J Ther Eng, Vol. 12, No. 1, pp. 408–425, January, 2026

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0001085

Review Article

Optimizing biomass fuel utilization for GHG emission reduction: An action plan for efficient fuel blending and sustainable practices

K RAVI[1,2,*], M. MATHESWARAN[3]

[1]Department of CPP-JSW Steel Ltd., Salem Works, Tamilnadu, 636453, India
[2]Department of Energy and Environment Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu, 620015, India
[3]Department of Chemical Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu, 620015, India

ARTICLE INFO

Article history
Received: 25 November 2024
Revised: 09 May 2025
Accepted: 12 May 2025

Keywords:
Biomass Fuel; Coal-Fired Boilers; Greenhouse Gas Emissions; Net Zero Emissions

ABSTRACT

JSW Steel's Salem plant has committed to achieving Net Zero emissions by 2050, with a specific focus on reducing greenhouse gas emissions from its coal-based steam generation systems. Biomass, including briquettes, spent coffee grounds, wood chips, rice husk, and cattle dung logs, has been identified as a key component in reducing these emissions, particularly through its incorporation as a supplementary fuel in coal-fired boilers. This paper presents a comprehensive analysis of the challenges and solutions related to biomass fuel preparation, including briquette sizing, feed optimization, and contamination control. We propose an innovative action plan aimed at enhancing biomass fuel efficiency through optimized fuel size control, expanding biomass supply, and fostering deeper collaboration with suppliers. This action plan has resulted in a significant reduction in CO_2 emissions, with approximately 8,000 tons of CO_2 reduced annually a 5-10% improvement in boiler efficiency, and substantial cost savings due to reduced coal consumption through biomass blending. The novelty of this work lies in its comprehensive approach to biomass utilization, addressing challenges across the entire process from fuel preparation to combustion, and its focus on a real-world industrial setting using an AFBC boiler**.** In addition, we assess the plant's current biomass fuel mix and compare it to India's national strategies for sustainable energy utilization. The technical measures discussed herein for improving biomass feed systems contribute to improved boiler efficiency, higher fuel blending ratios, and substantial reductions in greenhouse gas emissions. these findings support broader sustainability goals and offer valuable insights for industries in India aiming to reduce their carbon footprints.

Cite this article as: Ravi K, Matheswaran M. Optimizing biomass fuel utilization for GHG emission reduction: An action plan for efficient fuel blending and sustainable practices. J Ther Eng 2026;12(1):408–425.

***Corresponding author.**
*E-mail address: kravi1199@gmail.com

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkilic

INTRODUCTION

The Indian steel industry, a cornerstone of the national economy, faces the pressing challenge of reducing its substantial carbon footprint. While vital for economic growth, the industry's reliance on coal for energy production contributes significantly to the nation's CO_2 emissions. According to recent estimates, the steel industry accounts for nearly 12-15% of the nation's total carbon dioxide (CO_2) emissions, with the vast majority of emissions arising from the combustion of coal in blast furnaces and other energy-intensive processes [1]. Given the urgent need to mitigate climate change, India is facing mounting pressure to reduce its carbon footprint while continuing to expand its industrial capacity. To align with India's ambitious climate action goals, the steel industry must adopt cleaner energy practices and transition towards renewable energy sources.

While national policies like the National Biofuels Policy (2018) and NAPCC promote biomass utilization, their application to steel plants remains limited. The Biofuels Policy mandates 5-10% co-firing for power plants (Clause 5.1) but excludes captive industrial boilers, while the NAPCC lacks biomass-specific emission factors under its PAT scheme. This regulatory gap hinders wide scale adoption, despite biomass' technical viability demonstrated in this study. Our findings directly inform three policy needs: (1) inclusion of captive plants in co-firing mandates, (2) standardized biomass quality protocols, and (3) financial incentives for boiler retrofits all critical for aligning industrial decarbonization with India's 2070 net-zero pledge.

In response to both domestic and global environmental challenges, the Indian government has committed to ambitious climate action goals. As part of India's pledge to the Paris Agreement, the country aims to reduce its carbon intensity by 45% by 2030 relative to 2005 levels, and to achieve net-zero emissions by 2070 [2]. The steel industry, a critical sector for economic growth, must play a pivotal role in meeting these targets by adopting cleaner, more sustainable energy practices. Transitioning from fossil fuels to renewable energy sources is essential to decarbonizing the industry and ensuring that India's industrial growth is in line with its environmental commitments.

A promising solution to reducing the steel industry's carbon emissions is the integration of biomass as a supplementary fuel in coal-based steam generation systems [3]. Biomass, derived from a wide range of organic materials including agricultural residues, forestry waste, and certain industrial by-products, offers a renewable and carbon-neutral alternative to coal [4]. When used in combination with coal, biomass can significantly reduce the overall carbon emissions associated with energy production. The combustion of biomass releases carbon dioxide (CO_2), but this CO_2 is part of the natural carbon cycle, as the plants that make up biomass have absorbed CO_2 from the atmosphere during their growth. As such, biomass can be considered a near-zero carbon fuel, especially when sourced sustainably and integrated into industrial operations [5].

