	21.54	[43]
OS2-300	100	2.5	7.26	49.98	N/R	N/R	22.74	[43]
OS2-525	100	2.1	10.4	36.61	N/R	N/R	27.09	[43]
MS	100	7.7	4.2	82.4	N/R	N/R	16.86	[43]
MS-257.5	100	3.1	4.84	63.78	N/R	N/R	21.35	[43]
MS-300	100	1.8	6.97	51.11	N/R	N/R	22.21	[43]
MS-525	100	1.3	10.12	37.23	N/R	N/R	26.98	[43]
CIV	100	9.14	12.45	39.59	38.82	22.01	N/R	[44]
RH5	100	10.4	21.7	54.65	13.25	13.01	N/R	[44]
TR-303	100	2.84	46.34	23.49	27.33	13.64	N/R	[44]
TR-306	100	2.75	46.22	23.41	27.62	13.88	N/R	[44]
TR-309	100	2.77	46.31	23.47	27.45	13.67	N/R	[44]
TR-353	100	2.62	42.60	22.57	32.21	14.16	N/R	[44]
TR-356	100	2.66	42.34	22.24	32.76	14.24	N/R	[44]
TR-359	100	4.22	42.98	20.39	32.41	13.95	N/R	[44]
TR-403	100	2.16	51.85	20.67	25.32	12.28	N/R	[44]
TR-406	100	2.14	44.91	20.1	32.85	13.63	N/R	[44]
TR-409	100	1.09	51.05	18.32	29.54	11.79	N/R	[44]
CIV–TR-356	90/10 [5]	8.49	15.44	37.86	38.21	21.23	N/R	[44]
RCC	100	8.7	10.12	71.12	10.60	N/R	14.2	[45]
TRCC-202	100	1.56	3.10	60.34	35.09	N/R	17.3	[45]
TRCC-204	100	1.4	3.32	59.45	35.83	N/R	17.4	[45]
TRCC-206	100	1.34	4.23	58.43	36.00	N/R	18.0	[45]
TRCC-242	100	1.12	4.55	56.78	37.55	N/R	18.0	[45]
TRCC-244	100	0.98	4.66	50.32	39.07	N/R	18.6	[45]
TRCC-246	100	0.87	5.23	47.10	41.52	N/R	18.8	[45]
TRCC-262	100	0.75	5.45	45.01	44.37	N/R	18.8	[45]
TRCC-264	100	0.69	5.78	40.23	49.42	N/R	18.9	[45]
TRCC-266	100	0.56	5.80	38.41	49.56	N/R	18.9	[45]

[1] Evidence scale and experimental approach: Ref. [35]—laboratory thermogravimetric analysis of fuels and their blends. Ref. [37]—laboratory-scale co-firing in a drop-tube furnace at 1400 °C, followed by ash characterization. Ref. [38]—laboratory thermal analysis coupled with mass spectrometry. Ref. [39]—fuel characterization and CFD simulation of co-firing in a 315 MWe boiler, rather than experimental co-firing tests in that boiler. Ref. [40]—laboratory simultaneous thermal analysis (TG–DSC/DTA). Ref. [41]—torrefaction and combustion tests in a 20 kW_{th} entrained-flow reactor. Ref. [42]—laboratory torrefaction, fuel characterization, and grindability assessment. Ref. [43]—laboratory thermal treatment and TGA used to inform the design of a larger-scale torrefaction installation. Ref. [44]—laboratory torrefaction, fuel characterization, and assessment of ash-related risks using predictive indices. Ref. [45]—laboratory torrefaction and fuel characterization, including TGA of the untreated feedstock. [2] Composition ratios are given on a mass basis, with the components listed in the same order as in the "Fuel" column. [3] As-received basis: Ref. [39]; air-dried basis: Refs.

[40,43,44]. For Ref. [35], moisture basis was not specified; ash was reported on a dry basis, volatile matter on a dry ash-free basis, and LHV on a working/as-received basis. For Ref. [37], moisture was reported on an air-dried basis, whereas ash, volatile matter, fixed carbon, and LHV were reported on a dry basis. For Ref. [38], moisture and heating value were reported on a working/as-received basis, ash on a dry basis, and volatile matter on a dry ash-free basis. For Ref. [41], moisture and ash were reported on an as-received basis, whereas volatile matter and fixed carbon were reported on a dry basis; the basis of LHV and HHV was not specified. For Ref. [42], the source did not explicitly identify the analytical basis; the reported values indicate a dry basis for ash, volatile matter, fixed carbon, LHV, and HHV, whereas moisture was determined for the analyzed samples. For Ref. [45], proximate-analysis values were reported on an as-analyzed basis, although the formal basis was not specified; the basis of HHV was also not specified. [4] N/R—not reported in the original source; hereinafter, N/R is used without the superscript. [5] Optimal composition based on the reported properties. [6] Process terminology is used as reported in the original studies.

Chen et al. [37] compared bark mallee tree (BMT), bark-derived biochar (BMTC), Collie coal (ClC), and their blends (bark–biochar, bark–coal, and biochar–coal), focusing on both fuel characteristics and ash-related risks. The biochar produced during pyrolysis was found to be similar to coal in terms of volatile matter and fixed-carbon contents (Table 3). In addition, biochar and coal exhibited comparable concentrations of carbon, hydrogen, and oxygen, resulting in similar LHV values (Tables 3 and S2). The main difference between the investigated fuels was related to the alkaline index of their ashes. The ashes of bark and bark-derived biochar contained significant amounts of alkali and alkaline-earth metals in contrast to coal ash. Moreover, the concentration of these elements was higher in biochar ash due to their enrichment in the solid residue during pyrolysis, as volatile components were removed (Table 3). Coal ash was dominated by aluminosilicate minerals containing aluminum, silicon, and iron. As discussed previously, a high alkaline index (>0.34 g MJ^{-1}) is associated with an increased risk of fouling and slagging during combustion. To mitigate these problems, water leaching of either the original bark or the resulting biochar prior to combustion, or the use of appropriate blend ratios, is recommended. For example, the optimal proportions were reported to be 20/80 for bark–coal mixtures and from 5/95 up to a maximum of 20/80 for biochar–coal mixtures.

Gorshkov et al. [38] investigated the co-combustion of anthracite semi-coke (ASC) and wood-derived semi-coke produced from pine sawdust. Unlike the thermally treated biomass examined in the previous study, pine sawdust semi-coke (PSSC) was characterized by a low ash content (2.8%), which was substantially lower than that of anthracite semi-coke (21.4%, Table 3). Similar to other types of biomass-derived semi-coke, pine semi-coke contained virtually no sulfur (Table S2). At the same time, its carbon content (87.1%) was higher than that of anthracite semi-coke (73.8%). As a consequence, the LHV of pine semi-coke (33 MJ kg^{-1}) exceeded that of anthracite semi-coke (26.2 MJ kg^{-1}, Table 3). The addition of pine-derived semi-coke reduced nitrogen oxide emissions by an average of 24%. Furthermore, the reactivity of the blended fuel was increased, as evidenced by decreases in both the ignition and burnout temperatures of the fuel mixture and by a shift in the combustion process toward a lower-temperature region.

The range of thermally treated feedstocks also included biochar produced from ramie residue at 500 °C and co-combusted with the original biomass [46]. For these blends, the most favorable biochar content ranged from 10 to 30 wt.%. The combustion process was complex and involved significant interactions between the biomass and biochar components. When the biochar content exceeded 30 wt.%, a deterioration in the combustibility of the fuel blend was observed. The combustibility index followed the same trend as the average mass loss rate. At high biomass contents, the combustion temperature of the blend was lower than that of pure

biochar. Moreover, decreasing the amount of biochar led to a reduction in the overall combustion period of the blended fuel. Thermogravimetric analysis revealed a clear synergistic effect between the two fuel components. Comparison of the calculated and experimental DTG curves showed that the combustion behavior of the blends could not be accurately predicted solely from the combustion characteristics of the individual fuels. This finding indicates that the co-combustion process is governed by interactions between biomass and biochar, resulting in non-additive combustion behavior.

4.2. Hydrothermally Treated Biomass

Hydrothermal treatment of palm frond residue (FRD) for co-firing with coal (CII) in a tangentially fired pulverized-coal boiler was evaluated using computational fluid dynamics [39]. Raw palm fronds were treated at 200–250 °C to produce hydrothermally treated biomass (HT-FRD). The authors considered an HT-FRD content of 5% to be the most favorable for the modeled boiler conditions. At this ratio, the calculated gas temperature at the furnace exit increased by approximately 10%, while the CO_2 mass fraction decreased from 0.187 to 0.130. However, the simultaneous increase in the residual O_2 mass fraction from 0.042 to 0.084 and the relatively high CO concentration may indicate less complete combustion. As the HT-FRD content increased from 5 to 50%, the calculated CO_2 mass fraction increased from 0.130 to 0.159, whereas the residual O_2 mass fraction decreased from 0.084 to 0.062. The authors also reported an increase in CO with the addition of HT-FRD and attributed it to the higher volatile matter content of the biomass compared with coal (Table 3). These trends require further clarification based on the carbon balance, flue-gas flow rate, combustion completeness, and emissions normalized to the energy produced.

4.3. Torrefied Biomass

Umar et al. [40] analyzed the combustion behavior of a low-calorific-value coal (CIII) blended with torrefied biomass derived from tea plantation residues (twig, trunk, and weed) to support co-firing design for gasification feedstock preparation. The biomass samples were torrefied at 300 °C for 1 h under inert conditions and subsequently blended with coal at mass ratios of 25/75, 50/50, and 75/25. The resulting mixtures were evaluated using simultaneous thermal analysis (STA, TGA–DSC/DTA) at a heating rate from 10 °C min^{-1} to 800 °C. As shown in Table 3, coal–torrefied biomass blends are characterized by lower moisture and volatile matter contents. At the same time, the calorific value of the coal–torrefied twig blend is comparable to that of the parent coal. In contrast, torrefied weed is a low-quality additive because of its high ash content. The highest calorific value among the investigated blends was obtained when torrefied trunk was used as the biomass additive (Table 3). Among the additional advantages of torrefied biomass compared with raw biomass, the authors highlighted improved transportation efficiency and greater uniformity of fuel quality. The study established several important relationships governing biomass combustion. For the fuels investigated in [40], a higher fuel ratio (fixed carbon/volatile matter) was associated with a higher calorific value (Table 3). Conversely, a low fuel ratio is associated with a high volatile matter content. An increase in the fuel ratio resulted in a higher ignition temperature of the biofuel. Marangwanda et al. [27] associated the lower ignition temperatures of their coal–pine sawdust blends with volatile matter released from the sawdust. Bampenrat et al. [22] also reported a decrease in the ignition temperature of coal blends after adding the biomass residues they investigated. It was determined that fuel moisture content is a key parameter affecting combustion behavior [40]. In general, lower moisture contents promote higher combustion rates. A higher combustion rate, in turn, contributes to a reduction in the burnout temperature of the fuel. Based on a comprehensive assessment of the ignition temperature, maximum combustion temperature, combustion rate, and burnout temperature, the researchers concluded that

the coal–torrefied trunk blend at a 25/75 (coal/trunk) ratio exhibited the most favorable overall combustion performance among the tested mixtures. This conclusion concerns the comparison among the tested blends: the ignition and burnout temperatures of the coal–torrefied trunk 25/75 blend were higher than those of coal alone.

