Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 3	Month	: June
p-ISSN	: 1693-5462	Volume	: 24	Year	: 2026

Processing dates: received on 2026-01-25, reviewed on 2026-03-23, accepted on 2026-05-13 and online availability on 2026-06-30

Predictive efficiency analysis of biomass boilers using torrefied tropical fruit residues and washed wood waste

Hadi Prayitno*, Ricky Syahputra Tarigan, Ahmad Fauzan, Aryanda Fitrah Fardano, Muhammad Hlimy Assydiqie, Murtadho Agung Pratama
Department of Mechanical Engineering, University of Lampung,
Bandar Lampung 35145, Indonesia
*Corresponding Author: hadi.prayitno@eng.unila.ac.id

Abstract

Biomass-fired boilers are widely used in agro-industrial steam generation, yet their efficiency remains sensitive to fuel quality, boiler configuration, and the calorific value basis. This study developed a predictive thermal-efficiency assessment of four industrial biomass boilers, namely ZUG, Djaja Teknik, Vickers, and Isgec, by integrating biomass fuel characterisation, field operating data, and Hugot's direct-efficiency model. Its novelty lies in linking calorific-value changes in torrefied tropical fruit residues and distilled water-washed wood waste to boiler-specific operating parameters, rather than treating fuel upgrading as laboratory fuel improvement alone. Gross Calorific Value (GCV) was used as the primary basis for modelling, while NCV efficiency was calculated only when supporting fuel data were available. Baseline results showed GCV-based efficiencies of 77.12% for ZUG and 80.63-81.05% for Djaja Teknik, whereas Vickers and Isgec corresponded more closely to NCV-based efficiencies of 72.24% and 68.71–70.34%, respectively. Distilled water washing changed wood-waste GCV from 3,891-4,812 to 4,343-5,323 kcal/kg, with champaca increasing by approximately 21.6%. Torrefaction yielded higher GCV values of 6,519.28, 6,661.58, and 6,875.60 kcal/kg for coffee husk, cocoa shell, and mangosteen shell, respectively. Under fixed-flow Hugot assumptions, higher GCV increased fuel-energy input and could reduce numerical η_{GCV}, indicating model sensitivity rather than poorer fuel performance. The findings support SDGs 7, 12, and 13 through renewable heat assessment, biomass residue valorisation, and low-carbon energy pathways, while remaining limited to predictive boiler thermal efficiency.

Keywords:
Biomass boiler; torrefaction; washed wood waste; calorific value; Hugot model

1 Introduction

Biomass-fired boilers are widely used in agro-industrial steam generation because they enable the utilisation of locally available residues such as palm kernel shell, bagasse, fibre, rubber wood, and wood waste. In these systems, thermal efficiency is strongly influenced by fuel quality, particularly calorific value, moisture content, fuel consistency, fuel consumption rate, and boiler operating conditions [1], [2]. Low and variable biomass fuel quality reduces the effective heat input supplied to the boiler, increases fuel consumption per unit of steam produced, and lowers overall thermal performance [3], [4]. Therefore, evaluating the relationship between biomass fuel quality and boiler efficiency is essential for improving the performance of existing agro-industrial steam generation systems [5], [6].

Industrial boiler efficiency is not determined solely by calorific value, but by the interaction among fuel properties, steam generation rate, steam condition, feedwater condition, fuel flow rate, and boiler configuration. Fire-tube and water-tube boilers may exhibit different efficiency responses because they differ in heat-transfer characteristics, operating pressure, capacity, and combustion arrangement [7], [8]. For this reason, the present study evaluates four industrial boiler systems as baseline references, namely the ZUG fire-tube boiler, the Djaja Teknik fire-tube boiler, the Vickers water-tube boiler, and the Isgec water-tube boiler [9], [10]. These four boilers provide a comparative basis for assessing biomass boiler thermal efficiency across different industrial configurations and fuel types.

Fuel upgrading has been widely investigated as a practical strategy for improving the energy quality of biomass fuels. Torrefaction can increase biomass calorific value and energy density through controlled thermal treatment under oxygen-limited conditions, whereas distilled water washing can modify fuel quality by removing part of the water-soluble constituents and improving the relative contribution of combustible material [11], [12]. Previous studies have reported that torrefied biomass and washed biomass may exhibit improved fuel characteristics, particularly in terms of calorific value, fixed carbon content, and combustion-related fuel properties [13-19]. However, many of these studies remain focused on laboratory-scale fuel characterisation, pretreatment optimisation, reactor development, or simulation-based analysis, rather than linking experimentally measured fuel improvement with field-based boiler efficiency data [20], [21].

This limitation forms the specific research gap addressed in the present study. Although previous works have demonstrated that torrefaction and washing can improve biomass fuel properties, limited evidence exists on how these improvements affect predicted thermal efficiency in actual industrial boiler systems. In particular, few studies have integrated measured calorific value data with operational parameters from multiple industrial boilers, including steam flow rate, steam enthalpy, feedwater enthalpy, fuel consumption rate, boiler capacity, and recorded baseline efficiency. This integration is necessary because boiler efficiency is a system-level performance indicator and cannot be inferred solely from calorific-value improvements.

The novelty of this study lies in the integration of experimental characterisation of fuel calorific value, field-based operational data from four industrial boilers, and Hugot's direct efficiency model for predictive boiler efficiency analysis. Unlike previous studies that mainly examined torrefaction or washing as separate fuel-treatment processes, this study evaluates upgraded biomass fuels within an industrial boiler performance framework. The Gross Calorific Value (GCV) obtained from bomb calorimetry was used as the primary basis for efficiency prediction because it is directly measured and is commonly used in industrial boiler performance reporting. Net calorific value was additionally calculated and used as a supplementary sensitivity basis to examine the influence of calorific value basis on predicted boiler efficiency [22], [23].

Accordingly, this study aims to evaluate the thermal efficiency of biomass-fired industrial boilers using measured fuel calorific value data and field-based boiler operating parameters. The analysis covers four boiler systems: the ZUG fire-tube boiler fuelled by palm kernel shell, the Djaja Teknik fire-tube boiler fuelled by rubber wood, the Vickers water-tube boiler fuelled by fibre and shell, and the Isgec water-tube boiler fuelled by bagasse. The study further examines the predicted efficiency effect of substituting selected biomass fuels with torrefied tropical fruit residues and distilled water-washed wood waste. By integrating experimental fuel calorific value data with operational parameters from four industrial boilers, this study provides a focused and methodologically bounded assessment of biomass boiler thermal efficiency under industrially relevant conditions. Its contribution lies in clarifying how upgraded biomass fuels may affect predicted boiler performance, while explicitly limiting the interpretation to thermal efficiency rather than emissions, slagging, fouling, corrosion, maintenance behaviour, or economic feasibility.

2 Research methodology

2.1 Research design

This study adopted an experimental fuel characterisation and predictive boiler performance modelling approach to evaluate the effect of biomass fuel upgrading on the thermal efficiency of industrial boilers. The experimental stage quantified changes in calorific value resulting from torrefaction of tropical fruit residues and distilled water washing of wood waste, while the modelling stage incorporated these calorific value data with field-based boiler operating parameters, including steam flow rate, steam enthalpy, feedwater enthalpy, fuel consumption rate, and boiler configuration, into the Hugot direct efficiency model. Four industrial boilers were used as baseline references, namely ZUG, Djaja Teknik, Vickers, and Isgec. The predictive substitution analysis was conducted across all four boiler operating frameworks. The GCV obtained from bomb calorimetry was used as the primary basis for efficiency prediction because it is directly measured and commonly applied in industrial boiler performance reporting. In contrast, net calorific value was calculated as a supplementary sensitivity basis to represent usable thermal energy under non-condensing boiler operation [6], [8], [23], [24].

