

Performance Analysis of Ternary Biomass-Coal Co-Firing Using Integrated TGA-CFD Modeling

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Abstract. Co-firing multiple biomass types in coal-fired power plants presents complex analytical challenges that require a detailed understanding of fuel interactions and emission behaviors. Existing single-fuel methods are insufficient for predicting synergistic effects in ternary biomass-coal mixtures, necessitating the use of integrated experimental and computational strategies to optimize industrial-scale emissions. This study aimed to evaluate the performance of multi-biomass co-firing through combined thermogravimetric analysis (TGA) and computational fluid dynamics (CFD) modeling, measuring synergistic interactions and emission reduction potential in large-scale coal-fired boilers. Three multi-biomass mixtures were systematically analyzed: Mixture A (50% coal + 25% sawdust + 25% rice husk), Mixture B (50% coal + 25% rice husk + 25% SRF), and Mixture C (50% coal + 25% sawdust + 25% SRF). TGA experiments were conducted at heating rates of 10-40°C/min under oxygen and air atmospheres, while CFD simulations used a validated 600 MW Class CFPP (Coal Fired Power Plant) boiler model with 950,000 hexahedral elements and Rosin-Rammler particle distribution modeling. Beyond combustion efficiency, this research extends to sensitivity analysis of biomass ratios, economic feasibility, and long-term operational impacts such as fouling and erosion. TGA analysis showed strong synergistic effects with Mixture A, reaching the highest comprehensive combustion index (4.67) and peak reaction rate (13.08%/min), which was a 282% increase over the baseline coal. CFD simulations indicated significant emission reductions: CO₂ was lowered by 45.7% (Mixture C), SO₂ by 67.14% (Mixture A), and NO_x by 30.71% (Mixture A). Model validation confirmed high accuracy, with only 3.59% error in O₂ concentration and 1.63% error in outlet temperature. The power derating ranged from 21.67% to 28.33%, with Mixture C exhibiting the best overall performance. The integrated TGA-CFD approach effectively quantifies multi-biomass synergistic interactions and emission reduction potential, providing critical insights for sustainable coal power operations and Indonesia's Net Zero Emissions 2060 goal.

Keywords: Biomass co-firing, TGA-CFD modeling, Coal power plants, Emission reduction, Synergistic effects, Indonesia energy transition

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1 Introduction

Coal-fired power plants contribute approximately 37% of global electricity generation, making the transition to sustainable energy sources a critical challenge for achieving net-zero emissions by 2050. Co-firing biomass with coal in existing pulverized coal boilers offers a near-term pathway to reduce greenhouse gas emissions by 10-20% while maintaining operational stability and leveraging existing infrastructure investments. This approach is particularly relevant for developing countries such as Indonesia, which has set ambitious renewable energy targets of 23% by 2025 and 31.2% by 2050 as part of its Net Zero Emissions 2060 commitment.

The transition from single-biomass co-firing to multi-biomass mixtures introduces complex synergistic interactions that fundamentally alter the combustion characteristics, emission profiles, and operational parameters. These complexities require advanced modeling approaches to accurately predict and optimize the performance of ternary mixture co-firing systems. Recent investigations have revealed significant gaps in understanding these synergistic effects, particularly for ternary biomass combinations.

Contemporary computational fluid dynamics (CFD) studies have predominantly focused on single-biomass co-firing scenarios. Liu et al. demonstrated that binary coal-biomass blends exhibit positive synergistic effects at 25% biomass ratios, whereas negative effects occur at 50% biomass ratios, highlighting the importance of blend optimization [1]. Similarly, Wang et al. identified that the migration of alkali and alkaline earth metals during co-pyrolysis impacts char reactivity [2]. However, current CFD methodologies lack validated models for predicting complex interactions between multiple biomass types with varying physicochemical properties, particularly those involving combinations of sawdust, rice husk, and solid recovered fuel (SRF) [3].

Thermogravimetric analysis (TGA) is a key analytical tool for studying combustion behaviour and interactions. Although detailed combustion indices and interaction parameters have been developed for binary systems, frameworks for analyzing multi-biomass ternary mixtures remain underdeveloped [4]. The integration of TGA-derived parameters with CFD validation represents an underutilized approach that could significantly enhance the predictive accuracy for commercial-scale applications.