Improved grindability was also observed for torrefied beech wood. Sher et al. [41] compared its milling behavior with that of raw beech wood (BW) and El Cerrejon coal (EC). Beech wood was torrefied at temperatures of 200 (LTTBW), 250 (MTTBW), and 300 °C with a residence time of 30 min, and the resulting changes in fuel properties were evaluated, including moisture reduction, partial devolatilization, increased fixed-carbon content (Table 3), and improved grindability (Figure 1). They also summarized numerous experimental studies demonstrating that torrefied biomass behaves more similarly to coal than raw biomass during milling and combustion, thereby facilitating its utilization in existing coal-fired power plants. As shown in Figure 1, the proportions of material passing through a 75 μm sieve were 93% for coal, 33.9% for MTTBW, 20.04% for LTTBW, and only 6% for untreated biomass (BW). These results indicate that increasing the biomass pretreatment temperature enhances its grindability, resulting in a larger proportion of fine particles after grinding. During combustion of individual fuels, biomass torrefied at relatively low temperatures (200 °C, LTTBW) generated lower emissions of nitrogen oxides and sulfur oxides than biomass torrefied at intermediate temperatures (250 °C, MTTBW, Table S1). For CO, the relationship was reversed: MTTBW generated a lower concentration (1054 ppm) than LTTBW (3048 ppm, Table S1). Coal–torrefied biomass blends exhibited significantly lower NO_x and SO_2 emissions than coal alone. In particular, nitrogen oxide emissions were reduced by approximately 30%, while sulfur oxide emissions decreased by about 50% when coal–torrefied biomass blends with a composition of 50/50 were used (Table S1). At the same time, CO concentrations were higher than for coal alone, at 913 ppm for the EC–LTTBW 50/50 blend and 2373 ppm for the EC–MTTBW 50/50 blend. The higher CO concentrations may indicate less complete oxidation under the tested conditions. This result calls for further adjustment of combustion conditions, particularly air supply and fuel residence time, and verification that CO can be reduced before these blends are recommended for practical co-firing.

The effect of torrefaction on fuel properties was also examined across six agroforestry residues: Nunes [42] studied almond shells (ASs), kiwifruit pruning residues (KFPs), vine pruning residues (VPs), olive pomace (OP), pine woodchips (PWCs), and eucalyptus woodchips (EWCs) as potential fuels for electricity generation, investigating whether treatment could improve properties relevant to the use of these materials in coal-fired power plants, including grindability. Like the fuels discussed in [40,41], treatment reduced moisture and changed the balance between fixed carbon and volatile matter (Table 3). Nunes [42] noted that very high fuel moisture entails additional energy consumption for water evaporation. None of the six untreated samples in this study had a moisture content approaching 50%. Torrefaction at 300 °C reduced the moisture content of the investigated biomass materials from initial values ranging between 2.6 and 10.8% to less than 3%, depending on biomass type (Table 3). At the same time, the fixed-carbon content increased from 17.30–20.73% to 63.57–73.78% after torrefaction at 300 °C, while the volatile matter content decreased from 77.06–82.02% to 21.66–29.76% (Table 3). These values were obtained for the biomass samples investigated using the same thermogravimetric analysis procedure within the same study [42]. As shown in Table 3, torrefaction at 300 °C increased both the HHV and LHV. These gains in fuel properties came with a reduction in the mass of the solid product, as reported in [42]. The principal drawback of thermal pretreatment may be the increase in ash content. For the biomass types investigated in this study, the ash content after torrefaction ranged from a minimum of 0.94% for pine woodchips to a maximum of 7.98% for vine pruning residues (Table 3).

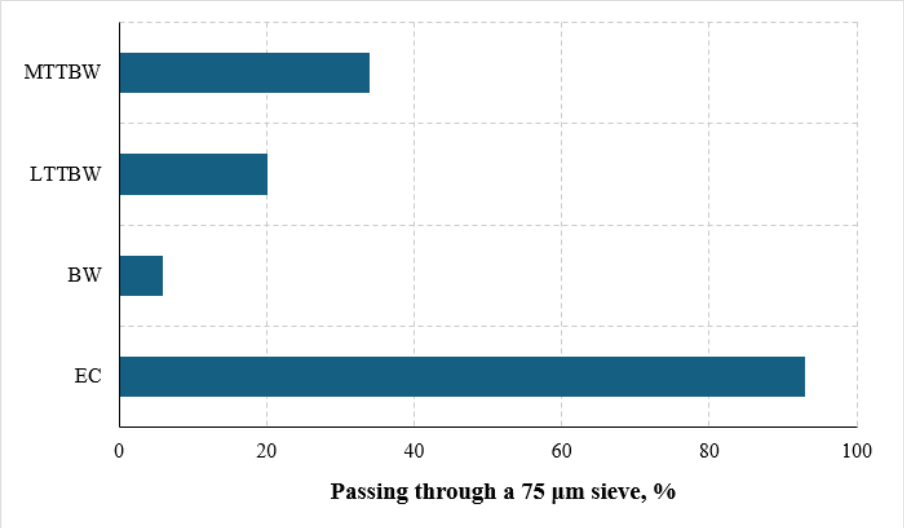
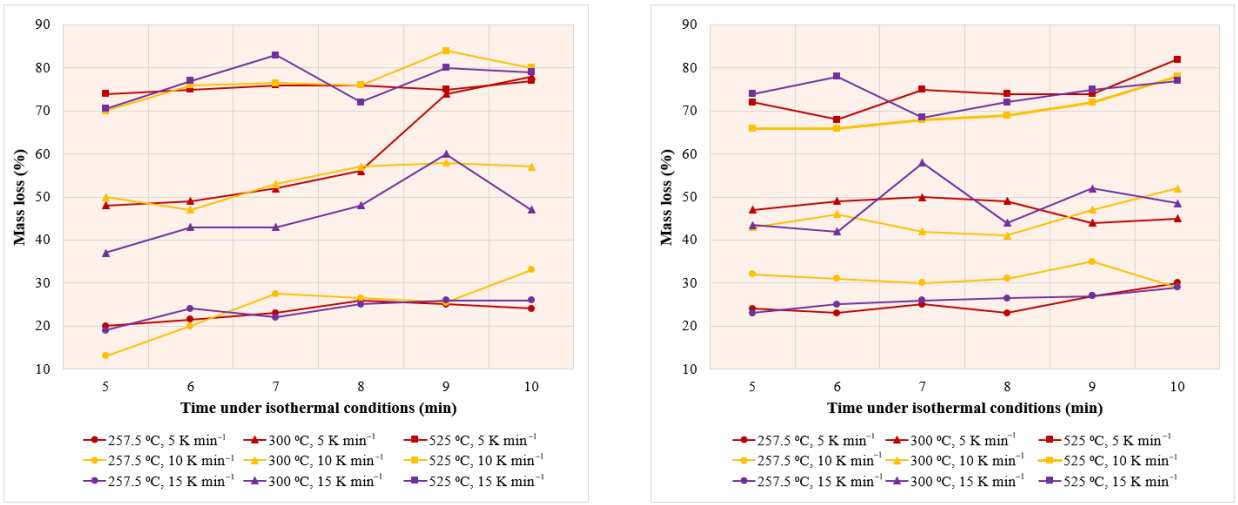


Figure 1. Comparison of the percentage of material passing through a 75 µm sieve after grinding coal, raw biomass, and biomass torrefied at various temperatures.

The loss of solid product observed during torrefaction in [42] makes treatment temperature an important consideration. Szufa et al. [43] examined its effect on oat (OS2) and maize (MS) straw intended for use as solid fuels. Using thermogravimetric analysis, as well as proximate and ultimate analyses, the authors demonstrated that the torrefaction process is influenced more strongly by temperature than by residence time during the isothermal treatment stage (Figure 2). Torrefaction significantly increased the HHV and carbon content of the biomass while simultaneously reducing the H/C atomic ratio (Tables 3 and S2). The temperature range of 290–330 °C was identified as the most suitable for the investigated straw. For maize straw, a mass loss of approximately 45–55% was used to select the treatment conditions. At thermal treatment temperatures above 400 °C, the biomass became further enriched in carbon, while mass and energy yields decreased.

The balance between fuel quality and treatment severity differs for rice husk, whose high ash content is an additional constraint. Umar et al. [44] examined its torrefaction for blending with sub-bituminous coal. The most favorable results were achieved at a torrefaction temperature of 350 °C and a residence time of 60 min. Under these conditions, the torrefied rice husk exhibited improved fuel properties, including a higher carbon content (37.8%), fixed-carbon content (32.76%), and calorific value (14.24 MJ kg^{-1}) compared with raw rice husk (33.29%, 13.25%, and 13.01 MJ kg^{-1}, respectively, Tables 3 and S2). Despite its higher ash content (42.34% compared with 21.7% for raw rice husk), torrefied rice husk contained significantly lower concentrations of alkali metals, particularly potassium, which are known to promote slagging and fouling in combustion systems. The results further demonstrated that torrefaction substantially reduced the moisture content of the biomass (Table 3), thereby improving its compatibility and ability to blend with coal. For the investigated coal, the CIV–TR-356 90/10 blend had an LHV of 21.23 MJ kg^{-1} (Table 3). At higher rice husk proportions, the calculated heating value fell below the threshold used by the authors [44].



(**a**) (**b**)

Figure 2. Effect of temperature, heating rate, and residence time during the torrefaction process on the mass loss of OS2 (**a**) and MS (**b**) samples.

For corn cob (RCC), Ibitoye et al. [45] examined a lower temperature range than that used for rice husk in [44], with attention to both fuel properties and product yields. Torrefaction was carried out for 20, 40, and 60 min at 200 °C (TRCC-202, TRCC-204, and TRCC-206, respectively), 240 °C (TRCC-242, TRCC-244, and TRCC-246, respectively), and 260 °C (TRCC-262, TRCC-264, and TRCC-266, respectively). The elemental compositions of the resulting products are summarized in Table S2. The results showed that torrefaction significantly increased the fixed-carbon content and HHV of the biomass while reducing its volatile matter and moisture content (Table 3). Both temperature and residence time affected the product properties, although torrefaction temperature had a much stronger influence on both product yield and fuel properties than residence time (Table 3 and Figure 3). A similar trend was observed in [43]. For corn cob, Ibitoye et al. [45] selected 260 °C and a residence time of 60 min as the most favorable of the tested conditions. As both torrefaction temperature and residence time increased, the yield of solid product decreased, whereas the yields of liquid and gaseous products increased (Figure 3). It was suggested that the liquid fraction should be further investigated to characterize its properties and assess potential applications, while the torrefied corn cob can be effectively utilized as a solid fuel.

The reduction in solid yield under more intensive treatment conditions also affects the emissions associated with producing and using the fuel. Cho et al. [47] assessed the life cycle of coal co-firing with torrefied residual wood and woodchips. Their analysis demonstrated that moderate torrefaction intensities provide the most favorable balance between improved fuel characteristics and the additional energy consumption associated with biomass pretreatment. The authors treated CO_2 released during biomass combustion as offset by CO_2 uptake during biomass growth. With this biogenic CO_2 excluded, the calculated emissions decreased as the biomass share increased. Total emissions, including biogenic CO_2, did not show the same decrease. Among the treatment temperatures compared for residual wood (230, 270, and 310 °C), 270 °C gave the lowest total CO_2-equivalent emissions under the modeled conditions. Increasing the torrefaction temperature to 310 °C increased the heating value of the treated fuel but sharply reduced its mass yield, limiting the calculated emissions benefit. The preferred treatment temperature therefore depends on which emissions measure is used, as well as the fuel heating value, solid yield, and energy consumed during pretreatment.