2.2 Biomass selection and sampling

The biomass materials consisted of tropical fruit residues and wood waste. The tropical fruit residues comprised coffee husk, cocoa shell, and mangosteen shell, selected for their regional availability and potential as upgraded solid biofuels. The wood waste samples consisted of eleven locally available species: white wood, mahogany, teak, champaca, bayur, sandalwood, acacia, kenam, alaban, damar, and merbau. All samples were obtained from local producers and wood-processing sources in the Bandar Lampung area [6].

Before treatment, the samples were air-dried to reduce initial moisture content and improve handling stability. The dried biomass was then cut, crushed, or milled to obtain a more uniform particle size, thereby reducing sample heterogeneity and improving the reproducibility of calorific value measurement. The tropical fruit residues were subsequently subjected to torrefaction, whereas the wood waste samples were treated using distilled water washing. The treated and untreated samples were then analysed by bomb calorimetry, and the resulting calorific value data were used as inputs for boiler efficiency prediction [25], [26].

2.3 Biomass Washing Procedure

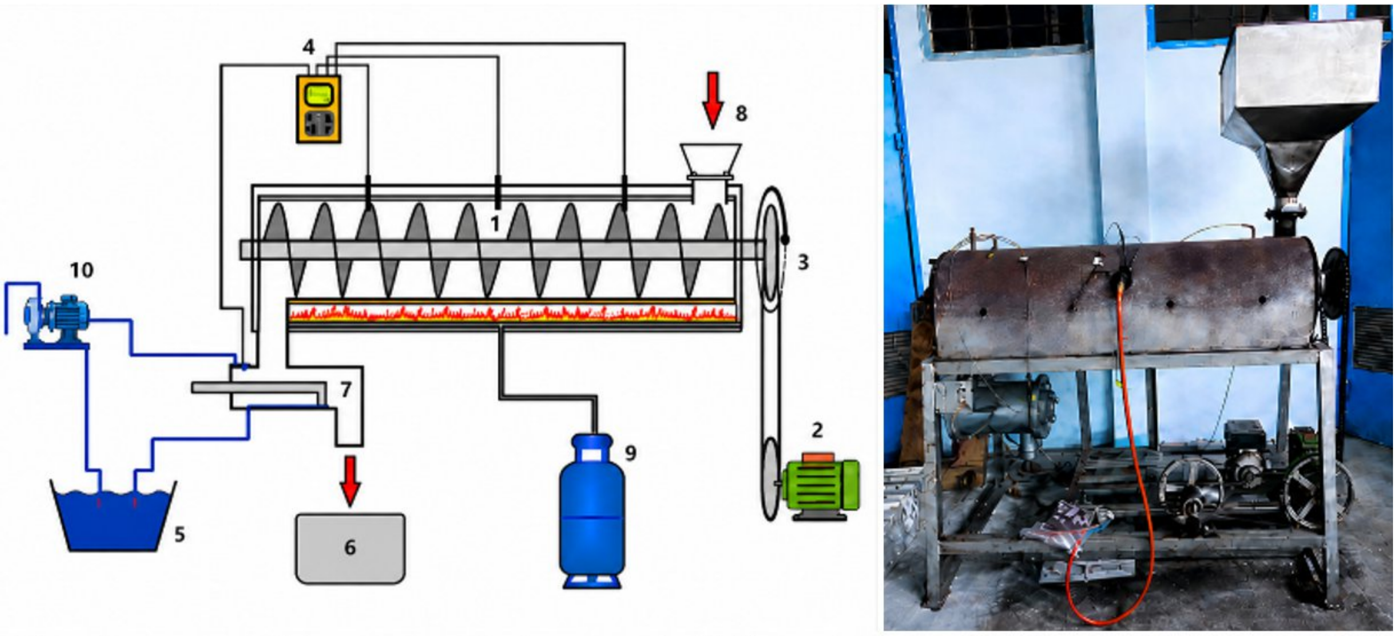
Distilled water washing was applied to the wood waste samples to reduce water-soluble inorganic constituents and improve fuel quality. This treatment was selected because alkali and alkaline earth metals, particularly potassium and sodium, may promote ash-related operational problems during biomass combustion, including fouling, slagging, and deposit formation [27], [28]. Previous studies have shown that washing or leaching can reduce soluble inorganic fractions and suppress ash-related risks in biomass combustion systems [29].

The washing procedure was performed by immersing the wood waste samples in distilled water at a biomass-to-water ratio of 1:10 for 4 h at approximately 27°C under continuous stirring [6], [30]. The samples were then filtered and oven-dried at 50°C until constant mass was achieved. Calorific value testing was conducted before and after washing to determine the effect of distilled water washing on fuel energy quality. The resulting GCV values were incorporated into the main Hugot efficiency model because HHV/GCV is commonly used in industrial boiler performance reporting and was the most consistently available basis in the baseline datasets. NCV-based efficiency was not estimated for the wood-waste substitution scenarios because complete hydrogen and moisture data were unavailable, thereby avoiding unsupported NCV conversion.

2.4 Biomass torrefaction procedure

Torrefaction was applied to coffee husk, cocoa shell, and mangosteen shell to enhance their quality as solid biomass fuels. The process was conducted under oxygen-limited conditions to prevent direct combustion while enabling controlled thermal decomposition, partial devolatilisation, moisture reduction, and carbon enrichment [13], [31]. Torrefaction is widely recognised as an effective biomass pretreatment method for increasing energy density, improving hydrophobicity and grindability, and enhancing the stability of solid biofuels [12], [32].

The torrefaction process was carried out using a temperature-controlled tubular reactor. The installation used in this study is shown in Fig. 1.



The main components of the reactor comprise the reactor tube (1), biomass feed hopper (8), drive system (electric motor and gear reducer) (2,3), LPG burner as the heat source (9), temperature recording system (data logger with K-type thermocouple sensor) (4), cooling-char system (5,7,10), and torrefaction product collection container (6).

Fig. 1. (a) Schematic representation of the tubular-type oil-jacket-heated torrefaction reactor; (b) photograph of the tubular-type oil-jacket-heated torrefaction reactor [13], [14]

Coffee husk and cocoa shell were torrefied at 275°C, whereas mangosteen shell was torrefied at 300°C. These conditions were selected based on previous findings indicating that coffee and cocoa residues achieve favourable fuel characteristics at approximately 275°C. At the same time, mangosteen shells require higher temperatures to improve thermal stability and reduce moisture-related limitations [13], [14]. After torrefaction, the samples were cooled, sealed, and prepared for calorific value testing. Their measured GCV values were used as the primary model inputs to ensure a consistent calorific-value basis across the predictive efficiency scenarios. This approach also aligns with industrial boiler performance reporting, in which GCV is commonly used for datasheet comparison and performance assessment, while NCV-based interpretation is retained as a supplementary net-energy perspective where applicable.

2.5 Determination of gross and net calorific values

The GCV of the biomass samples was determined using an Oxygen Bomb Calorimeter BK-1A+, as shown in Fig. 2, in accordance with ASTM D5865. The tested samples included untreated and distilled water-washed wood waste, as well as torrefied coffee husk, cocoa shell, and mangosteen shell. Prior to calorimetric testing, the samples were dried and pelletised to improve uniformity in mass, shape, and combustion behaviour. Each sample was tested in triplicate to improve data reliability and minimise experimental variation [14].