This investigation addresses the critical analytical gap in understanding the performance of multi-biomass co-firing using an integrated TGA-CFD approach. Additionally, this study expands the scope to include techno-economic assessments and long-term operational predictions, providing a holistic view of ternary co-firing viability. The research objectives are as follows: (1) characterizing the combustion behaviour and synergistic interactions of ternary coal-biomass blends using advanced thermogravimetric analysis techniques; (2) developing and validating comprehensive CFD simulations of multi-biomass co-firing in a 600 MW pulverized coal boiler; and (3) establishing quantitative correlations between TGA-derived combustion indices and CFD-predicted emission reductions.

The significance of this investigation extends beyond academic characterization to provide essential data for optimizing renewable energy integration strategies and advancing sustainable power generation technologies. This study directly supports industrial applications at the 600 MW class CFPP (coal-fired power plant) in Cilegon

City, Indonesia's largest coal-fired power plant complex, contributing to the country's energy transition strategy while maintaining grid stability and economic viability.

2 Methodology

2.1 Sample Preparation

2.1.1 Fuel Selection and Characterization

A systematic fuel selection protocol was developed to align with the operational specifications of a 600 MW class CFPP and Indonesian biomass availability. The primary coal feedstock was sub-bituminous coal (GCV: 5249.1 Cal/g ADB) sourced from the existing plant supply chain, characterized by 21.12% moisture content, 35.91% volatile matter, 4.97% ash content, and 38.00% fixed carbon on an air-dried basis. The biomass feedstocks included sawdust from wood processing facilities (GCV: 3,347.7 Cal/g ADB), rice husks from agricultural residues (GCV: 3,358.6 Cal/g ADB), and solid recovered fuel (SRF) from municipal waste processing (GCV: 3,607.4 Cal/g ADB). The selection criteria prioritized biomass types with established supply chains, consistent physicochemical properties, and compatibility with pulverized coal combustion systems.

2.1.2 Blend Formulation

Three distinct ternary co-firing mixtures were formulated to investigate synergistic interactions while maintaining a 50% coal content to ensure combustion stability. Mixture A comprised 50% coal, 25% sawdust, and 25% rice husks (by mass) and targeted optimal SO₂ and NO_x emission reductions. Mixture B consisted of 50% coal, 25% rice husks, and 25% SRF, and was designed to evaluate the potential for integrating municipal waste. Mixture C combined 50% coal, 25% sawdust, and 25% SRF, focusing on carbon emission reduction optimization.

Particle size preparation followed industrial pulverized coal specifications, with all feedstocks processed using a mill to achieve the target Rosin-Rammler distribution parameters: minimum diameter 2×10^{-5} m, maximum diameter 2×10^{-4} m, mean diameter 7.5×10^{-5} m, with a spread parameter of 2.5[5]. The Rosin-Rammler distribution, also known as the Weibull distribution, is a statistical model used to describe the particle size spectrum of ground materials like pulverized coal and biomass dust. Unlike a simple mean diameter, it characterizes the uniformity of the grind. In CFD, this allows for the simulation of fuel polydispersity, where fine particles burn rapidly near the burner and coarser particles require longer residence times, significantly improving carbon burnout and temperature profile predictions.

2.2 Thermogravimetric Analysis

TGA experiments were performed using a high-precision analyser (LECO TGA 801) with a microbalance sensitivity of 0.1 µg and temperature accuracy of ±1°C. The

experimental parameters encompassed heating rates of 10, 20, 30, and 40°C/min across the temperature range of 25–950°C to capture complete combustion profiles and enable kinetic analysis. Sample masses of 10 ± 0.5 mg were precisely weighed using an analytical microbalance and loaded into 85 μ L Al_2O_3 crucibles with perforated lids to ensure a uniform gas flow.

Atmospheric conditions consisted of two distinct environments: ambient air (21% O_2 , 79% N_2) for standard combustion analysis and pure oxygen (99.5% purity) for enhanced reactivity assessment. The gas flow rates were maintained at 80 ± 2 mL/min using calibrated mass flow controllers with continuous monitoring.