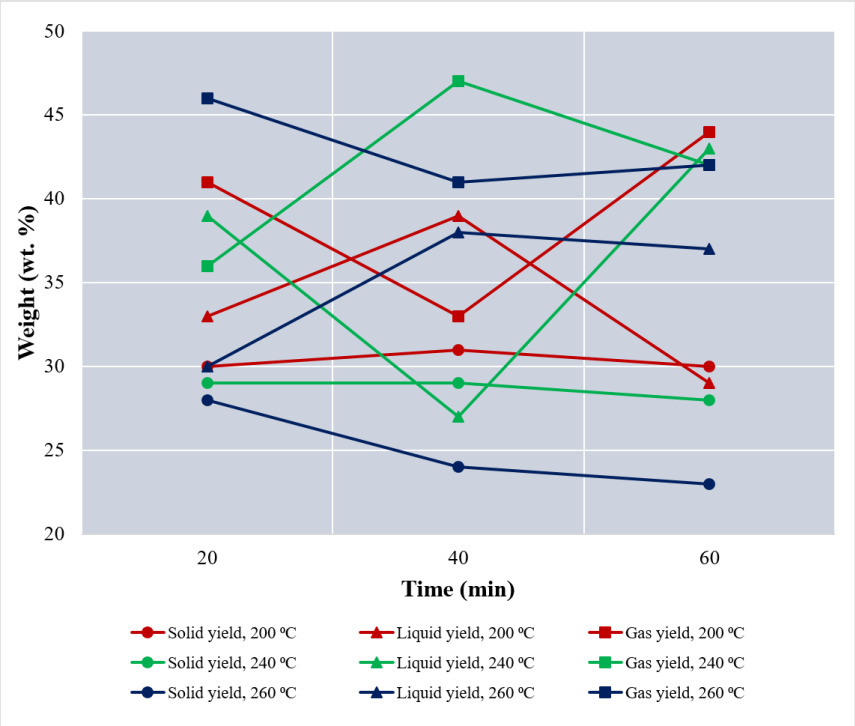


Figure 3. Variation in solid, liquid, and gaseous product yields (wt.%, based on the initial feedstock mass) during corncob torrefaction in a nitrogen atmosphere at 200, 240, and 260 °C for residence times of 20, 40, and 60 min. The three product fractions sum to 100 wt.%.

5. Densified Biomass and Biochar

5.1. Briquettes and Pellets from Untreated Biomass

Nikiforov et al. [48] analyzed the characteristics of bio-coal briquettes produced from sunflower husks (SHs) and leaves (SLVs) and coal industry waste (coal and coke dust from different deposits). For comparison, briquettes were prepared using two biomass fractions, 0–2 mm and 3–6 mm, without the use of a binder. The physicochemical and combustion characteristics of briquettes containing 30–80% biomass and 20–70% coal demonstrated their suitability for local applications. Briquettes produced from the finer biomass fraction were characterized by a lower combustion rate compared with briquettes prepared from the coarser fraction. The finer fraction was associated with a longer burning time, although the size of this difference varied among the tested compositions. A similar trend was observed with increasing coal content. Depending on the coal type (Karazhyra coal, KC, Shubarcul coal, ShC, or coke dust, CD) and the type of agricultural residue (sunflower husks or leaves), the percentage ratio of the components in the briquettes required to achieve optimal combustion characteristics varied. When sunflower husks were mixed with coal dust from the Karazhyra deposit (SH–KC) or with coke dust (SH–CD), the optimal ratio was 70/30 in both cases. In the case of coal dust from the Shubarcul deposit (SH–ShC), a reduction in sunflower husk content to 60% was required. A different pattern was observed when sunflower leaves were used. In mixtures with coal dust from the Shubarcul deposit (SLV–ShC), the optimal results were achieved at a ratio of 70/30, whereas in mixtures with coal from the other deposit (SLV–KC) it became possible to increase the biomass content to 80%. Figure 4 compares the calorific value, volatile matter content, and mechanical strength of briquettes produced from the optimum formulations using fine (0–2 mm) and coarse (3–6 mm) biomass fractions. The results demon-

strate that briquettes prepared from the finer feedstock fraction contain a higher proportion of volatile matter. At the same time, they exhibit greater mechanical strength and higher calorific values than briquettes produced from the coarser fraction.

Binder-free briquetting of agricultural residues was examined by Law et al. [49]. They investigated the mechanical properties of mixtures containing rice husk (RH), sugarcane bagasse (SB1), and spent coffee grounds (SCGs). Two-component mixtures were prepared (three combinations in total) using particle sizes below 2 mm and biomass ratios of 100/0, 80/20, 60/40, 40/60, 20/80, and 0/100 without the use of any binder. The authors used the natural ability of lignin present in biomass to act as a binder when heated. The biomass mixtures were heated to 150 °C and subsequently compressed under a pressure of 300 bar. Based on the determination of shatter resistance, abrasive resistance, and water resistance, the values of which should exceed 90–95% [49], the optimal compositions of the biomass residue mixtures were identified. The most favorable compositions were RH–SCG 20/80, SB1–SCG 20/80, and RH–SB1 40/60. These mixtures provided the best combination of mechanical properties and demonstrated the feasibility of producing durable biomass briquettes without the addition of external binders.

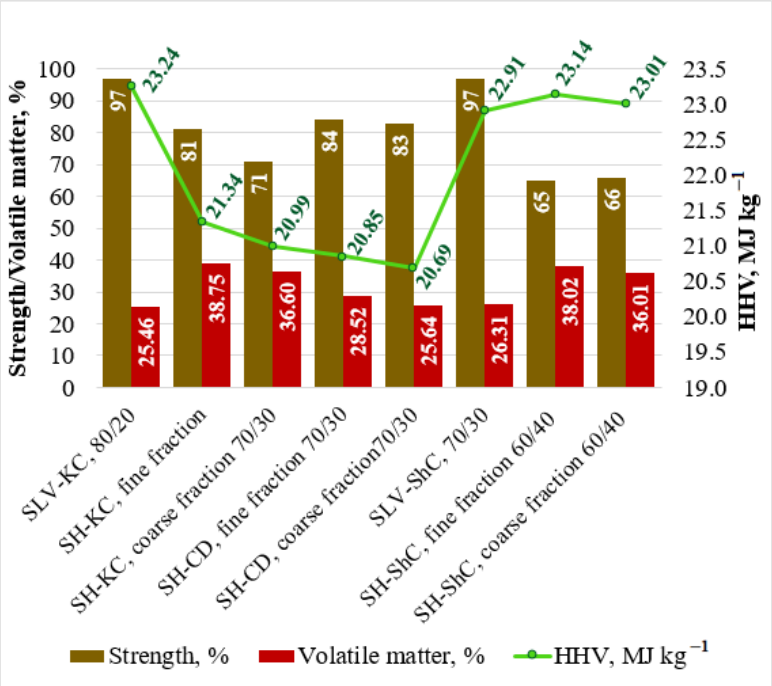


Figure 4. Calorific value, volatile matter content, and mechanical strength of briquettes produced from the investigated optimal formulations using fine (0–2 mm) and coarse (3–6 mm) biomass fractions.

Binders and pretreatment of biomass components have been used in briquette production. Malovanyy et al. [50] added tall oil soap to wood waste to reduce the pressure and power required for briquetting while maintaining briquette strength. Abdulkareem et al. [51] used sodium silicate and molasses as binders for briquettes containing charcoal, sawdust, and sugarcane bagasse. In the coal–maize cob briquettes studied by Wilaipon [52], the maize cob was treated with a 3% sodium hydroxide solution at 90 °C for 1 h before mixing with coal fines.

The reported results concern different properties of the prepared fuels. In Ref. [50], adding tall oil soap reduced engine power consumption by up to 40% and increased briquette density by up to 10%. The most suitable binder content was reported to be 4–6%, while excessive addition led to losses of binder and biomass during pressing. For the charcoal/sawdust/sugarcane bagasse mixtures in [51], the highest heating value was 24,613.69

kJ kg^{-1} at 20/50/30, and the lowest value in the source table was 22,469.89 kJ kg^{-1} at 20/40/40 (Table 4). The authors identified the 20/40/40 blend as the most favorable in terms of the tested combustion characteristics. In Ref. [52], briquette density depended on both the coal/biomass ratio (1/2 or 1/3) and the applied pressure (4–8 MPa).

Khan et al. [53] examined coal–biomass briquettes containing olive or pomegranate residues and optimized their composition with respect to calorific value. The authors employed a central composite design and response surface methodology. Pomegranate biomass yielded higher calorific values than olive biomass. The relationship between biomass content and calorific value was nonlinear. The predicted maximum was 6728 kJ kg^{-1} for a formulation containing 180 g of coal and 54 g of pomegranate biomass. The predicted optimum corresponded to a composite desirability value of 1.

Unchaisri and Fukuda [54] measured emissions during co-firing of coal and rice straw pellets in a laboratory-scale circulating fluidized-bed reactor. The rice straw pellet shares were 25 and 50 wt.%. Increasing the pellet share raised CO emissions while lowering NO_x and SO_2 emissions (Table S1). The higher volatile matter content of the pellets (65.5%, Table 4) and their lower nitrogen (0.48%) and sulfur (0.12%) contents compared with coal (47.8, 1.2, and 0.6 wt.%, respectively, Table S2) are consistent with these trends. The authors also examined the effect of airflow. Excess air lowered the bed temperature and overall combustion efficiency. Under these conditions, SO_2 formation decreased, whereas CO emissions increased because biomass volatiles burned less completely. The study associated the decrease in NO_x partly with reduction reactions involving CO and carbon.

The use of coal–biomass briquettes on operating equipment was examined by Taulbee et al. [55]. The authors discussed feedstock preparation, particle-size compatibility, and the importance of achieving homogeneous mixing prior to densification. Approximately four tons of engineered fuel, comprising two briquetted and two extruded formulations, were burned in a small stoker furnace over two days. All four fuels burned and discharged from the grate without major operating difficulties. Their measured NO_x and SO_x emissions were lower than those of the coal used for comparison in the study.

Table 4. Basic properties of biomass-based briquettes and pellets [1].