Fig. 2. Oxygen bomb calorimeter BK-1A+ [14]

The measured GCV values were used as the primary basis for calorific value in the Hugot direct efficiency model because GCV is directly obtained from bomb calorimetry and is widely used in fuel characterisation, boiler datasheets, industrial performance assessment, and guarantee testing. However, because most industrial biomass boilers operate under non-condensing conditions, NCV was also calculated to estimate the practically usable heat after excluding the latent heat associated with water vapour formed during combustion.

The NCV is estimated as Eq. (1), where NCV and GCV are expressed in MJ/kg, H is the hydrogen mass fraction of the fuel, M is the moisture mass fraction, and 2.442 MJ/kg is the latent heat of water evaporation under standard conditions [23].

$$NCV = HHV - 2.442(9H + M) \tag{1}$$

For fuel scenarios in which hydrogen and moisture data were unavailable or incomplete, the efficiency calculation was retained on a GCV basis to avoid unsupported NCV assumptions. Accordingly, NCV-based efficiency was treated as a supplementary sensitivity indicator rather than as the principal basis for comparing all biomass substitution scenarios. All calorific values were converted to a consistent energy unit before being used in the efficiency equations. The GCV values were used to calculate η_{GCV}, whereas the NCV values were used to calculate η_{NCV}.

2.6 Boiler performance prediction using the hugot direct efficiency method

Boiler efficiency was predicted using the Hugot direct efficiency method, which compares the useful heat absorbed by steam with the thermal energy supplied by fuel. The method is suitable for biomass-fired boiler analysis because it uses operational variables commonly available in industrial systems, including steam flow rate, steam condition, feedwater condition, fuel consumption rate, and fuel calorific value [8]. Although originally developed for bagasse-fired boilers, the method was adapted in this study for palm kernel shell, torrefied tropical fruit residues, and distilled water-washed wood waste by substituting the calorific value of each fuel scenario while maintaining the same boiler operating framework [23].

The general direct efficiency is expressed as Eq. (2), where the heat absorbed by the steam is expressed as Eq. (3).

$$\eta = \frac{Q_{steam}}{Q_{fuel}} \times 100\% \tag{2}$$

$$Q_{steam} = \dot{m}_{steam}\left(h_g - h_f\right) \tag{3}$$

For the primary GCV-based model, Eqs. (4) and (5) can be used.

$$Q_{fuel,\ GCV} = \dot{m}_{fuel} \times GCV \tag{4}$$

$$\eta_{GCV} = \frac{\dot{m}_{steam} \times \left(h_g - h_f\right)}{\dot{m}_{fuel} \times GCV} \times 100\% \tag{5}$$

For the supplementary NCV-based sensitivity analysis, Eqs. (6) and (7) can be used.

$$Q_{fuel,\ NCV} = \dot{m}_{fuel} \times NCV \tag{6}$$

$$\eta_{NCV} = \frac{\dot{m}_{steam} \times \left(h_g - h_f\right)}{\dot{m}_{fuel} \times NCV} \times 100\% \tag{7}$$

where η is boiler efficiency (%), Q_{steam} is total heat energy absorbed by water vapour, Qf_{uel} is heat energy of combustion products, hg is enthalpy of steam leaving the boiler (kJ/kg), hf is enthalpy of water entering the boiler (kJ/kg), $\dot{m}$ is mass flow rate (kg/hour), GCV is gross calorific value of fuel (kJ/kg), and NCV is net calorific value of fuel (kJ/kg).

The GCV-based efficiency was used as the primary performance indicator because it aligns with bomb calorimetric testing and industrial boiler performance reporting. The NCV-based efficiency was used only as a supplementary sensitivity indicator because it reflects net usable heat during non-condensing boiler operation. Since NCV is lower than GCV, η_{NCV} is generally higher than η_{GCV}. Therefore, both values were reported separately to avoid ambiguity in interpretation.

2.7 Boiler baseline cases and data analysis

The boiler operational data comprised steam flow rate, steam pressure and temperature, feedwater temperature, fuel consumption rate, fuel type, boiler capacity, and recorded baseline efficiency. Four industrial biomass-fired boilers were used as baseline cases: the ZUG fire-tube boiler fuelled by palm kernel shell, the Djaja Teknik fire-tube boiler fuelled by rubber wood, the Vickers water-tube boiler fuelled by fibre and shell, and the Isgec water-tube boiler fuelled by bagasse. These four boilers were selected to provide comparative operating contexts across different boiler configurations, capacities, and biomass fuel types. The inclusion of both fire-tube and water-tube systems enabled the analysis to evaluate how boiler thermal efficiency varied under distinct industrial operating conditions.

The data analysis was conducted in four stages. First, the GCV values of the biomass samples were obtained from bomb calorimetry, and the corresponding NCV values were calculated for supplementary sensitivity analysis. Second, the baseline efficiency of each boiler was calculated using the Hugot direct-efficiency method and compared with the recorded field efficiency to assess the suitability of the model under actual operating conditions. Third, the baseline fuel calorific values were replaced with the GCV values of torrefied tropical fruit residues and distilled water-washed wood waste to predict the effect of fuel upgrading on boiler thermal efficiency. Fourth, where NCV data or sufficient hydrogen and moisture data were available, NCV-based efficiency was calculated as a supplementary sensitivity indicator. For substitution scenarios with incomplete fuel-composition data, the analysis was retained on a GCV basis. This modelling strategy enabled a systematic comparison between GCV-based efficiency as the main industrially relevant indicator and NCV-based efficiency as a supplementary usable-energy interpretation [33].

In all predictive scenarios, the boiler operating parameters were held constant to isolate the effect of fuel calorific value. Thus, the model was not intended to simulate complete combustion dynamics, transient load variation, air–fuel ratio adjustment, heat-loss distribution, or operational degradation. Rather, it provided a comparative thermodynamic assessment of how improved biomass calorific value may influence predicted boiler efficiency under defined baseline operating conditions.

The analytical scope was deliberately confined to boiler thermal efficiency. The study did not include direct measurement or modelling of flue gas composition, exhaust emissions, ash deposition, slagging, fouling, corrosion, maintenance frequency, or economic feasibility. Accordingly, the results should be interpreted as a predictive efficiency assessment based on fuel calorific value and boiler operating data, rather than as a comprehensive combustion, environmental, maintenance, or techno-economic evaluation.

3 Results and discussion

3.1 GCV of untreated and pretreated biomass fuels

The GCV analysis provided the primary fuel-quality basis for the subsequent boiler efficiency prediction. The investigated biomass fuels were grouped into two pretreatment categories: distilled water-washed wood waste and torrefied tropical fruit residues. For the wood waste samples, distilled water washing generally increased the GCV relative to the untreated condition, although the magnitude of improvement varied among species. The untreated wood waste samples exhibited GCV values ranging from 3,891 to 4,812 kcal/kg, whereas the distilled water-washed samples ranged from 4,343 to 5,323 kcal/kg. The highest post-washing GCV was observed for champaca wood, increasing from 4,377 to 5,323 kcal/kg. By contrast, sandalwood decreased from 4,759 to 4,511 kcal/kg after washing, indicating that the calorific response to distilled water washing was species-specific rather than uniform across all wood biomass types. This species-dependent response is consistent with previous findings that water-based pretreatment may alter biomass fuel quality by removing soluble inorganic constituents. However, the final effect depends on the initial composition of each biomass material [27], [28].

The torrefied tropical fruit residues exhibited substantially higher GCV values than the wood waste samples. Coffee husk and cocoa shell torrefied at 275°C reached 6,519.28 and 6,661.58 kcal/kg, respectively, while mangosteen shell torrefied at 300°C reached 6,875.60 kcal/kg [6], [13]. These values were adopted as the GCV inputs for the torrefied biomass scenarios in the boiler efficiency model. The higher calorific values of the torrefied residues are consistent with the thermal upgrading effect of torrefaction, in which controlled heating promotes moisture reduction, partial devolatilisation, hemicellulose decomposition, and carbon enrichment of the biomass matrix [12], [14].