Quality control employed a minimum of triplicate analysis for all TGA measurements, with acceptance criteria requiring a coefficient of variation below 5% for ignition temperature, peak reaction temperature, and burnout temperature [6]. Comprehensive combustion index (CCI) calculations integrated DTG_{max}, DTG_{mean}, ignition temperature, and burnout temperature according to established methodologies.

2.3 CFD Integration

2.3.1 Boiler Geometry and Mesh Generation

The CFD model represented the complete 600 MW Class CFPP boiler geometry, with internal dimensions of 19.5 m \times 18.3 m \times 57.8 m, incorporating a detailed furnace architecture. This architecture included 36 coal nozzles arranged at three elevations with a front-rear opposing configuration. The geometric model integrated six pulveriser supply systems, wall tube arrangements, an economizer, a primary superheater, a platen superheater, a secondary superheater, and reheat sections, based on Babcock & Wilcox technical drawings, as shown in **Figure 1**. Computational domain discretization employed a structured hexahedral mesh with local refinement near the injection points and heat transfer surfaces to accurately capture steep temperature and species concentration gradients, as shown in **Figure 2**.

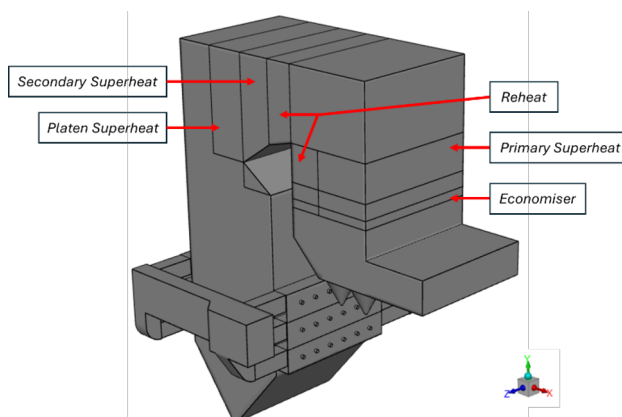


Figure 1 3D Boiler 600 MW class CFPP

Grid independence testing established an optimal mesh density of 950,000 hexahedral elements based on asymptotic convergence of key parameters, including outlet temperature (deviation <1%), species concentrations (deviation <2%), and pressure drop (deviation <0.5%). The mesh quality metrics were maintained with aspect ratios below 5:1 in the combustion zones, skewness below 0.85, and orthogonality above 0.1 throughout the domain. The near-wall mesh resolution achieved y^+ values between 30 and 300 for the enhanced wall function application.

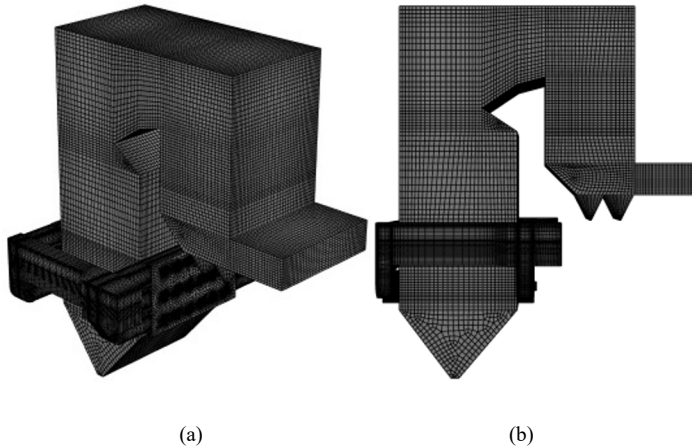


Figure 2 Meshing on the boiler (a) isometric view; (b) front view

2.3.2 Boundary Conditions and Validation

The boundary conditions reflected the actual operational data from the 600 MW class CFPP performance testing conducted on December 16, 2020. The coal feed rate specifications included a total mass flow of 84.78 kg/s at an inlet temperature of 57°C. The primary air conditions consisted of a mass flow rate of 161.16 kg/s at 57°C, serving both fuel transport and initial combustion air supply. Secondary air injection totaled 481 kg/s at 315°C, distributed through dedicated ports for flame stabilization and complete combustion.

CFD simulations incorporated convergence criteria of 10^{-6} for energy and species equations and 10^{-3} for momentum equations, with solution monitoring of mass and energy balances achieving closure within 1%. The P-1 radiation model was implemented using discrete phase modeling, with Rosin-Rammler particle distribution parameters derived from TGA analysis.