Fuel	Composition [2]	Moisture [3], %	Ash [3], %	Volatile Matter [3], %	Fixed Carbon [3], %	LHV [3], MJ kg^{-1}	HHV [3], MJ kg^{-1}	References
Briquettes and Pellets from Untreated Biomass								
ChC1–Sa1–Su	20/20/60	18.55	11.0	26.0	44.45	N/R [4]	23.97	[51]
ChC1–Sa1–Su	20/30/50	17.34	16.5	25.5	40.66	N/R	22.5	[51]
ChC1–Sa1–Su	20/40/40 [5]	19.88	14.0	27.5	38.62	N/R	22.47	[51]
ChC1–Sa1–Su	20/50/30	13.66	14.0	26.5	45.84	N/R	24.61	[51]
ChC1–Sa1–Su	20/60/20	17.75	14.5	27.0	40.75	N/R	23.03	[51]
CV	100	12.70	12.10	47.80	27.40	N/R	20.90	[54]
RSP	100	8.40	12.40	65.50	13.70	N/R	13.20	[54]
Briquettes and Pellets from Thermally Treated Biomass								
A	100	2.7	9.9	15.8	N/R	31.5	32.2	[56]
CB (starch)	N/R	0.9	4.8	15	N/R	32.9	33.2	[56]
CB (resin)	N/R	2.9	4.5	14.1	N/R	31.9	32.4	[56]
WCh	100	14.9	0.5	78.9	N/R	17.2	18.9	[56]
OSt	100	15.5	0.8	76	N/R	18.8	20.3	[56]
TWCh	100	2	1	67.7	N/R	21.3	22.3	[56]
TWCh (high starch)	N/R	4.9	1.5	54.5	N/R	21.8	22.9	[56]
TOSt	100	0.6	2.1	22.2	N/R	21.7	22.7	[56]
CfH	N/R	7.22	12.12	40.62	40.03	N/R	17.78	[57]
Sa2	N/R	7.2	8.62	42.44	41.75	N/R	19.16	[57]
KhW	N/R	7.24	14.93	39.39	38.62	N/R	16.66	[57]
DG	N/R	7.24	12.72	40.13	39.58	N/R	17.45	[57]

AB	100	N/R	N/R	<	N/R	18.4	N/R	[58]
SCGB-20	20 [6]	N/R	47.5	10.2	N/R	15.8	N/R	[58]
SRF	N/R	N/R	≤20	N/R	N/R	14.6	N/R	[58]
PKS2 (starch)	100	1.08	0.06	71.8	27.07	N/R	20.27	[59]
CCA	100	9.25	0.78	86.0	3.97	N/R	17.5	[59]
FWA	100	16.0	2.04	80.5	1.46	N/R	N/R	[59]
CR	100	8.03	7.2	77.63	14.53	18.24	19.94	[60]
SB2	100	7.24	13.13	77.7	8.65	17.97	19.56	[60]
WH	100	9.08	32.31	55.53	11.33	14.18	15.61	[60]
CR-char/starch/water	1.0/0.1/1.2 [5]	5.04	8.41	20.96	70.37	26.84	27.73	[60]
SB2-char/starch/water	1.0/0.05/1.0	6.15	13.50	19.53	66.59	26.67	27.50	[60]
WH-char/starch/water	1.0/0.05/1.0	4.57	29.70	13.33	56.77	16.76	17.44	[60]
ChC2	100	5.2	4.2	14.4	76.2	N/R	25.7	[61]
CHFB	50/50	7.1	12.3	16.9	62.7	N/R	19.8	[61]
CK	100	12.11	4.08	38.89	44.92	N/R	23.80	[62]
OPS	100	5.8	1.8	74.0	18.40	N/R	19.64	[62]
CN	100	7.87	0.94	74.70	16.49	N/R	18.39	[62]
OPS–CK-400	12.5/87.5	N/R	N/R	N/R	N/R	N/R	26.67	[62]
OPS–CK-400	20/80	N/R	N/R	N/R	N/R	N/R	24.50	[62]
OPS–CK-400	50/50	N/R	N/R	N/R	N/R	N/R	23.97	[62]
OPS–CK-400	80/20	N/R	N/R	N/R	N/R	N/R	22.99	[62]
OPS–CK-400	87.5/12.5	N/R	N/R	N/R	N/R	N/R	22.24	[62]
OPS–CK-500	12.5/87.5	N/R	N/R	N/R	N/R	N/R	27.16	[62]
OPS–CK-500	20/80	N/R	N/R	N/R	N/R	N/R	25.55	[62]
OPS–CK-500	50/50	N/R	N/R	N/R	N/R	N/R	23.15	[62]
OPS–CK-500	80/20	N/R	N/R	N/R	N/R	N/R	23.71	[62]
OPS–CK-500	87.5/12.5	N/R	N/R	N/R	N/R	N/R	22.85	[62]
CN–CK-400	12.5/87.5	N/R	N/R	N/R	N/R	N/R	24.56	[62]
CN–CK-400	20/80	N/R	N/R	N/R	N/R	N/R	23.09	[62]
CN–CK-400	50/50	N/R	N/R	N/R	N/R	N/R	21.52	[62]
CN–CK-400	80/20	N/R	N/R	N/R	N/R	N/R	21.34	[62]
CN–CK-400	87.5/12.5	N/R	N/R	N/R	N/R	N/R	20.81	[62]
CN–CK-500	12.5/87.5	N/R	N/R	N/R	N/R	N/R	25.59	[62]
CN–CK-500	20/80	N/R	N/R	N/R	N/R	N/R	24.46	[62]
CN–CK-500	50/50	N/R	N/R	N/R	N/R	N/R	22.99	[62]
CN–CK-500	80/20	N/R	N/R	N/R	N/R	N/R	21.65	[62]
CN–CK-500	87.5/12.5	N/R	N/R	N/R	N/R	N/R	21.87	[62]

[1] Evidence scale and experimental approach: Ref. [51]—laboratory briquette preparation, fuel characterization, and combustion tests. Ref. [54]—co-firing in a laboratory-scale circulating fluidized-bed reactor at a fuel feed rate of 14 kg h^{-1}. Ref. [56]—continuous biomass torrefaction at the Arigna Fuels plant, briquette preparation involving an integrated pilot plant, and subsequent laboratory fuel characterization and thermogravimetric assessment of CO_2 reactivity. Ref. [57]—small-scale briquette preparation using a manual press and laboratory fuel characterization. Ref. [58]—fuel characterization and combustion tests in a briquette boiler. Ref. [59]—small-scale charcoal production and briquetting, laboratory fuel characterization, and cooking-fuel combustion tests. Ref. [60]—small-scale charcoal briquette production, fuel characterization, and combustion tests in a community gasifier stove. Ref. [61]—combustion and emission measurements in a ceramic cookstove. Ref. [62]—laboratory briquette preparation, fuel characterization, and combustion and emission tests. [2] Composition ratios are given on a mass basis, with the components listed in the same order as in the "Fuel" column. [3] As-received basis: proximate-analysis data in [51]. Air-dried basis: proximate-analysis data for the raw materials in [62]. Dry basis: HHV in [51]; ash and volatile matter in [56]; volatile matter, fixed carbon, and ash in [57]; and volatile matter, fixed carbon, ash, LHV, and HHV in [60]. In Ref. [56], moisture, LHV, and HHV were reported on an as-received basis. In Ref. [57], moisture was reported on a wet basis, whereas the basis of HHV was not specified. In Ref. [60],

moisture was reported on a wet basis. For Ref. [54], proximate-analysis values were reported on an as-received basis, whereas HHV was reported on a dry basis. For Ref. [58], the analytical basis was not specified. For Ref. [61], moisture was determined by oven drying, and ash and volatile matter were determined using oven-dried samples; however, the analytical basis was not explicitly identified in the original source. For Ref. [62], the basis of the heating values was not specified; the briquettes were oven-dried at 105 °C before analysis. For Ref. [59], the analytical basis was not explicitly specified; the reported proximate-analysis values correspond to an as-analyzed basis. [4] N/R—not reported in the original source; hereinafter, N/R is used without the superscript. [5] Composition identified by the original authors as optimal or favorable under the investigated conditions. [6] Mass fraction of carbonized spent coffee grounds in the briquette, wt.%.

At a larger operational scale, Xiao et al. [63] compared tobacco-stalk briquettes with coals of different qualities in industrial tobacco-curing barns at six locations. The biomass briquettes were uniform in size, ignited more easily, and exhibited more stable combustion behavior. Heat consumption per unit mass of dry tobacco leaves was 26.4 ± 3.5 MJ kg^{-1} for the briquettes and 31.8 ± 4.2 MJ kg^{-1} for coal. Energy efficiency reached 40 ± 4% for tobacco-stalk briquettes compared with 36 ± 4% for coal. The study also reported less ash generation and lower emissions of toxic pollutants when tobacco-stalk briquettes were used instead of coal.

The environmental and economic performance of coal co-firing with conventional and carbonized wood pellets was assessed by Ashizawa et al. [64] for pellets supplied from Canada and Vietnam to power plants in Japan. For carbonized pellets containing 25 wt.% fixed carbon, the calculated annual electricity consumption during pellet production was 19,636 MWh, compared with 27,291 MWh for conventional pellets. Transportation fuel consumption was lower as well. For Canada, land transport consumption decreased from 1191 to 782 kL $year^{-1}$ and marine transport consumption from 1850 to 1214 kL $year^{-1}$. For Vietnam, the corresponding values decreased from 556 to 365 and from 4618 to 3031 kL $year^{-1}$. Under the assumptions used in the study, these differences contributed to lower calculated CO_2 emissions for carbonized pellets. Their production facilities, however, required a higher initial investment than facilities for conventional pellets (29 versus 19.5 million USD). The calculated electricity generation cost also depended on the pellet supply route and co-firing share. For conventional pellets from Canada, it rose to approximately 1.4–1.5 times the coal-only cost as the co-firing share increased. For carbonized pellets containing 25 wt.% fixed carbon from Vietnam, it remained nearly unchanged even at a high co-firing share. Thus, the study indicates that carbonized wood pellets can provide economic and environmental advantages over conventional wood pellets when favorable feedstock costs, production conditions, and transportation logistics are ensured.

5.2. Briquettes and Pellets from Thermally Treated Biomass

According to Arteaga-Pérez et al. [65], studies of combustion systems in which a portion of coal is replaced with alternative fuel materials should not be limited to the analysis of combustion characteristics alone. The environmental impacts of the fuel should also be assessed throughout its entire life cycle. Therefore, the authors compared the environmental and sustainability aspects of coal-only combustion with co-firing systems utilizing untreated (UB) and torrefied (TB) biomass pellets. The assessment used pilot-scale experimental data extrapolated to a 250 MWe plant, assuming negligible changes in energy efficiency, temperature profiles, and flue-gas composition at coal substitution levels up to 20%. Their results demonstrated that, in both cases, the partial replacement of coal led to lower life-cycle emissions of fossil CO_2, CO, NO_x, and SO_2 per kWh of generated electricity (Table S1) and a lower overall environmental burden. However, slightly better results were obtained when untreated biomass was used (Table S1). These benefits included lower energy consumption and reduced emissions

associated with biomass preparation, particularly when compared with systems requiring preliminary thermal treatment of the biomass.

In Refs. [56,66,67], the preparation of torrefied briquettes involved different ways of balancing fuel properties and mechanical strength. Aamiri et al. [66] considered briquetting as an effective approach to overcoming the brittleness of torrefied biomass during storage and transportation. Their approach was based on utilizing the binding properties of the lignin naturally present in biomass. Since lignin loses its binding ability due to thermal degradation at high torrefaction temperatures, the authors proposed torrefying biomass at different temperatures to obtain materials with complementary properties. To increase carbon content, calorific value, and hydrophobicity, coarse biomass particles (1–20 mm) were torrefied at 280 °C. In contrast, to obtain a material capable of acting as a natural binder, finely ground biomass was torrefied under milder conditions at 200 °C, a temperature at which lignin softens and becomes viscous. The two torrefied products were subsequently mixed at a ratio of 80/20, adjusted to a moisture content of 10%, and densified under pressure to produce briquettes. The resulting air-dried briquettes had a durability index of 68% and an energy density of 21,792 kJ kg^{-1}.