In the present analysis, the terms “untreated” and “pretreated” were used to distinguish the treatment condition of each biomass fuel. For wood waste, the pretreated condition refers to distilled water washing, whereas for tropical fruit residues it refers to torrefaction at the selected operating temperature. This classification ensures that the calorific value data are interpreted as treatment-based fuel-quality parameters rather than as moisture-basis categories.

The GCV data in Table 1 show two distinct fuel-quality responses. Distilled water washing produced moderate and species-dependent changes in the calorific value of wood waste, while torrefaction produced substantially higher GCV values in tropical fruit residues.

These measured GCV values were subsequently used as the main calorific value inputs in the Hugot direct efficiency model. For the wood waste scenarios, untreated and distilled water-washed GCV values were compared across the four boiler models. For the tropical fruit residue scenarios, the torrefied GCV values were applied to evaluate the effect of thermally upgraded biomass on predicted boiler efficiency [6], [34].

Table 1. GCV of untreated and pretreated biomass fuels [6], [13]

No.	Biomass type	Untreated GCV (kcal/kg)	Pretreated GCV (kcal/kg)	Pretreatment condition
1	White wood	3,891	4,343	Distilled water washing
2	Mahogany	4,313	4,362	Distilled water washing
3	Teak	4,654	4,959	Distilled water washing
4	Champaca	4,377	5,323	Distilled water washing
5	Bayur	4,353	4,403	Distilled water washing
6	Sandalwood	4,759	4,511	Distilled water washing
7	Acacia	4,039	4,490	Distilled water washing
8	Kenam	4,721	4,751	Distilled water washing
9	Alaban	4,369	4,511	Distilled water washing
10	Damar	4,369	4,467	Distilled water washing
11	Merbau	4,812	4,888	Distilled water washing
12	Coffee husk	4,495	6,519	Torrefaction
13	Cocoa shell	4,236	6,661	Torrefaction
14	Mangosteen shell	5,656	6,875	Torrefaction

3.2 Baseline boiler efficiency using existing fuels

Baseline boiler efficiency was calculated using the existing fuel for each industrial boiler to establish the thermodynamic reference for the subsequent biomass substitution scenarios, as summarised in Fig. 3. The assessment covered the ZUG fire-tube boiler fuelled by palm kernel shell, the Djaja Teknik fire-tube boiler fuelled by rubber wood, the Vickers water-tube boiler fuelled by a 70% fibre and 30% shell mixture, and the Isgec water-tube boiler fuelled by bagasse. The calculation was primarily performed on a GCV basis because GCV was the most consistently available calorific-value basis across the datasets and was adopted as the principal input in the Hugot direct efficiency model. NCV-based efficiency was calculated only when NCV data, or sufficient hydrogen and moisture data for NCV estimation, were available; accordingly, no NCV-based efficiency was reported for Djaja Teknik because the available dataset lacked complete supporting fuel-composition data. For Vickers, the available fuel data included both GCV and NCV, allowing both η_{GCV} and η_{NCV} to be calculated.

The baseline results in Fig. 3 show that the reported field efficiency was not always expressed on the same calorific-value basis. For ZUG, the calculated η_{GCV} was 77.12%, closely matching the reported field efficiency of 77.00%, whereas recalculation on an

NCV basis increased the value to 91.98%. For Djaja Teknik, the GCV-based efficiency ranged from 80.63% to 81.05%, consistent with the reported operating range of approximately 80.00–81.00%. For Vickers, the GCV-based calculation yielded 60.70%, while the NCV-based calculation yielded 72.24%, closely corresponding to the reported value of 72.20%. A similar pattern was observed for Isgec, with η_{GCV} ranging from 54.91% to 55.92%, whereas η_{NCV} ranged from 68.71% to 70.34%. The Vickers dataset explicitly reports the 70% fibre and 30% shell fuel mixture and its NCV basis, supporting the inclusion of η_{NCV} for this boiler.

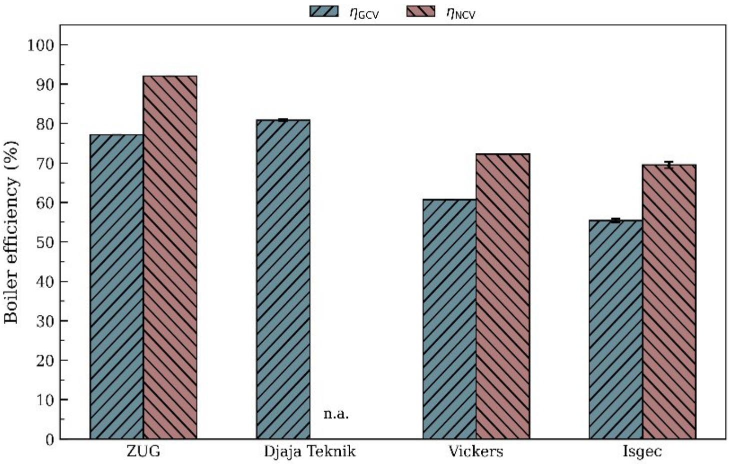


Fig. 3. Baseline efficiencies of the investigated industrial boilers using existing fuels on GCV and NCV bases

These findings indicate that boiler efficiency is not a single transferable value, but a thermodynamic outcome shaped by calorific-value basis, fuel consumption rate, steam production rate, enthalpy rise, and boiler configuration. The distinction between η_{GCV} and η_{NCV} is therefore essential: η_{GCV} provides the main comparable basis for predictive modelling, while η_{NCV} is reported only when the available fuel data support its calculation. Fig. 3 consequently provides the baseline framework for evaluating distilled water-washed wood waste and torrefied tropical fruit residues under boiler-specific operating conditions, without imposing unsupported NCV assumptions on fuels for which hydrogen, moisture, or NCV data are unavailable.

3.3 Predicted effect of distilled water-washed wood waste on boiler efficiency

The effect of distilled water-washed wood waste on boiler efficiency was evaluated by applying the GCV values of untreated and washed wood samples to the Hugot direct efficiency model under the operating conditions of the four baseline boilers. Because complete hydrogen and moisture data were not consistently available for all wood species, the analysis was restricted to GCV-based efficiency, η_{GCV}. As shown in Figs. 4 to 7, the paired untreated–washed comparison was performed for eleven wood species in the ZUG, Djaja Teknik, Vickers, and Isgec boilers. This structure enabled the treatment effect to be interpreted within each boiler-specific operating framework while avoiding unsupported NCV assumptions.

Across the four boilers, the calculated efficiency varied markedly with boiler configuration and operating condition. For untreated wood waste, the predicted η_{GCV} ranged from 65.66–81.20% in the ZUG boiler, 70.78–87.54% in the Djaja Teknik boiler, 61.10–75.56% in the Vickers boiler, and 26.81–33.16% in the Isgec boiler. After distilled water washing, the corresponding ranges became 59.36–72.75%, 63.99–78.43%, 55.23–67.70%, and 24.24–29.71%, respectively. The highest calculated efficiency across the entire wood-waste scenario was obtained in the Djaja Teknik boiler using untreated white wood, at 87.54%, while the highest value after washing was also found in the Djaja Teknik boiler using washed white wood, at 78.43%. The lowest values were consistently produced by the Isgec model, with washed champaca giving the minimum predicted efficiency of 24.24%.