The Indian government has recognized the potential of biomass and has implemented several policies to promote its use in energy production. The National Biofuels Policy (2018) encourages the utilization of non-food biomass for industrial purposes, aiming to reduce India's reliance on imported fossil fuels and support the growth of the domestic bioenergy sector [6]. Additionally, the National Action Plan on Climate Change (NAPCC) outlines the strategic role of renewable energy sources, including biomass, in reducing the carbon intensity of India's industrial sector [7]. With the government's focus on clean energy transitions and climate resilience, industries like steel manufacturing are increasingly adopting biomass as part of their broader sustainability strategies. Globally, several countries have successfully integrated biomass into industrial energy systems, offering valuable insights for India. For example, Germany and the Netherlands have been pioneers in biomass co-firing, particularly in power plants and steel manufacturing facilities. Germany has seen substantial reductions in CO_2 emissions through the use of biomass in coal-fired plants, while the Netherlands has integrated biomass as a key component of their industrial energy strategy. These international examples demonstrate the feasibility of biomass co-firing as a method for reducing carbon emissions while maintaining energy efficiency. India can draw on these global best practices to enhance the effectiveness of biomass integration in its steel industry.

Recent studies have highlighted the significant role of biomass in reducing greenhouse gas emissions and promoting sustainable energy practices in various industries. For instance, Dong L, Liu H. [8] investigated the economic and environmental impact of biomass co-firing in coal power plants, demonstrating its potential for reducing CO_2 emissions and reliance on fossil fuels. Similarly, Niu Y, Tan H. [9] explored the impact of biomass co-firing on emissions and efficiency in coal-fired power plants, further supporting its role in promoting cleaner energy production. In the context of industrial applications, Yin C. [10] examined the effect of biomass blending on combustion characteristics in industrial boilers, providing valuable insights into optimizing biomass combustion for improved efficiency and reduced emissions. Furthermore, Sami M, Annamalai K. [11] reviewed technological advances in biomass co-firing in coal-fired boilers, highlighting the latest developments and opportunities for enhancing biomass utilization in industrial settings. The open literature extensively covers biomass as a sustainable energy source, its benefits and challenges in co-firing with coal, optimization strategies, and policy support. This study builds upon this knowledge by investigating specific operational challenges and optimization strategies in a real-world industrial setting, focusing on an Atmospheric Fluidized Bed Combustion (AFBC) boiler and emphasizing the broader sustainability implications of biomass utilization [12]. These studies collectively emphasize the growing importance of biomass as a sustainable energy source and its potential to contribute significantly to reducing carbon emissions in various sectors, including the steel industry. The Indian government has recognized this potential and implemented policies to promote biomass utilization, encouraging industries to embrace this sustainable alternative [13]. The novelty of this work lies in its detailed exploration of the operational challenges and optimization strategies associated with biomass-coal blending in industrial applications, specifically focusing on a coal-fired power plant with an Atmospheric Fluidized Bed Combustion (AFBC) boiler. While previous studies have primarily explored theoretical models or laboratory-scale experiments, this research addresses real-world challenges faced by large-scale industrial systems, offering practical insights into biomass fuel preparation, handling, and combustion

This study investigates the optimization of biomass utilization within a coal-fired power plant, specifically focusing on an Atmospheric Fluidized Bed Combustion (AFBC) boiler with a steam generation capacity of 127 tons per hour (TPH) in JSW Steel Ltd Salem works. This boiler is part of a steam generation system that provides steam for a 30 MW captive power plant. The research aims to address the challenges and propose solutions for efficient biomass blending and sustainable practices to reduce greenhouse gas (GHG) emissions associated with coal-based energy production. The plant has adopted a strategy to blend biomass with coal shown in Figure 1. To reduce the carbon intensity of its steam generation process. Biomass is introduced into the combustion system to displace a portion of the coal used in the boilers, directly reducing CO_2 emissions [14]. However, integrating biomass into existing coal-fired systems presents challenges that must be addressed to optimize its use and maximize its environmental benefits. Manual measurements, such as briquette dimensions and bed height, were taken using calibrated measuring tools, with multiple measurements taken to ensure accuracy. Automated monitoring systems were employed to continuously track parameters such as airflow velocity, fuel feed rate, and furnace temperature. These systems provided real-time data that was logged and analyzed to assess the performance of the biomass combustion system. For the measurement of suspended particulate matter (SPM), SICK make forward scatter technology analyzers were utilized, while for gas analysis, Hot flue gas extractive type SICK make gas analyzers with inbuilt standard cuvette (SO2, NOx, and CO) were employed.