For torrefied woodchips (WChs) and olive stones (OSts), Trubetskaya et al. [56] reported a reduction in moisture and volatile matter contents (Table 4), which are among the key parameters determining the calorific value of biomass fuels. The TWCh and TOSt briquettes exhibited thermal properties comparable to those of the anthracite (A) and coal (CB) examined in that study. The addition of a binder had only a minor effect on the heating value of briquettes produced from either anthracite or torrefied biomass, causing a slight increase (Table 4). Thermogravimetric analysis showed that CO_2 reactivity depended mainly on heat treatment temperature, organic composition, and porosity. The briquettes used in [67] contained sub-bituminous coal and torrefied biomass at a ratio of 95/5, with a bentonite content varying from 2 to 10%. Bentonite had a more pronounced effect on the properties measured for these coal–biomass briquettes: as its content increased, the drop-to-fracture value rose from 100 to 150 and impact resistance increased from 2000 to 3000, while the water resistance index, carbon content, fixed-carbon content, and calorific value decreased. With 2% bentonite, the briquettes had a carbon content of 72%, a fixed-carbon content of 65%, and a calorific value of 24 MJ kg^{-1}. With 10% bentonite, the reported heating value fell to 17.68 MJ kg^{-1}. The authors recommended 2% bentonite as it offered a balance between mechanical durability and energy content.

The balance between durability and heating value also depended on the binder used with carbonized agricultural residues. Kodji et al. [68] investigated bark of Grewia bicolor, gum arabic, starch of cassava flour, black clay, and cow dung as binders for briquettes produced from carbonized rice husk, peanut shells, and straw. All tested binders improved the durability and density of the briquettes. This effect became more pronounced as the binder content increased from 5 to 15%, regardless of the binder type or the carbonized residue used. Increasing the binder content generally decreased the LHV. However, the opposite trend occurred when the LHV of the binder exceeded that of the biomass. For rice husk (LHV = 14.54 MJ kg^{-1}), increasing gum arabic (LHV = 16.015 MJ kg^{-1}), cassava starch (LHV = 19.082 MJ kg^{-1}), or cow dung (LHV = 17.088 MJ kg^{-1}) from 5 to 20% increased the briquette LHV. This effect was not observed for peanut shell (LHV = 26.28 MJ kg^{-1}) or straw (LHV = 22.25 MJ kg^{-1}), whose initial heating values were substantially higher than those of the binders.

Kebede et al. [57] evaluated briquettes produced from carbonized coffee husk (CfH), sawdust (Sa2), khat waste (KhW), and dry grass (DG), using waste paper pulp or clay soil as binders. The carbonized feedstocks were ground to a particle size of approximately 2 mm and mixed with a binder at a biomass/binder ratio of 3/1. Among the biomass residues, sawdust briquettes had the highest mean fixed-carbon content (41.75%) and calorific value (19.15 MJ kg^{-1}), as well as the lowest ash (8.62%) and sulfur (0.03%) contents (Tables 4 and

S2). The authors identified briquettes made from carbonized sawdust and waste paper pulp at a sawdust/pulp ratio of 3/1 as the most favorable formulation.

Kim et al. [58] evaluated the heating and emission characteristics of briquettes produced from carbonized spent coffee grounds (SCGs). The primary objective was to develop briquettes with mechanical strength comparable to that of anthracite briquettes (ABs). To achieve this goal, bottom ash and kaolinite were used as binders. Owing to the presence of silicon, aluminum, and iron oxides, these materials became hardened at elevated temperatures when mixed with water and calcium hydroxide at a ratio of 20/1, thereby ensuring that the briquettes retained their shape after combustion. According to the authors, the solid components of SCGB-20 comprised 20 wt.% carbonized SCG, 71 wt.% bottom ash, and 9 wt.% kaolinite. During production, a water/$Ca(OH)_2$ solution prepared at a ratio of 20/1 was added to achieve the reported 15 wt.% moisture content. The strength of the resulting briquettes before and after combustion reached 86.82% and 99.46%, respectively. The heating value was not particularly high (15.8 MJ kg^{-1}, Table 4). In particular, the resulting CO and CO_2 emissions were substantially lower than those of anthracite briquettes (Table S1). Emissions of NO_2 and SO_2 were higher than those from anthracite briquettes due to the presence of the binders. However, their concentrations (3.7 and 6.8 ppm, respectively, at 13% O_2) remained below the emission limits for general boilers reported in the original study with reference to the Republic of Korea Air Conservation Act (NO_2: 70–120 ppm and SO_2: 70–180 ppm). Based on the physicochemical characterization and combustion tests, the authors concluded that the briquette containing 20 wt.% SCG could be used as an alternative fuel to anthracite briquettes.

Briquettes from carbonized plant residues were compared with several conventional solid biomass fuels in [59] and an additional fuel in [60]. Bonsu et al. [59] examined the combustion behavior of charcoal briquettes produced from palm kernel shells (PKS2s) and compared their performance with conventional charcoal (Acacia, CCA) and fuelwood (Acacia, FWA). Starch was used as a binder during briquette production. The PKS2 briquettes were characterized by a lower moisture content (1.08% compared with 9.25% and 16.00% for charcoal and fuelwood, respectively), a higher fixed-carbon content (27.07% compared with 3.97% and 1.46%, respectively), and a high calorific value (20.27 MJ kg^{-1}), which was comparable to that of charcoal (17.50 MJ kg^{-1}, Table 4). Although PKS2 briquettes were more difficult to ignite and required a longer ignition time, they exhibited a longer burning duration than the reference fuels. Furthermore, combustion experiments demonstrated that PKS2 briquettes burned cleanly, producing minimal smoke, with an ash content of 0.06% [59].

Suttibak and Loengbudnark [60] investigated the production of charcoal briquettes from sugarcane bagasse (SB2), cassava rhizomes (CRs), and water hyacinth (WH). The char obtained from the carbonization of these three biomass types was ground to a particle size of less than 0.5 cm and mixed with cassava starch and water using 5 kg/0.5 kg/6 dm^3 for CR and 2 kg/0.1 kg/2 dm^3 for both SB2 and WH, respectively. For the mass ratios reported in Table 4, water volumes were converted to mass assuming a water density of 1 kg dm^{-3}. Only in the case of cassava rhizome char was the amount of water increased by a factor of 1.2 relative to the amount used for the other biomass chars. Among the investigated materials, the CR briquettes exhibited the most favorable combustion characteristics (Table 4). Their lower heating value was the highest (26.84 MJ kg^{-1}), exceeding those of SB2 and WH briquettes (26.67 and 16.67 MJ kg^{-1}, respectively) and satisfied the relevant fuel quality requirement of 20 MJ kg^{-1} at minimum. The mechanical strength of the briquettes also varied depending on the biomass source. The compressive strengths of the CR, SB2, and WH briquettes were 80.84, 54.74, and 40.99 kg cm^{-2}, respectively, while the moisture contents of the CR, SB2, and WH briquettes were 5.04, 6.15, and 4.57 wt.%, respectively, compared with 8.03, 7.24, and 9.08 wt.% for the corresponding raw materials.

The ash content was 8.41, 13.5, and 29.7 wt.% for the briquettes and 7.20, 13.13, and 32.31 wt.% for the raw materials. The fixed-carbon content was 70.37, 66.59, and 56.77 wt.% for the briquettes and 14.53, 8.65, and 11.33 wt.% for the raw materials. Considering these properties together, the authors regarded CR briquettes as a possible alternative to conventional coal fuels under the investigated conditions.

In Ref. [61], briquettes made from carbonized human feces and sawdust were co-combusted with charcoal (ChC2) at 50/50 wt.%. The briquettes (CHFB) contained carbonized human feces (50 wt.%) and carbonized sawdust (50 wt.%), with molasses used as a binder at 10 wt.% of the total mass. The blend generated substantially more heat than charcoal alone, as evidenced by the higher flue-gas temperature, 475 versus 222 °C. The higher heating value of the alternative fuel briquettes (19.8 MJ kg^{-1}) was only slightly lower than that of charcoal (25.7 MJ kg^{-1}, Table 4). However, co-combustion of charcoal with the biofuel briquettes (ChC2–CHFB) resulted in increased emissions of nearly all monitored gaseous pollutants, including CO, CO_2, H_2S, and NO (Table S1). Therefore, although briquettes produced from human feces and sawdust demonstrate considerable potential as alternative solid fuels, their utilization as a substitute for charcoal requires the development of effective measures to reduce harmful emissions generated during combustion.

Yuliansyah et al. [62] investigated the preparation and characterization of bio-coal briquettes produced from blends of pyrolyzed coal (CK) and pyrolyzed biomass, specifically oil palm shell (OPS) and canarium nutshell (CN). The study demonstrated that pyrolysis pretreatment significantly modifies the physicochemical properties of the resulting briquettes. As shown in Table 4, increasing the pyrolysis temperature from 400 °C to 500 °C resulted in higher calorific values of the bio-coal briquettes, as demonstrated by the OPS–CK-400/OPS–CK-500 and CN–CK-400/CN–CK-500 sample pairs. In addition, briquettes produced using oil palm shell exhibited higher calorific values than those prepared from canarium nutshell biomass. As the biomass content in the briquettes increased from 12.5 to 87.5%, the ignition time (t_i) and burnout time (t_b) decreased, whereas the overall burning rate (v_b) increased in general (Figure 5). At the same time, substantial reductions in CO and CO_2 emissions were observed. For oil palm shell, increasing the pyrolysis temperature from 400 to 500 °C increased CO_2 emissions while reducing CO emissions during the combustion of OPS–CK briquettes. In contrast, the opposite trend was observed for canarium nutshell, where combustion of CN–CK-400 briquettes produced higher CO emissions and lower CO_2 emissions than CN–CK-500 briquettes (Table S1). Thus, the effect of pyrolysis temperature on CO and CO_2 emissions differed between the two biomass sources.

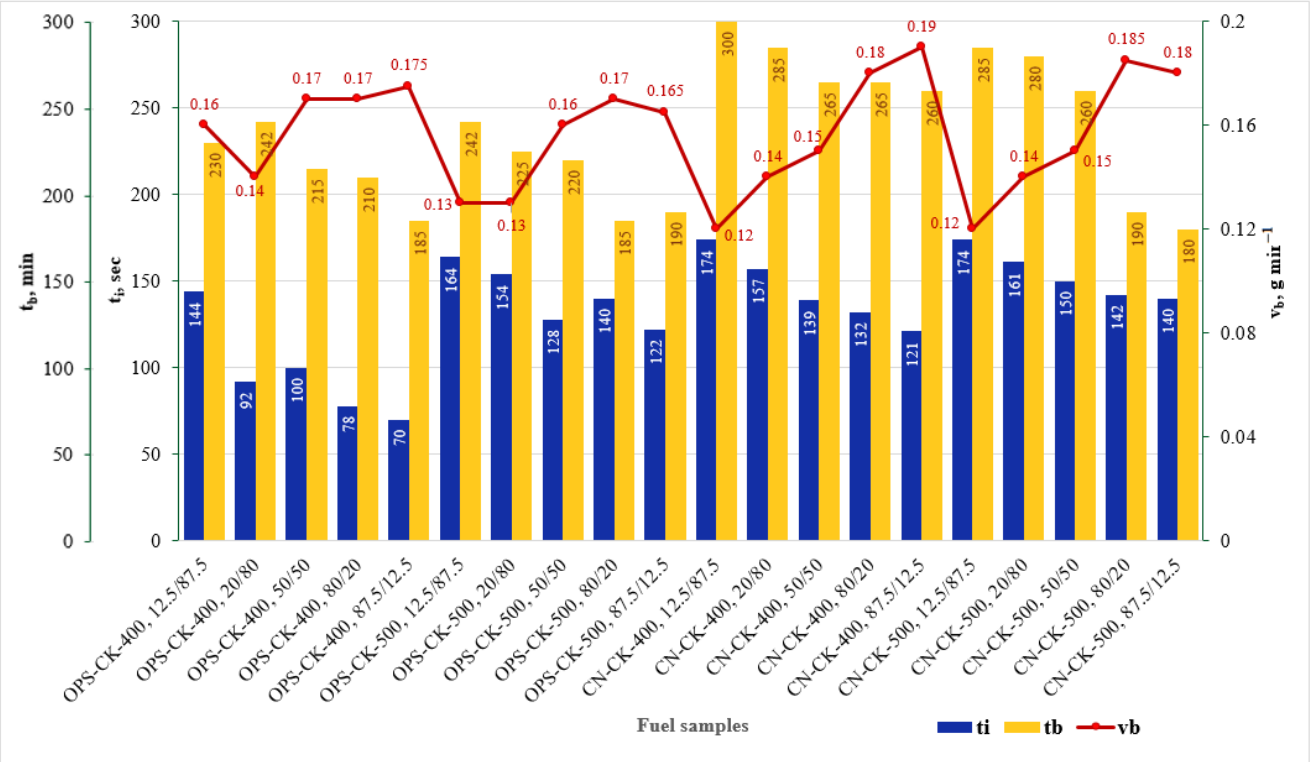


Figure 5. Variation in ignition time, burnout time, and burning rate depending on the biomass content of the briquette and its pyrolysis temperature.