Averaged across all eleven wood species, distilled water washing changed the predicted η_{GCV} from 71.73% to 68.40% in ZUG, from 77.32% to 73.73% in Djaja Teknik, from 66.74% to 63.64% in Vickers, and from 29.29% to 27.93% in Isgec. These correspond to average reductions of 3.33, 3.59, 3.10, and 1.36 percentage points, or approximately 4.42–4.43% relative to the untreated condition. The largest decrease occurred for champaca wood, whose substantial GCV increase after washing produced the greatest change in the efficiency denominator, reducing the predicted η_{GCV} by 12.83 percentage points in ZUG, 13.83 percentage points in Djaja Teknik, 11.94 percentage points in Vickers, and 5.24 percentage points in Isgec. Conversely, sandalwood showed an opposite trend: its GCV decreased after washing, and the calculated η_{GCV} increased by 3.65, 3.94, 3.39, and 1.49 percentage points in the ZUG, Djaja Teknik, Vickers, and Isgec boilers, respectively.

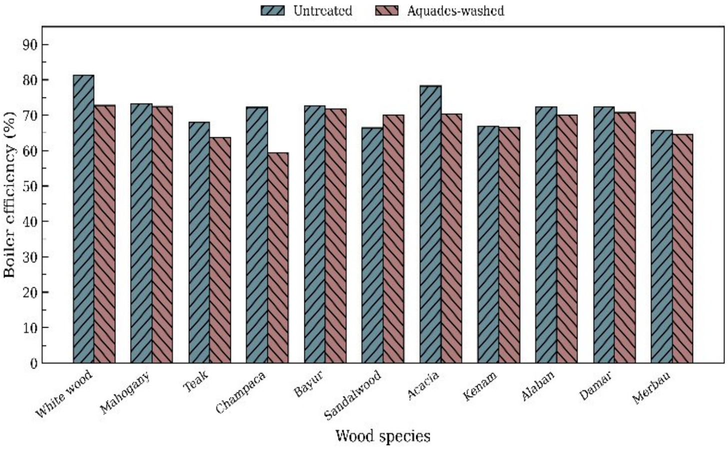


Fig. 4. Predicted GCV-based boiler efficiencies of untreated and distilled water-washed wood waste in the ZUG fire-tube boiler

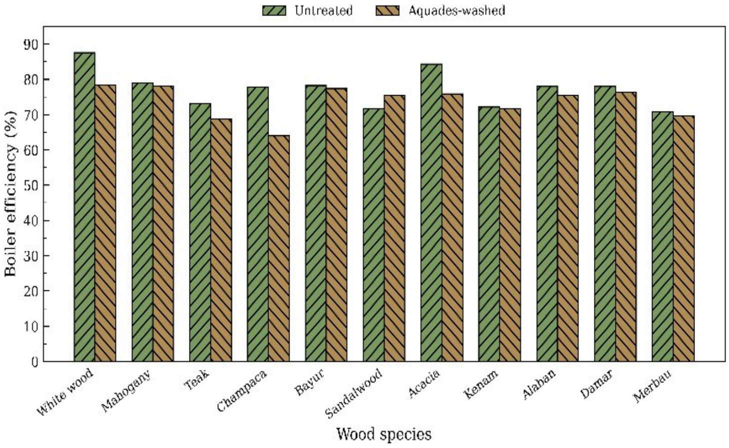


Fig. 5. Predicted GCV-based boiler efficiencies of untreated and distilled water-washed wood waste in the Djaja Teknik fire-tube boiler

The species-specific response suggests that distilled water washing modifies wood waste as a fuel through competing physicochemical mechanisms. In most wood species, washing likely removed part of the water-soluble inorganic fraction, including alkali and alkaline earth metals such as potassium and sodium, as well as soluble ash-forming compounds. The removal of these non-combustible mineral constituents can increase the relative proportion of combustible organic matter and improve the measured calorific value of the fuel. Similar effects have been reported in biomass washing and leaching studies, where water-based pretreatment reduced soluble inorganic fractions and improved selected combustion-related fuel characteristics [35], [36]. In practical boiler operation, such an improvement may be beneficial because cleaner, higher-quality fuel can reduce inert mineral loading, support more stable heat release, and potentially lower the fuel mass required to maintain a given steam duty.

However, the calculated efficiency trend in Figs. 4 to 7 must be interpreted within the mathematical structure of the Hugot direct method. In this predictive scenario, steam output, fuel flow rate, and enthalpy rise were held within the baseline operating framework, while only the fuel GCV was substituted. Under this fixed-flow assumption, an increase in GCV raises the calculated fuel-energy input in the denominator; consequently, the numerical η_{GCV} may decrease even though the washed biomass has a higher fuel quality. Therefore, the apparent reduction in η_{GCV} for most washed samples does not imply that distilled water washing is detrimental to boiler operation. Rather, it indicates that the present calculation isolates the sensitivity of boiler efficiency to calorific-value substitution. Operational efficiency gains would be expected only if the boiler responds to the higher-quality washed fuel by reducing fuel consumption, improving combustion stability, or increasing useful steam output. Thus, the primary effect of distilled water washing in this study is best understood as a fuel-quality modification, with boiler-level implications that depend on how the operating system adjusts to the upgraded biomass.

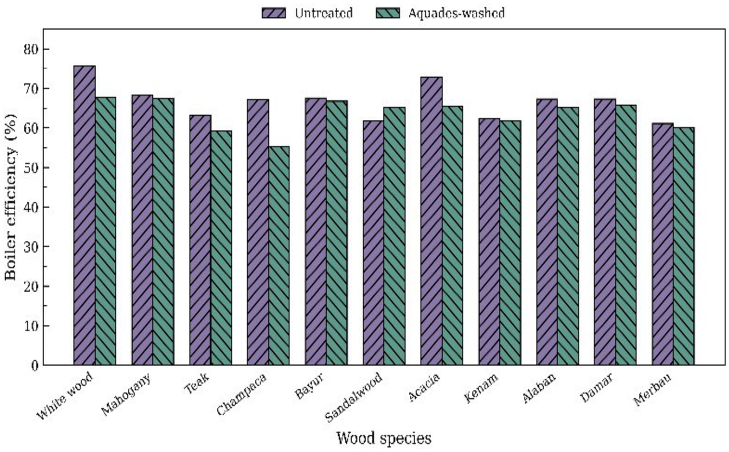


Fig. 6. Predicted GCV-based boiler efficiencies of untreated and distilled water-washed wood waste in the Vickers water-tube boiler

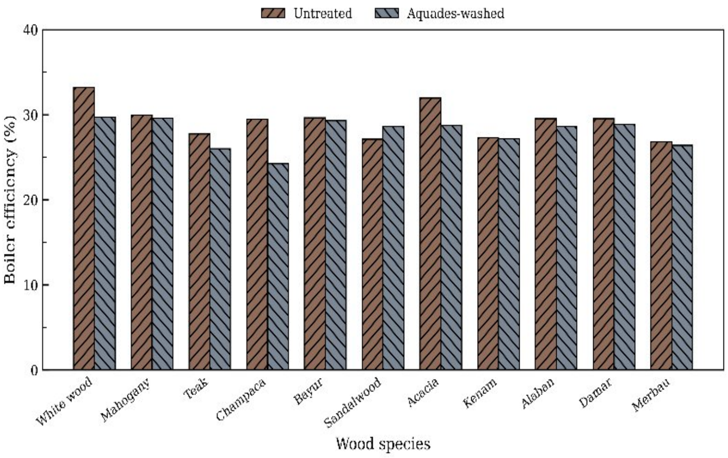


Fig. 7. Predicted GCV-based boiler efficiencies of untreated and distilled water-washed wood waste in the Isgec water-tube boiler

3.4 Predicted effect of torrefaction of tropical fruit residues on boiler efficiency

The effect of torrefaction on boiler efficiency was evaluated by substituting the GCV of raw tropical fruit residues with that of their torrefied counterparts in the Hugot direct-efficiency model under the fixed operating conditions of the four baseline boilers. Because complete hydrogen and moisture data were not available for all torrefaction cases, the analysis was confined to the GCV basis. The torrefied GCV values of coffee husk, cocoa shell, and mangosteen shell were taken from [6]. In contrast, the corresponding raw values were inferred from the same study using the reported calorific-value profile and energy-density ratios. As presented in Figs. 8 to 11, this framework isolates the effect of calorific-value upgrading on the calculated η_{GCV} while preserving boiler-specific steam duty, fuel-flow structure, enthalpy rise, and configuration.