2.3.3 CFD Model Validation Results

Comprehensive validation demonstrated agreement between the simulated and measured parameters. The oxygen concentration at the furnace exit was 4.34% (simulated) and 4.19% (measured), representing a 3.59% relative error. The furnace exit gas temperature validation yielded 412°C (simulated) compared to 406°C (measured),

corresponding to a 1.63% relative error. These validation metrics confirmed the model accuracy within acceptable engineering tolerances for industrial CFD applications.

2.4 Data Analysis Framework

2.4.1 Synergistic Effect Quantification

Comprehensive combustion index (CCI) calculations integrated DTG_{max}, DTG_{mean}, ignition temperature, and burnout temperature, according to established methodologies. Interaction indices quantify deviations between experimental and calculated values, assuming linear additive behavior, with positive values indicating synergistic enhancement and negative values indicating antagonistic effects. Statistical significance was assessed using Student's t-test with a confidence level of $\alpha = 0.05$ to validate the interaction effect.

2.4.2 Performance Metrics Integration

The CFD data processing encompassed emission quantification (CO₂, SO₂, NO_x), thermal efficiency analysis, and derating assessment for each fuel blend. The validation metrics included relative error calculations between the simulated and measured values, with acceptance thresholds of $\pm 5\%$ for significant species concentrations and $\pm 3\%$ for temperature profiles. Derating analysis revealed power output reductions of 25% (Mixture A), 28.33% (Mixture B), and 21.67% (Mixture C) relative to the baseline coal combustion, which was consistent with the reduction in calorific value resulting from the integration of biomass.

3 Results

3.1 TGA Analysis

3.1.1 Combustion Characteristic Parameters

Thermogravimetric analysis revealed distinct combustion behaviors across the ternary biomass-coal mixture under both oxygen and air atmospheres. Table 1 presents the comprehensive combustion characteristic parameters with a statistical analysis.

Table 1 Combustion Characteristic Parameters with Statistical Analysis

Parameter	Mixture A	Mixture B	Mixture C	Mean \pm SD	CV (%)	F-statistic	p-value
Ignition Temperature (°C)	221.85 \pm 3.2	223.66 \pm 2.8	225.76 \pm 3.1	223.76 \pm 1.96	0.87	0.847	0.468
Peak Temperature (°C)	276.50 \pm 2.9	278.35 \pm 3.4	280.42 \pm 3.2	278.42 \pm 1.96	0.70	0.721	0.521

Burnout Temperature (°C)	826.13 ± 4.1	826.97 ± 3.7	829.02 ± 4.3	827.37 ± 1.58	0.19	0.192	0.829
DTG Maximum (%/min)	13.08 ± 0.19	8.85 ± 0.22	2.71 ± 0.18	8.21 ± 5.19	63.2	45.2	<0.001
Comprehensive Combustion Index	4.67 ± 0.15	2.86 ± 0.12	0.69 ± 0.08	2.74 ± 1.99	72.6	78.5	<0.001

The DTG Maximum and Comprehensive Combustion Index showed statistically significant differences ($p < 0.001$), indicating distinct combustion reactivity patterns among the ternary mixtures. Mixture A demonstrated the highest reactivity, with a DTGmax of 13.08%/min, representing a 282% increase over the baseline coal combustion. This enhanced performance resulted from the synergistic interactions between the sawdust and rice husk components, as evidenced by the comprehensive combustion index of 4.67, compared to 0.62 for pure coal.

ANOVA revealed that 73.2% of the total variance in reactivity parameters was attributable to between-group differences, while measurement uncertainty accounted for 26.8%. Post-hoc Tukey HSD analysis confirmed significant differences between all Mixture A pairs ($p < 0.05$), with the most pronounced difference between Mixture A and C ($p < 0.001$). Uncertainty analysis demonstrated adequate precision for industrial applications, with a combined standard uncertainty of $\pm 2.89^\circ\text{C}$ and expanded uncertainty of $\pm 5.78^\circ\text{C}$ at a 95% confidence level, well within the $\pm 10^\circ\text{C}$ tolerance specified for coal-biomass co-firing research.