6. Discussion

The present review demonstrates the broad geographical scope of research on biomass fuels for energy generation. Relevant studies have been conducted across numerous countries and regions, including China [1,10,12,15,25,26,41,69], Europe [2,11,31,34,41,46], Russia [34–36], the United States [2,9], Indonesia [5,30], Pakistan [3,41], Canada [25], Türkiye [14], Brazil [18], Colombia [32], India and Nigeria [16], Thailand [22], and Malaysia [4]. This geographical distribution confirms the international scope of research on the use of biomass as a solid fuel and in coal co-firing.

For the purposes of this review, the available studies were examined according to two complementary characteristics: the pretreatment state of the biomass (untreated or thermally treated) and its physical fuel form (non-densified or densified). Evaluation of the reported results within these categories, including comparisons with conventional solid fuels where supported by the original studies, enabled the identification of the key advantages and limitations associated with their use for energy generation (Tables 5–7).

Table 5. Advantages and disadvantages of raw, carbonized, and densified biomass relative to conventional solid fuels.

Advantages	References	Limitations of Biomass Utilization	References
Reduced ash formation	[19]	Low calorific value	[19]
Reduced emission of harmful pollutants	[19,30,38,54,65]	Increased consumption of biomass or blended fuels	[19,30]
Lower ignition temperature	[22,27,28,70]	Increased carbon monoxide formation	[19,39,54]
Higher porosity of the char residue	[27]	Variability in chemical composition	[19]
Enhanced reactivity	[26,29,38]	Instability of energy performance indicators	[19]
Higher combustion temperature	[25]	High biomass moisture content	[11]
Reduced amount of unburned carbon in ash	[23]	Reduced ash fusion temperature due to the elevated content of alkali metal compounds	[20,37]
Presence of synergistic effects	[21,24–28,34,35,46,70]	Increased corrosion of pulverized-coal boilers	[1,13]

No need for boiler design modifications at low biomass contents	[70]	Positive effects are observed only at relatively low biomass contents	[25,28,41,46, 48,49]

Table 6. Comparative advantages and disadvantages of carbonized biomass–coal and raw biomass–coal fuel blends.

Advantages	References	Disadvantages	References
Increased combustion duration and higher burnout temperature	[34,35,37]	Environmental pollution associated with biomass pretreatment processes (torrefaction, pyrolysis, carbonization)	[2]
Reduced moisture and volatile matter contents	[40]	Reduction in solid yield, changes in carbon balance and fuel characteristics, and the need for optimization of thermal pretreatment conditions	[47]
Improved transportation efficiency, grindability, hydrophobicity, and fuel quality uniformity; increased fixed-carbon content	[40–45,56]	Necessity of leaching of the original biomass to reduce the ash content of biochar and prevent fouling and slagging during energy generation	[37]

Table 7. Comparative advantages and disadvantages of densified and undensified biomass fuels.

Advantages	References	Disadvantages	References
Improved durability, density, compressive strength, and mechanical strength	[50,58,68]	Increased briquette production costs	[2]
Prevention of brittleness during storage and transportation	[66]	Deterioration of briquette quality due to binder addition (reduced lower heating value, water resistance index, and fixed-carbon content)	[67,68]
Quality of briquettes produced from thermally treated biomass comparable to that of solid-fuel briquettes	[51,56,59,60]	Increased emissions of harmful gases (NO_x, SO_2, H_2S, etc.) depending on binder composition	[58,61]
Reduced dust generation from fine coal particles and improved combustion characteristics of briquetted biomass–low-rank coal blends	[55]	Need for blend composition optimization to achieve optimal combustion characteristics	[53]

For biomass in general, the predominant trend reported in the reviewed combustion experiments is a reduction in ash formation and lower emissions of NO, NO_x, and SO_2 compared with fossil coal [19,38,54]. This trend was observed for different biomass-based fuels, including oat straw [19], pine-derived semi-coke [38], and rice-straw pellets [54]. Separately, a life-cycle assessment of coal co-firing with untreated and torrefied biomass pellets reported lower life-cycle NO_x and SO_2 emissions per kWh of generated electricity under the adopted assumptions [65]. However, the magnitude and direction of these effects depend on biomass type, pretreatment, fuel composition, and combustion conditions. For example, in the case of acacia bark co-firing [30], SO_2 emissions decreased, whereas NO_x emissions increased. This contrasts with rice-straw pellet co-firing, where increasing the biomass share reduced both NO_x and SO_2 but increased CO [54]. In that study, nitrogen and sulfur contents and excess-air conditions influenced the emission trends. These contrasting results indicate that biomass addition cannot be assumed to reduce all pollutants simultaneously, and trends obtained in a laboratory reactor [54] should not be transferred directly to an industrial boiler [30]. In contrast, carbon monoxide behavior depends on the type of conventional fuel used for comparison. For example, higher CO emissions were measured in [19,54], whereas increased CO concentrations were predicted by the CFD model in [39]. This effect was attributed to the incomplete combustion of volatile matter, the content of which in biomass is substantially higher than in coal [11,21,27]. Carbon monoxide formation is also influenced by biomass pretreatment conditions. In the case of biomass torrefied at 200 °C, lower CO concentrations at the furnace outlet, corrected to 6% O_2, were observed than for biomass thermally treated at 250 °C [41]. This

behavior is apparently associated with the temperature-dependent decomposition pathways of biomass and the corresponding changes in its chemical composition during thermal treatment. The role of these decomposition pathways is illustrated by studies of rice husk thermal decomposition [71–74], which show that the major structural components decompose over different temperature ranges and that the composition of the resulting gaseous products changes substantially with temperature. Thus, the effect of thermal pretreatment on gaseous emissions cannot be interpreted independently of feedstock composition and treatment conditions.

Although a high volatile matter content may contribute to CO formation when the released gases are not fully burned, it also offers an advantage: biomass fuels generally exhibit relatively low ignition temperatures compared with conventional solid fossil fuels [27]. The porous structure of the char formed during biomass conversion can additionally promote fuel reactivity [27]. Increased porosity facilitates the release of volatile products and contributes to the higher reactivity reported for biomass-derived fuels [26,38]. Another potential benefit of biomass–coal co-combustion is a reduction in the amount of unburned carbon remaining in the ash [23]. Several authors [21,35] have reported synergistic effects during biomass–coal co-combustion. At the same time, non-additive combustion behavior [35,46] indicates that the performance of a blend cannot always be predicted solely from the characteristics of its individual components. From a practical perspective, biomass–coal co-firing can, under suitable fuel and operating conditions, be implemented without major modifications to some existing boilers at low biomass shares [70]. Favorable co-combustion behavior has been reported at relatively low biomass shares, commonly within the range of 5–30% in the studies considered here [22,26,39,44,46,70]. However, this range should not be considered universal, since higher biomass shares may be favorable in specific systems, as demonstrated for the coal–torrefied trunk blend in [40]. One proposed approach for increasing the biomass proportion in fuel blends to approximately 50% while maintaining favorable combustion characteristics is the use of finely ground biomass with particle sizes of 100–200 μm [29]. However, achieving such fine particle sizes is challenging because of the fibrous structure and high moisture content of biomass [11]. Additional challenges associated with biomass utilization include variations in chemical composition and instability of fuel properties, although similar issues are also characteristic of fossil coals [19]. Most biomass types exhibit lower ash fusion temperatures due to their elevated contents of alkali metal compounds [20,37]. A high alkali index can result in slagging and fouling in boilers and may also accelerate corrosion processes [1,13,37,44]. Another drawback of biomass is its relatively low calorific value, which increases the consumption of the biomass or biomass–coal fuel blends required to generate a given amount of energy [19,30].

To improve the physicomechanical and fuel properties of biomass, a variety of upgrading techniques have been investigated. These include thermal pretreatment methods, such as torrefaction, carbonization, and pyrolysis, as well as densification through pelletization or briquetting. These technologies have been applied to both raw and carbonized biomass, either individually or in combination with coal, with the aim of enhancing fuel quality and combustion performance [11].

Thermal pretreatment of biomass contributes to reductions in moisture and volatile matter contents [40,45]. As a result, the biomass exhibits improved transportability, grindability, and hydrophobicity [40–42]. Thermal treatment also promotes the homogenization of biomass quality, increases the fixed-carbon content, and enhances the calorific value of the resulting fuel [43–45,56]. The reviewed studies also suggest differences between the combustion behavior of untreated biomass–coal blends and blends containing pre-carbonized biomass [21,34,35,37]. In untreated biomass–coal blends, the more reactive biomass component may be consumed before efficient coal ignition is achieved, which can

limit interactions between the two fuel components [21]. In contrast, the use of pre-carbonized biomass alters the reactivity and combustion characteristics of the biomass component [34,35,37]. However, the mechanisms governing these differences cannot be established from the available data alone, particularly because the reported results were obtained for different biomass types, coals, blend compositions, and thermal treatment conditions. This observation raises the question of how biomass pretreatment affects interactions between the fuel components. The results obtained for rice husk char provide an illustrative example: its co-combustion behavior differed depending on the coal with which it was blended [21]. This indicates that the interaction between biomass-derived char and coal cannot be explained solely by the fixed-carbon or volatile matter content of an individual fuel component but depends on the properties of both components. Systematic studies under comparable experimental conditions are therefore required to clarify these interactions and the role of biomass pretreatment in their development.

The reviewed studies indicate that no single thermal treatment temperature can be considered optimal for all biomass fuels and applications. Depending on the biomass type and the target fuel properties, favorable treatment temperatures reported in the literature vary considerably, from 200 °C [41] and 260–280 °C [45,47,66] to 290–330 °C [43] and 350 °C [44]. The intended subsequent use of the treated biomass is also important. For binderless briquetting, relatively low pretreatment or torrefaction temperatures of 150–200 °C have been proposed to preserve the binding properties of lignin [49,66], whereas preliminary pyrolysis at 400–500 °C has been used when increasing the calorific value before briquetting was the primary objective [62]. Furthermore, although carbonized wood pellets required higher initial investment than conventional wood pellets, carbonization reduced annual electricity consumption and transportation fuel consumption. Under the assumptions adopted in the study, carbonized wood pellets containing 25 wt.% fixed carbon showed lower CO_2 emissions, whereas their economic advantages depended strongly on the production location and supply conditions [64].