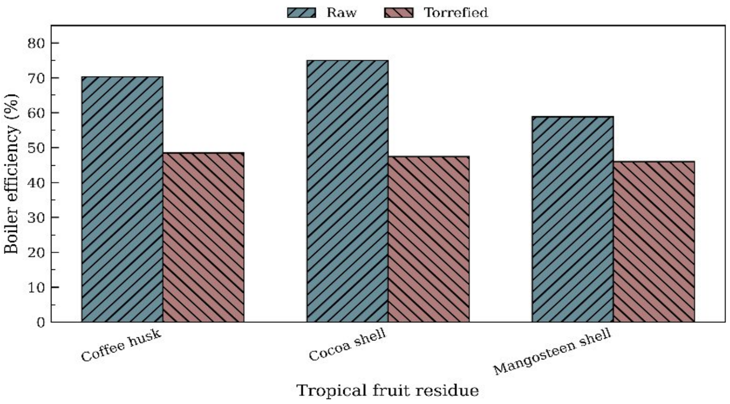


Fig. 8. Predicted GCV-based boiler efficiencies of raw and torrefied tropical fruit residues in the ZUG fire-tube boiler

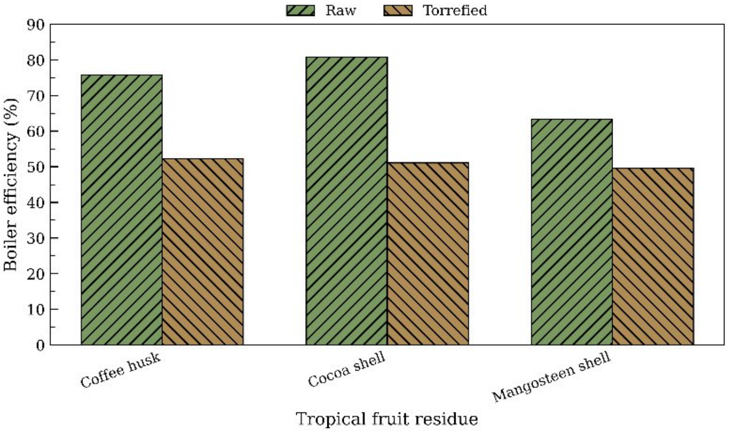


Fig. 9. Predicted GCV-based boiler efficiencies of raw and torrefied tropical fruit residues in the Djaja Teknik fire-tube boiler

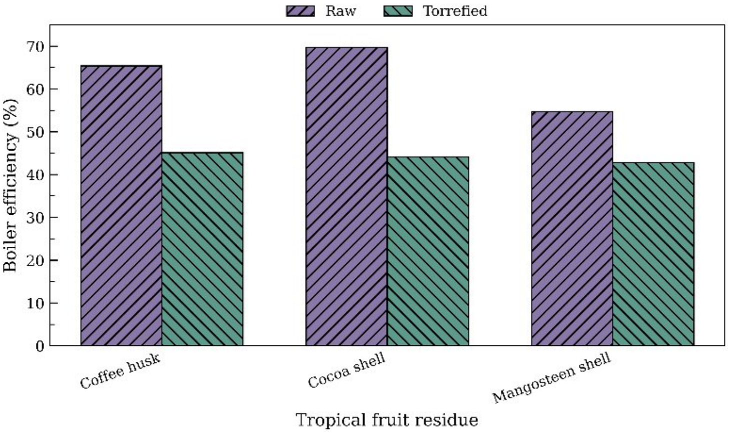


Fig. 10. Predicted GCV-based boiler efficiencies of raw and torrefied tropical fruit residues in the Vickers water-tube boiler

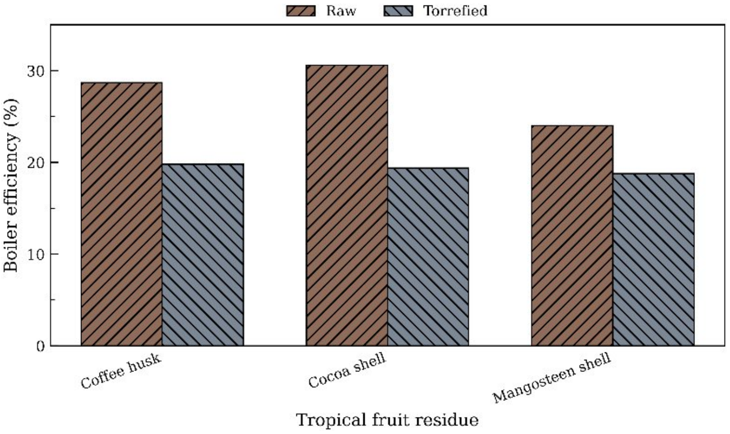


Fig. 11. Predicted GCV-based boiler efficiencies of raw and torrefied tropical fruit residues in the Isgec water-tube boiler

A clear and consistent pattern emerged across all four boilers. For the raw residues, the η_{GCV} ranged from 58.82–74.94% in ZUG, 63.41–80.79% in Djaja Teknik, 54.73–69.73% in Vickers, and 24.02–30.60% in Isgec. After torrefaction, these ranges decreased to 45.95–48.46%, 49.54–52.25%, 42.76–45.10%, and 18.77–19.79%, respectively. The highest calculated efficiency in the raw-biomass scenario was obtained in the Djaja Teknik boiler with raw cocoa shell (80.79%). In contrast, the highest value after torrefaction was observed in the Djaja Teknik boiler with torrefied coffee husk (52.25%). At the opposite end, the lowest values were consistently produced by the Isgec boiler, with torrefied mangosteen shell giving the minimum predicted efficiency of 18.77%. In relative terms, torrefaction reduced the calculated η_{GCV} by approximately 31.03% for coffee husk, 36.71% for cocoa shell, and 21.88% for mangosteen shell across all four boilers, indicating that cocoa shell exhibited the largest numerical sensitivity to torrefaction, whereas mangosteen shell exhibited the smallest.

This apparently counter-intuitive decline in calculated efficiency does not indicate that torrefaction worsens fuel quality; rather, it reflects the mathematical structure of the GCV-based Hugot model. Under the fixed-flow assumption adopted here, a higher GCV enlarges the denominator of the efficiency equation and therefore lowers the numerical η_{GCV}, even though the fuel itself has been upgraded. In practical terms, torrefaction is well known to improve biomass as a fuel by reducing moisture, increasing carbon concentration and energy density, lowering the O/C ratio, improving hydrophobicity and grindability, and often promoting a more stable combustion behaviour [6], [14]. Hence, the lower η_{GCV} values in Figs. 8 to 11 should be interpreted as a controlled thermodynamic sensitivity to calorific-value substitution, not as evidence of poorer operational performance. In an actual boiler, the upgraded torrefied fuel could instead reduce fuel consumption, improve combustion stability, or sustain steam production more effectively; such dynamic operational adjustments, however, were beyond the scope of the present predictive model.