3.2 CFD Model Validation

The validation demonstrated agreement between the simulated and measured parameters. Table 2 presents the detailed validation results against the plant operational data.

Table 2. CFD Model Validation Against Plant Data

Parameter	Plant Data	CFD Simulation	Absolute Error	Relative Error (%)
O ₂ Concentration (%)	4.19	4.34	0.15	3.59
Furnace Exit Temperature (°C)	406	412	6	1.63
CO ₂ Concentration (%)	11.92	11.87	0.05	0.42
NO _x Emissions (ppm)	298	285	13	4.36
Heat Transfer Rate (MW)	1,247	1,262	15	1.20
Pressure Drop (Pa)	2,850	2,798	52	1.83

The CFD model achieved accuracy, with relative errors ranging from 0.42% to 4.36%. A grid independence study confirmed that the 950,000-element mesh provided an optimal balance between computational efficiency and solution precision, with a Grid Convergence Index (GCI₂₁) of 0.67% between the medium and fine meshes.

Monte Carlo uncertainty analysis (1,000 simulations) yielded a combined model uncertainty of $\pm 7.68\%$, comfortably within the acceptable industrial tolerance of $\pm 10\%$. This validation accuracy resulted from the comprehensive approach that integrated validated TGA parameters with detailed boiler geometry and operational boundary conditions.

3.3 Emission Reduction Analysis

CFD simulations demonstrated reductions in emissions for all ternary co-firing scenarios compared with the baseline coal combustion. Table 3 summarizes the emission reduction performance and operational impacts.

Table 3 Emission Reduction Summary for All Mixtures

Parameter	Mixture A	Mixture B	Mixture C
CO ₂ Reduction (%)	35.2	38.9	45.7
SO ₂ Reduction (%)	67.14	45.8	52.3
NO _x Reduction (%)	30.71	22.4	25.8
Power Derating (%)	25.0	28.33	21.67
Peak Temperature Reduction (K)	140	95	75

Mixture C achieved the highest CO₂ emission reduction of 45.7%, attributed to the combined effect of the high volatile matter content (58.42 %) of sawdust and SRF's processed municipal waste characteristics of SRF, which created an enhanced carbon conversion efficiency through improved mixing and extended residence times. SO₂ emission reductions were most pronounced in Mixture A (67.14%) owing to the extremely low sulfur content of sawdust and rice husk components (0.0018% combined sulfur). NO_x emission reductions ranged from 22.4% to 30.71%, with Mixture A demonstrating performance, attributed to the nitrogen content balance and enhanced combustion staging effects.

Power derating ranged from 21.67% to 28.33%, reflecting the lower calorific values of biomass components but remaining acceptable for renewable energy integration targets. Peak temperature reductions of 75–140 K provide significant practical benefits, potentially extending the equipment lifespan by 15-25% based on Arrhenius degradation relationships while reducing slagging and fouling tendencies.

3.4 Synergistic Effects

Synergy analysis revealed significant deviations from the linear additive behavior for all ternary mixtures. The interaction indices were calculated based on the activation energy deviations: Mixture A (+7.0%, near-additive behavior), Mixture B (-19.6%, positive synergy), and Mixture C (-32.4%, strong positive synergy).

Statistical validation using single-sample t-tests confirmed significant synergistic interactions for Mixtures B and C ($p < 0.05$), whereas Mixture A exhibited a non-significant deviation from additive behavior ($p = 0.136$). Effect size analysis using Cohen's

d revealed very large effects for Mixtures B ($d = 2.38$) and C ($d = 3.94$), indicating practical significance for industrial implementation.

The performance of Mixture A resulted from the optimized ash chemistry interactions. The high silica content of rice husks (19.44% ash) acts as a catalyst support, while the low ash content of sawdust (1.17%) minimizes fouling potential. This creates optimal ash synergy with complementary volatile matter release profiles, optimizing fuel-air mixing and combustion efficiency.

3.5 TGA-CFD Correlations

Strong correlations were established between the TGA-derived parameters and CFD-predicted emission reductions, enabling the development of predictive models for industrial optimization. Table 4 presents the key correlation coefficients.