The environmental assessment of biomass utilization should distinguish combustion-stage emissions from the overall life-cycle environmental burden, including impacts associated with fuel preparation and supply. Life-cycle assessments depend on the system boundaries, functional unit, and assumptions concerning feedstock supply, transportation, fuel preparation, and energy conversion. Accordingly, the environmental and economic findings are interpreted within each study's assessment framework, without directly ranking biomass utilization routes across studies with different functional units, system boundaries, or supply conditions. Drying, grinding, densification, and thermal pretreatment require energy inputs, with associated emissions depending on the amount of energy consumed and the sources of heat and electricity. For example, CO_2 emissions associated with the energy consumed during fuel preparation increase total life-cycle CO_2 emissions compared with an assessment limited to combustion [47].

In addition to the environmental impacts associated with energy consumption, biomass thermal pretreatment has several other limitations (Table 6). Among the most important are the environmental impacts arising from torrefaction, pyrolysis, and carbonization processes [2], reductions in solid fuel yield, alterations in carbon balance and combustion characteristics, and the need for careful optimization of thermal treatment conditions [47]. Another challenge is the necessity of leaching the original biomass or the resulting biochar to reduce ash-related problems and prevent fouling and slagging during energy generation [37].

Densification can improve the handling and mechanical properties of biomass fuels and can reduce problems associated with the brittleness of torrefied materials during storage and transportation [66]. When external binders are used, they can further improve durability, density, compressive strength, and overall mechanical strength [50,58,68] and

facilitate the densification of feedstocks that are otherwise difficult to compact. Co-briquetting biomass with coal fines can also reduce dust generation and improve the combustion characteristics of low-rank coal fuels [55]. Briquettes produced from torrefied or carbonized biomass have shown fuel properties comparable to those of conventional solid-fuel briquettes in the studies considered [51,56,59,60].

On the other hand, briquette production is associated with increased costs, partly due to the use of binders [2]. Moreover, binders do not always exert a positive influence on the briquetting process. The incorporation of binders may reduce the lower heating value of the resulting fuel [68]. Depending on the type of biomass and binder employed, emissions of harmful gases such as NO_x, SO_2, and H_2S may also increase [58,61]. The use of inorganic binders can adversely affect the water resistance index, as well as the carbon and fixed-carbon contents of briquettes [67]. For example, in the system investigated in [67], limiting the bentonite content to 2% was associated with more favorable combustion characteristics. The effect on heating value also depends on binder composition. Increasing bentonite content reduced the calorific value in [67], whereas organic binders increased the reported LHV when their own heating value exceeded that of the carbonized feedstock [68]. Binder selection therefore requires balancing mechanical strength with fuel energy content rather than maximizing durability alone.

Particle size is another important parameter in briquette production. In the studies considered here, biomass was commonly reduced to particle sizes below 2 mm before densification [49,52,57]. Finer particle fractions can reduce the combustion rate and prolong combustion [48], although the resulting behavior also depends on fuel composition. The performance of densified biomass should therefore be evaluated in relation to its intended application. For example, tobacco-stalk briquettes showed higher energy efficiency than coal under the specific conditions of tobacco leaf curing investigated in [63].

The technical and environmental advantages discussed above support biomass utilization, but their practical value depends on the economic balance across the entire fuel preparation, supply, and energy-conversion chain [10,30,64]. Realizing these advantages involves expenditure on biomass procurement, preparation (including drying, grinding, and densification where required), and delivery, as well as possible plant modifications, which can offset the savings from reduced coal consumption. Improvements in fuel properties through thermal treatment or densification may be accompanied by lower costs for subsequent processing and transportation, but the extent to which these savings offset the initial investment depends on production and supply conditions, including transport distance [64]. This economic balance includes the costs of meeting environmental requirements, linking economic feasibility to the environmental considerations discussed above. Feedstock, energy, and transportation prices vary across locations and over time, so using the same biomass may be economically viable in one case and unprofitable in another. The cited economic assessments support conclusions within their respective scenarios, whereas savings from unquantified processing steps or plant modifications remain potential rather than demonstrated benefits. Each application therefore requires a separate economic calculation accounting for the combined technical, logistical, and environmental factors and their associated costs and savings at the intended biomass blending ratio.

Taken together, the reviewed findings show that, despite extensive research in this field, no universal relationship has yet been established between combustion characteristics and the type, structure, and proportion of biomass incorporated into a fuel blend [26,48]. Biomass utilization is highly case-specific, with combustion behavior depending on the biomass type, fuel composition, pretreatment, particle size, and combustion conditions, as well as on the properties of the coal in co-firing systems [25,26,48]. Consequently, favorable combustion performance requires optimization of both the fuel components and their pro-

portions for the specific application [48,53,59,60]. Furthermore, many of the reviewed studies address specific feedstocks, fuel combinations, and experimental conditions, which limits their direct transfer of their results to other combustion systems. Further systematic studies under comparable conditions are therefore needed to distinguish feedstock-specific effects from more general trends and to support optimization of raw, thermally treated, and densified biomass used either alone or in combination with coal. Integrated techno-economic and environmental assessments under clearly defined supply and operating conditions would help establish how the technical benefits identified in this review translate into practical outcomes. Figure 6 summarizes the factors governing the selection and assessment of biomass preparation and combustion routes for a specific application.

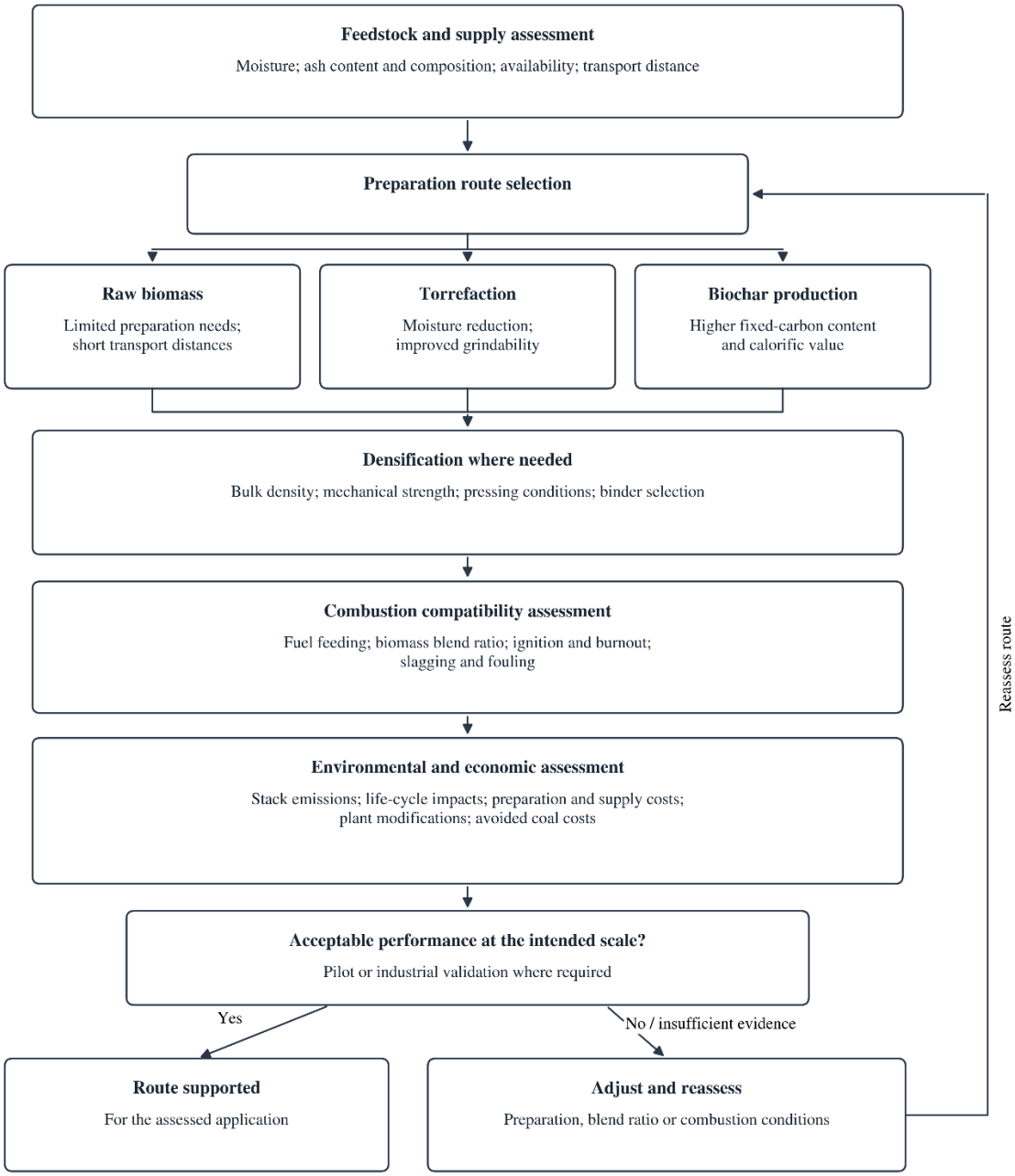


Figure 6. Decision framework for selecting biomass preparation and combustion routes based on feedstock properties, supply conditions, combustion compatibility, environmental impacts, costs, and evidence at the intended scale.

7. Conclusions

Biomass can be used as a feedstock for the production of thermal and electrical energy. Its utilization, including as a fuel additive, can provide environmental benefits, such as reductions in certain harmful emissions, depending on the biomass type, fuel composition, pretreatment, and combustion conditions.

Various approaches to the utilization of biomass waste for energy generation are currently under investigation. These include the use of raw biomass, thermally treated biomass, and biochar in both non-densified and densified forms. The reviewed studies demonstrate that combustion behavior depends on feedstock properties, fuel composition, pretreatment, particle size, and combustion conditions, as well as on the properties of the coal in co-firing systems. Consequently, the advantages and limitations of individual biomass utilization routes are system-specific.

The use of raw biomass reduces the number of preparation steps and is appropriate when transport distances are short and its properties meet the requirements of the intended combustion system. Torrefaction reduces moisture content and improves biomass grindability, facilitating its preparation for coal co-firing, but reduces solid product yield. Biochar production increases fixed-carbon content and calorific value relative to the untreated feedstock, but its use requires combustion conditions that ensure adequate ignition and burnout, together with control of ash-related risks. Thermal treatment entails additional energy and financial costs and generates additional emissions whose contribution to the overall life-cycle balance depends on process conditions and the energy source. Densification increases fuel bulk density and mechanical strength, facilitating handling, storage, and transportation. However, pressing conditions and binder selection involve a trade-off between mechanical strength and calorific value, while the effects of organic binders on emissions require separate consideration. The choice of biomass preparation and combustion route therefore depends on the combination of feedstock properties, the requirements of the intended combustion system, and supply conditions, with separate assessments of environmental and economic viability.

Direct comparison of raw biomass, torrefied biomass, biochar, and their densified forms remains difficult because the available studies differ considerably in feedstocks, fuel combinations, pretreatment conditions, blend ratios, and experimental methods. Comparative investigations of the same biomass feedstock in different pretreatment states and physical fuel forms under comparable conditions remain limited. Likewise, only a few studies have validated laboratory findings under pilot-scale or industrial-scale conditions. Further research should therefore focus on systematic comparisons under comparable experimental conditions, pilot- and industrial-scale validation, and integrated techno-economic and environmental assessment of biomass utilization pathways.