3.5 Comparative interpretation of fuel-quality scenarios

The results from Sections 3.1–3.4 show that biomass pretreatment influences predicted boiler efficiency through its effect on fuel calorific value, although the numerical response depends on the structure of the Hugot direct-efficiency model. Under the fixed operating assumptions used in this study, steam output, fuel flow rate, and enthalpy rise were held constant. In contrast, the GCV of each fuel scenario was substituted into the model. Consequently, an increase in GCV enlarges the fuel-energy denominator and may reduce the calculated η_{GCV}, even when the fuel itself has been upgraded. This explains why several distilled water-washed and torrefied biomass scenarios produced lower numerical efficiencies despite showing improved fuel quality. The result should therefore be interpreted as a controlled thermodynamic sensitivity to calorific-value substitution, rather than as evidence that fuel upgrading reduces practical boiler performance.

The distilled water-washing results confirm that water-based pretreatment produces species-dependent changes in the quality of wood-waste fuel. This agrees with previous studies showing that biomass washing or leaching can remove soluble inorganic constituents, particularly alkali and alkaline earth metals such as K, Na, Ca, and Mg, as well as other ash-forming compounds [15], [27]. By reducing part of the inert mineral fraction, washing may increase the relative contribution of combustible organic matter and improve selected fuel characteristics. Torrefaction produced a stronger fuel-quality modification, consistent with studies reporting that controlled thermal treatment decomposes hemicellulose, reduces moisture and oxygenated volatiles, increases carbon concentration, and improves energy density [19], [37]. In practical boiler operation, these upgraded fuel properties may be expressed not simply as a higher calculated efficiency at constant fuel flow, but as lower fuel consumption, more stable heat release, or improved fuel handling under adjusted operating conditions.

From a broader sustainability perspective, the use of distilled water-washed wood waste and torrefied tropical fruit residues supports the valorisation of underutilised biomass streams within existing agro-industrial energy systems. This is closely aligned with SDG 7 by contributing to renewable and locally available bioenergy options, SDG 12 by promoting the responsible use of agricultural and wood-processing residues, and SDG 13 by strengthening biomass-based pathways that may reduce dependence on fossil-derived heat, although direct emission reductions were not quantified in this study. It also relates to SDG 2 because the approach improves the circular use of residues from food and agro-industrial value chains without relying on edible biomass fractions [13]. Within this boundary, the study demonstrates that fuel upgrading should be understood as both a material-level improvement and a boiler-specific thermodynamic scenario, whose efficiency implications depend on the interactions among calorific value, fuel consumption rate, steam generation, enthalpy rise, and boiler configuration [38].

4 Conclusions

This study confirms that biomass boiler efficiency is determined by the interactions among calorific value, fuel flow rate, steam generation, enthalpy rise, calorific-value basis, and boiler configuration. GCV provided the most consistent basis for comparative prediction across the four boilers, while NCV was applied only where supporting fuel data were available. Distilled water washing modified the wood-waste fuel quality in a species-dependent manner; for example, champaca wood increased from 4,377 to 5,323 kcal/kg after washing, equivalent to approximately 21.6%, although under the fixed-flow Hugot model, this higher GCV reduced the calculated η_{GCV} because the fuel-energy input denominator increased. Torrefaction produced a stronger fuel-upgrading effect, with cocoa shell reaching 6,661.58 kcal/kg at 275°C, and showing the largest model sensitivity, with an average predicted η_{GCV} reduction of approximately 36.71% under constant steam output and fuel flow assumptions. These reductions therefore indicate thermodynamic sensitivity to calorific-value substitution, rather than poorer fuel performance. The findings support SDG 7 through biomass-based renewable thermal energy, SDG 12 through residue valorisation, and SDG 13 through pathways that may reduce dependence on fossil-derived heat, although emissions were not directly assessed. Future studies should incorporate adjusted fuel feed rates, combustion trials, flue gas analysis, ash chemistry, slagging–fouling assessment, long-term boiler operation, and techno-economic evaluation to verify the practical performance of washed and torrefied biomass under industrial conditions.

Acknowledgment

The authors gratefully acknowledge the financial support provided by the Institute for Research and Community Service (LPPM), University of Lampung, through BLU funding under Contract No. 2022/UN26.21/PN/2025.

References

[1] S. E. Ibitoye, R. M. Mahamood, T. Jen, C. Loha, and E. T. Akinlabi, “An overview of biomass solid fuels : Biomass sources , processing methods , and morphological and microstructural properties,” *J. Bioresour. Bioprod.*, vol. 8, no. 4, pp. 333–360, 2023, doi: 10.1016/j.jobab.2023.09.005.

[2] W. Sun *et al.*, “Simulation Study on Coal and Ammonia Co-Firing in a Tangential Firing Boiler Under Different Ammonia Injection Methods,” *Sci. Rep.*, 2025, doi: 10.1038/s41598-025-98792-5.

[3] A. Alifatul *et al.*, “South African Journal of Chemical Engineering Engineering study of coal co-firing based on biomass mixture and slagging-fouling control in the steam power plant,” *South African J. Chem. Eng.*, vol. 55, no. May 2024, pp. 191–221, 2026, doi: 10.1016/j.sajce.2025.11.008.

[4] Y. Cheng *et al.*, "Design of the Control and Remote Monitoring Energy System Based on an Embedded Biomass Boiler," *Front. Energy Res.*, 2024, doi: 10.3389/fenrg.2024.1434112.

[5] M. Obradović, N. Karličić, D. Todorović, D. Radić, and A. Jovović, "Experimental Studies of Wood Chips Charactristics Influence on Boiler Performance and Pollutant Emissions," *Therm. Sci.*, 2023, doi: 10.2298/tsci2301121o.

[6] H. Prayitno, H. Rustamaji, Y. Arafat, and A. Darma, "Thermochemical-Mechanical Assessment of Washed and Torrefied Biomass Co-Firing in Boilers for a Sustainable Energy Transition," vol. 7, no. 1, pp. 99–116, 2026, doi: 10.46456/jisdep.v7i1.1010.

[7] M. Elwardany, "Enhancing steam boiler efficiency through comprehensive energy and exergy analysis : A review," *Process Saf. Environ. Prot.*, vol. 184, no. January, pp. 1222–1250, 2024, doi: 10.1016/j.psep.2024.01.102.

[8] D. Suntoro, P. Sinaga, R. C. Yudanto, and Faridha, "Energy Efficiency and Energy Saving Potential Analysis of Biomass Boiler at the PT Greenfields Indonesia Milk Processing Plant," *Iop Conf. Ser. Earth Environ. Sci.*, 2022, doi: 10.1088/1755-1315/1034/1/012012.

[9] M. Z. U. Haq and H. M. Masood, "Performance enhancement of an industrial fire tube boiler", JPIChE, vol. 48, no. 1, pp. 43–48, Nov. 2022. https://doi.org/10.54693/piche.04815

[10] H. Prayitno, T. O. Ba'albaqi, M. D. Susila, and Harmen, "The Effect of Bagasse Waste Quality as Biomass Fuel on The Efficiency of Water Tube-Type Boilers", Anal. Environ. Chem., vol. 9, no. 01, pp. 140–150, Sep. 2024. https://doi.org/10.23960/analit.v9i01.162

[11] S. Guo, X. Deng, D. Zhao, S. Zhu, H. Qu, and X. Li, "An Optimized Method for Evaluating the Preparation of High-Quality Fuel from Various Types of Biomass through Torrefaction," Molecules 2024, 29(8), 1889; https://doi.org/10.3390/molecules29081889

[12] J. S. Tumuluru, B. Ghiasi, N. R. Soelberg, and S. Sokhansanj, "Biomass Torrefaction Process , Product Properties , Reactor Types , and Moving Bed Reactor Design Concepts," vol. 9, no. September, pp. 1–20, 2021, doi: 10.3389/fenrg.2021.728140.