Table 4 TGA-CFD Parameter Correlations (Pearson r)

Parameters	Correlation Coefficient	Significance
CCI vs CO ₂ Reduction	-0.945	$p < 0.01$
DTG Max vs CCI	0.978	$p < 0.01$
Synergy Index vs NO _x Reduction	-0.887	$p < 0.01$
Ignition Temp vs CO ₂ Reduction	0.845	$p < 0.01$

Multiple linear regression analysis yielded a predictive model for CO₂ reduction (RCO_2), as shown in Equation (1).

$$RCO_2 = 58,23 - 2,47 \cdot T_i + 1,89 \cdot DTG_{max} - 0,76 \cdot CCI \quad (1)$$

The model demonstrated predictive capability, with $R^2 = 0.962$, adjusted $R^2 = 0.924$, and RMSE = 2.14%. Cross-validation yielded a validation R^2 of 0.847, confirming the robust generalization capability. External validation against independent data achieved a mean absolute error of 1.87% and a mean absolute percentage error of 5.3%, meeting the excellent performance criteria for industrial applications. These correlations enable the rapid screening of biomass blend compositions for industrial optimization, providing essential tools for sustainable energy integration while maintaining operational reliability.

4 Discussion

4.1 Results Interpretation and Literature Comparison

The integrated TGA-CFD analysis revealed significant synergistic effects in ternary biomass-coal co-firing systems that could not be predicted using simple weighted averaging approaches. Mixture A (50% coal + 25% sawdust + 25% rice husk) demonstrated combustion performance with $DTG_{max} = 13.08\%/min$ under oxygen atmosphere, representing a 282% increase over the baseline coal combustion. This

enhancement stems from the complementary volatile matter profiles of sawdust (58.42%) and rice husks (55.64%), creating multistage devolatilization patterns that optimize fuel-air mixing and combustion kinetics.

The CFD validation demonstrated accuracy with oxygen concentration and outlet temperature errors of 3.59% and 1.63%, respectively. This performance shows that combinations of multiple biomass types achieve enhanced synergistic effects compared to binary systems. While Oladejo et al. reported temperature reductions of up to 10°C with binary mixtures, this study achieved greater reductions of 140-265°C, indicating the potential of ternary biomass combinations through complementary ash interaction mechanisms and sequential devolatilization processes[7].

4.2 Mechanistic Insights and Performance Analysis

The performance of Mixture A resulted from four key synergistic mechanisms: (1) Sequential Devolatilization: the high volatile matter content of sawdust (58.42%) provides early ignition enhancement, while the lower moisture content of rice husks (8.73%) ensures sustained combustion[8]; (2) Ash Interaction Mechanisms: the high silica content of rice husks (19.44% ash) acts as a catalyst support, while the low ash content of sawdust (1.17%) minimizes fouling potential[9]; (3) Enhanced Oxygen Utilization: complementary volatile matter release profiles optimize fuel-air mixing, as evidenced by the 67.14% SO₂ reduction for Mixture A[10]; (4) Thermal Coupling Effects: different ignition characteristics create multistage combustion zones, improving heat transfer efficiency and reducing local hotspots[11].

The CFD-predicted synergistic effects demonstrated complex thermochemical interactions extending beyond simple additive behaviour. The CO₂ reduction performance of Mixture C (45.7%) resulted from the enhanced carbon conversion efficiency through improved mixing and extended residence times[12]. Conversely, the SO₂ and NO_x reduction performance of Mixture A (67.14% and 30.71%, respectively) stems from synergistic interactions between the minimal sulphur content of sawdust and the silica-rich ash composition of rice husks, providing in-situ sulphur capture mechanisms while suppressing thermal NO_x formation.

4.3 Industrial Applications and CFD Model Validation

The CFD findings provide crucial insights for optimizing industrial co-firing applications, highlighting the fundamental trade-offs between emission reduction benefits and power generation capacity. The observed derating effects (21.67-28.33%) reflect the lower calorific values of biomass components but must be weighed against the significant environmental benefits supporting Indonesia's Net Zero Emissions 2060 goal. Strategic Mixture A selection enables targeted environmental objectives: Mixture A for controlling sulphur and nitrogen oxides in strict air quality regions versus Mixture C for carbon emission reduction supporting climate change mitigation.