8. Limitations of the Review

Several limitations of this review should be acknowledged. The studies included in the comparative analysis are heterogeneous in terms of feedstock characteristics, blend composition, particle size, experimental conditions, and reactor type and scale, which limits direct comparison of the reported results. In addition, the literature uses different units and reporting approaches for some parameters, preventing their direct quantitative comparison. Potential publication bias cannot be excluded because studies reporting significant or favorable results may be more likely to be published. Source screening and classification were performed by a single author, which may have affected the objectivity of source selection. In addition, source-selection counts were not recorded at each stage and cannot be reliably reconstructed, limiting the retrospective assessment of search completeness. Although non-English sources were considered when directly relevant and reliably

interpretable, language-related limitations may have affected the coverage of the available literature. Conference proceedings and an official technical report were included where relevant; however, the availability and level of detail of such gray literature are variable. Finally, most of the available evidence is based on laboratory-scale experiments, including TGA studies, whereas comparable pilot-, demonstration-, and industrial-scale data remain limited. Therefore, laboratory-scale findings should not be directly extrapolated to full-scale combustion systems without additional validation.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en19215139/s1, Table S1: Reported Gaseous Emissions from the Investigated Fuels and Fuel Blends; Table S2: Ultimate Analysis of the Investigated Fuels and Fuel Blends.

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Abbreviations

The following abbreviations are used in the manuscript:

A	Anthracite
AI	Artificial intelligence
AB	Anthracite briquettes
AS	Almond shells
AS-300	Almond shells after torrefaction at 300 °C
ASC	Anthracite semi-coke
AWB	Acacia wood bark
BA	Blair Athol low rank coal
BA–RHC	Blair Athol low-rank coal (BA) and rice husk char (RHC) blend
BC	Bituminous coal
BLC	Borodino lignite coal
BLC–SCL	Borodino lignite coal and larch carbonisate blend
BLC–SCP	Borodino lignite coal and pine carbonisate blend
BMT	Bark mallee tree
BMTC	Biochar produced from bark mallee tree
BR	Beet residues after extracting sugar
BW	Raw beech wood
C	Cedar
CI, CII, CIII, CIV, CV	Coal in [30], [39], [40], [44], and [54], respectively
CV–RSP	Coal (CV) and rice straw pellet (RSP) blend
CB	Coal briquette
CIII–Twig	Coal (CIII) blended with twig biomass

CIII–Trunk	Coal (CIII) blended with trunk biomass
CIII–Weed	Coal (CIII) blended with weed biomass
CIV–TR-356	Coal (CIV) blended with rice husk torrefied at 350 °C for 60 min (TR-356)
CC	Chernogorskiy coal
CCA	Conventional charcoal (Acacia)
CC–CCN	Chernogorskiy coal (CC) and chopped cedar needle (CCN) blend
CCN	Chopped cedar needle
CD	Coke dust
CfH	Coffee husk
CI–AWB	Coal (CI) and acacia wood bark (AWB) blend
ChC1, ChC2	Charcoal in [51] and [61], respectively
ChC1–Sa1–Su	Charcoal, sawdust [51] and sugarcane bagasse blend
CHFB	Briquettes produced from carbonized human feces and sawdust using molasses
ChC2–CHFB	Briquettes produced from carbonized human feces and sawdust using molasses and mixed with charcoal at 50/50 ratio
CK	Kalimantan mining coal
ClC	Collie coal
CLS	Coal from Lower Silesia, Poland
CMEP	Coal collected from the Maasvlakte energy plant (Rotterdam, the Netherlands)
CMEP–CS	Coal from the Maasvlakte energy plant (CMEP) and corn straw (CS) blend
CMEP–W	Coal from the Maasvlakte energy plant (CMEP) and wheat straw (W) blend
CN	Canarium nutshell
CN–CK-400, CN–CK-500	Blends of canarium nutshell (CN) and Kalimantan mining coal (CK), with both components pyrolyzed at 400 and 500 °C, respectively
Coal–UB	Coal blended with untreated biomass (UB) pellets
Coal–TB	Coal blended with torrefied biomass (TB) pellets
CS	Corn straw
CRs	Cassava rhizomes
CR-char/starch/water	Cassava rhizome charcoal briquettes
CYLPT	Coal from Yantai Longyuan Power Technology Co., Ltd., Yantai, China
CYLPT–PM	Coal from Yantai Longyuan Power Technology Co., Ltd. (CYLPT) and pig manure (PM) blend
CYLPT–ST2	Coal from Yantai Longyuan Power Technology Co., Ltd. (CYLPT) and straw (ST2) blend
DG	Dry grass
DSC	Differential scanning calorimetry
DTA	Differential thermal analysis
DTG	Thermal differential weight loss
EC	El Cerrejon coal
EC–BW	El Cerrejon coal (EC) blended with raw beech wood (BW)
EC–LTTBW	El Cerrejon coal (EC) blended with low torrefied temperature beech wood (LTTBW)
EC–MTTBW	El Cerrejon coal (EC) blended with medium torrefied temperature beech wood (MTTBW)
EWC	Eucalyptus woodchips
EWC-300	Eucalyptus woodchips after torrefaction at 300 °C
FWA	Fuelwood (Acacia)
HC	Hwange bituminous coal
HC–PS	Bituminous coal (HC) and untreated pine sawdust (PS) blend
FRD	Palm frond residue
HHV	Higher heating value
HT-FRD	Palm frond after hydrothermal treatment
KC	Karazhyra coal
KFP	Kiwifruit pruning residues
KFP-300	Kiwifruit pruning residues after torrefaction at 300 °C
KhW	Khat waste

L	Larch
LC	Lakhra coal, Sindh, Pakistan
LC–SFR	Lakhra coal (LC) blended with sunflower residues (SFR)
LC–PNS	Lakhra coal (LC) blended with pine nut shells (PNSs)
LC–PopS	Lakhra coal (LC) blended with poplar sawdust (PopS)
LC–RH2	Lakhra coal (LC) blended with rice husk (RH2)
LCOE	Levelized cost of electricity
LHV	Lower heating value
LtC	Lignite coal
LtC–PKS1	Lignite coal (LtC) and palm kernel shell (PKS1) blend
LtC–R	Lignite coal (LtC) and cassava root (R) blend
LtC–RH4	Lignite coal (LtC) and rice husk (RH4) blend
LTTBW	Low torrefied temperature beech wood
ND	Not detected
MB	Mukah Balingian low rank coal
MB–RHC	Mukah Balingian low-rank coal (MB) and rice husk char (RHC) blend
MBm	Microalgae biomass
MBm–BC	Microalgae biomass and bituminous coal blend
MS	Maize straw
MS-257.5	Maize straw (MS) after torrefaction at 257.5 °C for 10 min
MS-300	Maize straw (MS) after torrefaction at 300 °C for 6 min
MS-525	Maize straw (MS) after torrefaction at 525 °C for 5 min
MTTBW	Medium torrefied temperature beech wood
OP	Olive pomace
OP-300	Olive pomace after torrefaction at 300 °C
OPS	Oil palm shell
OPS–CK-400, OPS–CK-500	Blends of oil palm shell (OPS) and Kalimantan mining coal (CK), with both components pyrolyzed at 400 and 500 °C, respectively
OS1, OS2	Oat straw in [19] and [43], respectively
OS1–CLS	Oat straw (OS1) and Lower Silesian coal (CLS) blend
OS2-257.5	Oat straw (OS2) after torrefaction at 257.5 °C for 9 min
OS2-300	Oat straw (OS2) after torrefaction at 300 °C for 7 min
OS2-525	Oat straw (OS2) after torrefaction at 525 °C for 5 min
OSt	Olive stones
PKS1, PKS2	Palm kernel shells in [22] and [59], respectively
P	Pine
PM	Pig manure
PNSs	Pine nut shells
PopS	Poplar sawdust
PS	Pinus sawdust
PSSC	Pine sawdust semi-coke
PWC	Pine woodchips
PWC-300	Pine woodchips after torrefaction at 300 °C
R	Cassava root
RCC	Raw corncob
RH1, RH2, RH3, RH4, RH5, RH	Rice husk in [20], [23], [21], [22], [44], and [49], respectively
RH–SB1	Rice husk (RH) and sugarcane bagasse (SB1) blend
RH–SCG	Rice husk (RH) and spent coffee grounds (SCG) blend
RHC	Rice husk char
RS	Rice straw
RSPs	Rice straw pellets
Sa1, Sa2	Sawdust in [51] and [57], respectively
SB1, SB2	Sugarcane bagasse in [49] and [60], respectively
SB1–SCG	Sugarcane bagasse (SB1) and spent coffee grounds (SCG) blend
SB2-char/starch/water	Sugarcane bagasse charcoal briquette
SCC	Semi-coke produced from cedar
SCGs	Spent coffee grounds
SCL	Semi-coke produced from larch

SCP	Semi-coke produced from pine
SFRs	Sunflower residues
SCGB-20	Spent coffee ground briquettes consisting of 20 wt.% carbonized spent coffee grounds, 71 wt.% bottom ash, 9 wt.% kaolinite, and 15 wt.% $Ca(OH)_2$ solution prepared at a water-to-$Ca(OH)_2$ ratio of 20/1
SH	Sunflower husk
SHC	Shenhua coal
ShC	Shubarcul coal
SHCC	Shenhua coal semi-char
SHCC–ST1	Shenhua coal semi-char (SHCC) and straw (ST1) blend
SH–CD	Sunflower husk and coke dust blend
SH–KC	Sunflower husk and Karazhyra coal blend
SH–ShC	Sunflower husk and Shubarcul coal blend
SL	Silantek medium rank coal
SLV	Sunflower leaves
SLV–KC	Sunflower leaves and Karazhyra coal blend
SLV–ShC	Sunflower leaves and Shubarcul coal blend
SNI	Indonesian National Standard
SRF	Solid Refuse Fuel Quality Standard
ST1, ST2	Straw in [24] and [26], respectively
STA	Simultaneous thermal analysis
Su	Sugarcane bagasse in [51]
TBs	Torrefied biomass pellets
T_b	The burnout temperature
t_b	Burnout time
T_i	The ignition temperature
t_i	Ignition time
TGA	Thermogravimetric analysis
TOSt	Torrefied olive stones
TR-303	RH5 after torrefaction at 300 °C for 30 min
TR-306	RH5 after torrefaction at 300 °C for 60 min
TR-309	RH5 after torrefaction at 300 °C for 90 min
TR-353	RH5 after torrefaction at 350 °C for 30 min
TR-356	RH5 after torrefaction at 350 °C for 60 min
TR-359	RH5 after torrefaction at 350 °C for 90 min
TR-403	RH5 after torrefaction at 400 °C for 30 min
TR-406	RH5 after torrefaction at 400 °C for 60 min
TR-409	RH5 after torrefaction at 400 °C for 90 min
TRCC-202	RCC after torrefaction at 200 °C for 20 min
TRCC-204	RCC after torrefaction at 200 °C for 40 min
TRCC-206	RCC after torrefaction at 200 °C for 60 min
TRCC-242	RCC after torrefaction at 240 °C for 20 min
TRCC-244	RCC after torrefaction at 240 °C for 40 min
TRCC-246	RCC after torrefaction at 240 °C for 60 min
TRCC-262	RCC after torrefaction at 260 °C for 20 min
TRCC-264	RCC after torrefaction at 260 °C for 40 min
TRCC-266	RCC after torrefaction at 260 °C for 60 min
TWCh	Torrefied woodchips
UB	Untreated biomass pellets
v_b	Burning rate
VP	Vine pruning residues
VP-300	Vine pruning residues after torrefaction at 300 °C
W	Wheat straw
WCh	Woodchips
WH	Water hyacinth
WH-char/starch/water	Water hyacinth charcoal briquette

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