[13] H. Prayitno, Amrul, R. Lestari, and R. Kurniawansah, "Potential Torrefaction of Tropical Forest Fruits Waste," *J. Phys. Conf. Ser.*, vol. 2739, no. 1, 2024, doi: 10.1088/1742-6596/2739/1/012005.

[14] Amrul, A. Apriyanto, H. Prayitno, and M. S. azmar "Effect of residence time on the torrefaction characteristics of Calliandra wood as solid biofuel," *Polimesin*, vol. 23, no. 3, pp. 293–300, 2025. http://dx.doi.org/10.30811/jpl.v23i3.6656

[15] M. Bajcar, M. Zardzewiały, B. Saletnik, G. Zaguła, C. Puchalski, and J. Gorzelany, "Torrefaction as a Way to Remove Chlorine and Improve the Energy Properties of Plant Biomass," *Energies*, 2023, doi: 10.3390/en16217365.

[16] A. Nebyvaev, D. Klimov, A. Ryzhenkov and M. Brulé, "Preliminary Results of Innovative Two-Stage Torrefaction Technology Applied for Thermochemical Treatment of Sunflower Husk," *Processes*, 2023, doi: 10.3390/pr11082486.

[17] D. Wu *et al.*, "Soybean Yield Response of Biochar-Regulated Soil Properties and Root Growth Strategy," *Agronomy*, vol. 12, no. 6, 2022, doi: 10.3390/agronomy12061412.

[18] X. Wang *et al.*, "Flue Gas-Enhanced Water Leaching: AAEM Removal From Agricultural Organic Solid Waste and Fouling and Slagging Suppression During Its Combustion," *Acs Omega*, 2023, doi: 10.1021/acsomega.3c00690.

[19] M. N. Cahyanti, T. R. K. C. Doddapaneni, M. Madissoo, L. Pärn, I. Virro, and T. Kikas, "Torrefaction of agricultural and wood waste: Comparative analysis of selected fuel characteristics," *Energies*, vol. 14, no. 10, pp. 1–19, 2021, doi: 10.3390/en14102774.

[20] K. Bukhsh *et al.*, "Comparative analysis of combustion behavior of raw and torrefied biomass pellets in a customized high-temperature flat flame furnace," *Fuel*, vol. 404, no. PB, p. 136301, 2026, doi: 10.1016/j.fuel.2025.136301.

[21] K. Bharadwaj, S. Shenbagaraj, P. Kumar, K. Sharma, P. Kumar, and W. Chen, "Biomass torrefaction : An overview of process and technology assessment based on global readiness level," *Fuel*, vol. 324, no. January, p. 124663, 2022, doi: 10.1016/j.fuel.2022.124663.

[22] N. S. Raghuvanshi, "Optimized Low-Emission Combustion in Domestic Biomass Boilers: A Comparative Study Using Artificial Bee Colony Algorithm for Enhanced Efficiency and Reduced Pollutant Emissions," *Heat Transf.*, 2025, doi: 10.1002/htj.70096.

[23] E. Hugot - Handbook of Cane Sugar Engineering (1986, Elsevier Science)

[24] A. Klavina and R. Šeļegovskis, "Influence of Wood Chip Quality on Boiler House Efficiency," 2021, doi: 10.22616/erdev.2021.20.tf082.

[25] H. Rahmani, A. Algirdas, A. Shestavetska, and D. Vaiciukyniene, "Preparation and mechanical characterization of pressed carbonized wood sawdust bio- composite," Sci Rep 15, 14981 pp. 1–17, 2025. https://doi.org/10.1038/s41598-025-98658-w

[26] N. John, P. S. Fathima, V. S. Harsha, N. M. Paul, and P. Nisha, "Physical Conversion of Biomass: Dewatering, Drying, Size Reduction, Densification, and Separation. In: Thomas, S., Hosur, M., Pasquini, D., Jose Chirayil, C. (eds) Handbook of Biomass. Springer," 2023. https://doi.org/10.1007/978-981-19-6772-6_37-1

[27] D.-G. Lee, M.-J. Ku, K. Kim, J.-S. Kim, S.-M. Kim, and C. Jeon, "Experimental Investigation of the Ash Deposition Characteristics of Biomass Pretreated by Ash Removal During Co-Combustion With Sub-Bituminous Coal," *Energies*, 2021, doi: 10.3390/en14217391.

[28] X. Wang *et al.*, "Flue Gas-Enhanced Water Leaching : AAEM Removal from Agricultural Organic Solid Waste and Fouling and Slagging Suppression during Its Combustion," 2023, doi: 10.1021/acsomega.3c00690.

[29] M. Farghali *et al.*, "Strategies to Save Energy in the Context of the Energy Crisis: A Review," *Environ. Chem. Lett.*, 2023, doi: 10.1007/s10311-023-01591-5.

[30] A. Javanmard, W. M. A. W. Daud, M. F. A. Patah, and C. Y. Ying, "Impact of water-washing pretreatment on key properties of torrefied palm kernel shells: A statistical optimization study," *Ind. Crops Prod.*, vol. 228, no. February, p. 120729, 2025, doi: 10.1016/j.indcrop.2025.120729.

[31] A. Mukherjee, J. A. Okolie, C. Niu, and A. K. Dalai, "Experimental and Modeling Studies of Torrefaction of Spent Co ff ee Grounds and Co ff ee Husk : E ff ects on Surface Chemistry and Carbon Dioxide Capture Performance," 2021, doi: 10.1021/acsomega.1c05270.

[32] P. Basu, P., & Kaushal, *Biomass Gasification, Pyrolysis, and Torrefaction*. Elsevier, 2024. doi: 10.1016/C2022-0-02464-8.

[33] R. Zahedi, A. Shaghaghi, M. T. Tahooneh, and A. Ahmadi, "Numerical simulation of combustion of sulfide- biomass

concentrate ingredients and contaminants in copper furnace smelting," *Futur. Energy*, vol. 2, no. 1, pp. 1–8, 2022, doi: 10.55670/fpll.fuen.2.1.1.

[34] R. Nabila *et al.*, "Oil palm biomass in Indonesia : Thermochemical upgrading and its utilization," *Renew. Sustain. Energy Rev.*, vol. 176, no. January, p. 113193, 2023, doi: 10.1016/j.rser.2023.113193.

[35] J. V Reinoso-Moreno, M. G. Pinna-Hernández, M. D. Fernández, J. A. Sánchez-Molina, J. C. López Hernández, and F. G. Acién, "Boiler Combustion Optimization of Vegetal Crop Residues From Greenhouses," *Agronomy*, 2021, doi: 10.3390/agronomy11040626.

[36] J. Wang, Q. Yao, X. Jin, and L. Deng, "The Influence of Co-Firing Coal With Biomass Syngas on the Thermodynamic Parameters of a Boiler," *Appl. Sci.*, 2023, doi: 10.3390/app132011477.

[37] W. Chen *et al.*, "Progress in biomass torrefaction : Principles , applications and challenges," vol. 82, 2021, doi: 10.1016/j.pecs.2020.100887.

[38] R. Raman and A. Sreenivasan, "iScience Analyzing the contributions," *ISCIENCE*, vol. 28, no. 4, p. 112157, doi: 10.1016/j.isci.2025.112157.