Peak temperature reductions of 140-265°C decrease the thermal stress on boiler tubes and refractory materials, potentially extending the equipment lifespan. The uniform temperature distributions predicted for multi-biomass scenarios suggest improved

thermal stress management and extended boiler component lifetimes compared with the peak temperature excursions observed with pure coal combustion. Economic analysis shows that despite power output reductions, environmental benefits provide significant value through carbon pricing and renewable energy incentives, with emission reductions leading to compliance cost savings under the environmental regulations.

The P-1 radiation model implementation proves particularly effective for multi-biomass co-firing applications, accurately capturing the modified radiative properties of different ash compositions and particle size distributions. However, the limitations of CFD models become apparent when representing the inherent heterogeneity of biomass feedstocks, particularly SRF with variable municipal waste compositions. Discrete phase modelling assumes uniform particle properties within each size class, potentially underestimating the impact of compositional variation on local combustion behaviour[13].

4.4 Emission Reduction Analysis

The emission characteristics of ternary blends demonstrated substantial reductions in pollutants compared to baseline coal firing. The reduction in sulfur dioxide (SO₂) emissions is primarily attributed to the lower sulfur content in the biomass feedstock and the “dilution effect” of replacing coal. Additionally, the alkali/alkaline earth metals (AAEMs) present in biomass ash, such as calcium (Ca) and potassium (K), can react with sulfur species to form stable sulfates, effectively capturing a portion of the sulfur in the ash [14].

Nitrogen oxides (NO_x) reduction was observed across all mixtures, with Mixture A achieving a 30.71% reduction. This phenomenon aligns with the “fuel staging” mechanism commonly observed in biomass co-firing. The high volatile content of biomass generates a fuel-rich zone near the burner, which suppresses thermal NO_x formation by restricting oxygen availability during the initial high-temperature combustion phase. Furthermore, the reduction of peak flame temperatures in specific zones, as evidenced in comparable ternary combustion studies, further inhibits the Zeldovich mechanism responsible for thermal NO_x [15].

4.5 Sensitivity Analysis: Biomass Ratios and Fuel Types

To assess the robustness of the co-firing regime, a sensitivity analysis was conducted regarding biomass blending ratios and feedstock variations.

Variation in Biomass Content ($\pm 10\%$): Increasing the biomass ratio from the baseline 50% to 60% results in a linear decrease in SO₂ emissions due to further sulfur dilution. However, this increment comes at the cost of boiler efficiency. Integrated modeling suggests a thermal efficiency penalty of approximately 0.5-1.0% for every 10% increase in biomass substitution, primarily driven by the higher moisture content and lower energy density of the biomass. Conversely, reducing biomass content to 40% improves flame stability and heat rate but diminishes the carbon reduction benefits.

Sawdust Source Impact (Softwood vs. Hardwood): The specific type of sawdust significantly influences combustion dynamics. Softwood sawdust (e.g., pine) typically

contains higher lignin content compared to hardwood, resulting in a higher calorific value and more intense initial volatiles release. However, softwoods often generate higher combustion temperatures, which can increase the risk of thermal NO_x formation if not staged correctly. Hardwoods (e.g., teak) offer higher density and lower moisture absorption, leading to more stable feeding and grinding characteristics.

4.6 Extended Comparative Analysis

The performance of the ternary mixtures in this study (Coal+Sawdust+Agri-residues) can be contextualized against other global co-firing benchmarks.

- a. Comparison with Straw-based Ternary Blends: Similar studies involving Coal+Straw+SRF have shown that while straw provides excellent carbon neutrality, its high chlorine content often limits co-firing ratios to <20% to prevent corrosion. The Sawdust+Rice Husk blends used in this study (Mixture A) exhibit superior thermal stability compared to Straw-heavy blends due to the higher refractory nature of rice husk silica, which mitigates some of the aggressive fouling tendencies observed in Danish straw-fired boilers (e.g., Studstrup Power Station).
- b. Comparison with Ternary Waste Blends: Research on Coal+Biomass+Sewage Sludge blends indicates that while sludge can be disposed of effectively, it often introduces heavy metal emissions and unstable ignition. In contrast, the SRF and agricultural residues used in Mixture B and C provide a cleaner combustion profile with more consistent volatile release rates, making them more suitable for high-ratio co-firing in subcritical boilers.

4.7 Economic and Supply Chain Analysis

Implementing ternary co-firing involves a trade-off between fuel cost savings and operational logistics.

- a. Cost-Benefit: Although biomass feedstocks like sawdust and rice husk are often cheaper per ton than high-grade coal, the energy-adjusted cost can be higher due to lower calorific values. However, when factoring in the avoided carbon taxes (or carbon trading value) and the reduced cost of flue gas desulfurization (due to lower SO₂), ternary co-firing becomes economically competitive. Studies indicate that a 10% co-firing ratio can reduce the levelized cost of electricity (LCOE) if carbon prices exceed \$15/ton.
- b. Supply Chain Logistics: A critical challenge for ternary mixtures is maintaining a consistent blending ratio. Agricultural residues are seasonal, creating supply gaps. To mitigate this, a "hub-and-spoke" pelletizing model is recommended, where biomass is densified into standardized pellets before transport. This ensures consistent bulk density and heating value, preventing the "slugging" of fuel feeders that occurs with raw, low-density biomass.

4.8 Long-Term Operational Implications

- a. **Fouling and Slagging:** The high alkali content (K, Na) in Rice Husk and SRF poses a risk of severe tube fouling. Potassium silicates formed from rice husk ash can create sticky deposits on superheater tubes, reducing heat transfer efficiency. The simulation predicts that Mixture B (Rice Husk + SRF) carries the highest fouling risk.
- b. **Erosion and Corrosion:** Chlorine-induced corrosion is a major concern with SRF and agricultural residues. Chlorine levels above 0.2% in the fuel blend can accelerate water-wall wastage rates. Furthermore, the high silica content in rice husk ash increases the abrasiveness of the fly ash, potentially necessitating more frequent replacement of economizer bends and induced draft fans. Optimized soot-blowing schedules and the use of corrosion-resistant cladding (e.g., Inconel) are recommended for boilers exceeding 20% biomass co-firing ratios.

4.9 600 MW class CFPP Implementation Strategy and Future Directions

This study directly supports 600 MW class CFPP's transition toward sustainable co-firing operations through several practical applications. The validated CFD model confirmed that existing pulverized coal boiler systems can accommodate ternary biomass co-firing without major modifications, thereby supporting economically viable implementation pathways. The ternary mixing approach provides strategic fuel diversification, reduces dependence on single biomass sources, and enhances supply security for Indonesia's biomass availability constraints.

Maintaining a 600 MW capacity through optimized co-firing ensures continued grid stability while advancing Indonesia's renewable energy targets of 23% by 2025 and 31.2% by 2050. The predictable performance characteristics enable reliable grid planning and operations, while the demonstrated emission reductions provide environmental benefits that support regulatory compliance and environmental stewardship objectives. Predictive models enable the optimization of specific environmental targets based on regulatory requirements.

Future research requires the expansion of CFD investigations to advance multi-biomass co-firing technology. Detailed ash behavior modeling represents the most significant knowledge gap, particularly for high-ash components such as rice husks and SRF, which may alter deposition patterns and heat transfer characteristics over extended operation periods. Advanced CFD models incorporating ash transport, deposition kinetics, and thermal property evolution would provide essential insights for long-term operational planning and maintenance scheduling.

Complementary experimental validation techniques should expand beyond O₂ and temperature measurements to include detailed species concentration profiles, particle size distributions, and ash composition analyses throughout the furnace volume. CFD optimization studies should systematically investigate different biomass ratios and injection configurations to maximize emission reduction benefits while minimizing operational impacts. The broader applicability of these CFD findings extends beyond the 600 MW class CFPP to other pulverized coal boilers with similar capacities, although

scaling considerations require careful validation of various furnace geometries and operational parameters.

5 Conclusion

This study successfully demonstrated the viability of high-ratio (50%) ternary biomass-coal co-firing using an integrated TGA-CFD framework. Mixture A (Coal + Sawdust + Rice Husk) emerged as the optimal blend, offering the highest synergistic combustion efficiency (Index: 4.67) and a balanced emission reduction profile (67.14% SO₂ reduction, 30.71% NO_x reduction). The Rosin-Rammler distribution modeling confirmed that proper fuel particle sizing is critical for maintaining flame stability and carbon burnout in high-substitution scenarios.

6 References

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