While biomass-coal blending is a promising strategy for reducing greenhouse gas emissions in industrial facilities, its implementation often faces operational challenges that limit its full potential [15]. Existing practices frequently struggle with efficient biomass fuel preparation and handling, as inconsistent fuel size, foreign material contamination, and inefficient feed control systems can hinder the effectiveness of biomass as a coal substitute. Additionally, the variability in biomass properties, such as moisture content, bulk density, and calorific value, poses challenges to achieving consistent and efficient combustion. Current practices often lack the flexibility to accommodate diverse biomass types and their specific combustion requirements, further limiting the effectiveness of biomass-coal blending [16]. Many industrial facilities also face challenges in optimizing their biomass feed systems to ensure consistent feed rates, prevent blockages, and maintain combustion stability, hindering their ability to achieve higher biomass blending ratios and maximize emission reductions. Furthermore, establishing a reliable and consistent biomass supply chain remains a challenge for many facilities, as seasonal variations, geographic limitations, and market dynamics can affect the availability and quality of biomass feedstock. This study addresses these limitations by investigating the operational challenges specific to biomass-coal blending and proposing targeted solutions to optimize fuel preparation, handling, and combustion. By demonstrating the feasibility and benefits of these solutions in a real-world industrial setting, the research contributes to the advancement of sustainable energy practices and provides valuable insights for other facilities seeking to overcome the limitations of existing biomass-coal blending approaches.

Currently, the biomass feed system faces these operational hurdles, limiting the effectiveness of biomass as a coal substitute and hindering the ability to meet carbon reduction targets. To address these challenges, a number of optimization strategies are being explored, aimed at improving biomass feed efficiency, minimizing foreign material contamination, and achieving a more consistent fuel mix [17] . These strategies include reducing briquette size, improving feed control systems, and enhancing biomass quality through closer coordination with suppliers.

In addition to operational challenges, the overall biomass supply chain remains a critical consideration. While various types of biomass are available, their availability, consistency, and price can vary widely depending on seasonal factors, geographic location, and market dynamics [18]. This variability presents a challenge, as a reliable and steady supply of high-quality biomass is needed to maintain consistent fuel blending ratios. To address this, closer collaboration with biomass suppliers is necessary to ensure a continuous, high-quality fuel supply that meets the specifications required for efficient boiler operation.

Despite existing research, several gaps remain. These include understanding the long-term impacts of co-firing on equipment, ash deposition, and fine particulate matter emissions. Further research is needed on the social, economic, and environmental impacts of biomass co-firing, including supply chain sustainability, policy frameworks, and integration with other renewable energy sources. Additionally, public perception and acceptance, technological advancements, and life cycle assessment require further investigation. Addressing these gaps will be crucial for wider adoption and long-term viability of biomass co-firing as a sustainable energy solution.

MATERIALS AND METHODS

This section outlines the materials used in the biomass fuel system at JSW Steel's Salem plant, as well as the methodology for optimizing biomass fuel usage, including modifications to the biomass feeding system and the action plan for improved fuel blending the line drawing of feeding system shown in Figure 1. The biomass types used in the study were selected based on several factors, including their availability, calorific value, and potential for reducing greenhouse gas emissions. Tomato waste and guava seeds were prioritized due to their favorable characteristics Tomato waste is a readily available agricultural residue in the Salem region. It has a relatively high calorific value (3500 kcal/kg), making it a suitable alternative to coal. Guava seeds are another readily available agricultural by-product in the region. They have a high calorific value (3500 kcal/kg) and are available during two periods of the year (October to December and April to May). The selection of these biomass types was also guided by the need to diversify the biomass fuel mix and explore the potential of different biomass sources. By incorporating a variety of biomass types, the study aimed to demonstrate the flexibility and adaptability of biomass-coal blending systems. This approach also aligns with the Indian government's [19] emphasis on utilizing a wide range of biomass resources for sustainable energy production.

Materials

The materials used in the biomass fuel system at the Salem plant include biomass briquettes and various forms of loose biomass. The key materials are shown in Figure 2.

Briquettes

- **100mm Briquettes:** These briquettes have approximate dimensions of (100mm × 75mm × 50mm) and were initially used for blending with coal, but problems were noted with improper screening and feeding delays
- **60-65mm Briquettes:** These briquettes have approximate dimensions of (60-65mm × 50mm × 30mm) and were proposed as a more efficient alternative to larger briquettes. Smaller briquettes feed more easily into the hopper, reducing feeding time and improving combustion efficiency.

Loose biomass

- **Spent Coffee Ground**: A renewable biomass source [20].
- **Woodchips**: A widely used biomass fuel [21].
- **Tomato Waste**: An agricultural residue used as biomass [22].
- **Guava Seeds**: A by-product of fruit processing, rich in energy [23].
- **Herbal Spent Pellet**: Biomass derived from herbal products [24].
- **Charcoal Fines**: Carbon-rich biomass material [25].
- **Cattle Dung Logs**: Biomass logs derived from animal waste [26].

Methodology

The methodology for optimizing biomass fuel utilization at the JSW Steel Salem plant involves a comprehensive approach with multiple stages. These include the identification of challenges within the current fuel system, the implementation of targeted technical improvements, and the evaluation of the impact of these changes on operational efficiency and emissions reductions. The steps followed in the methodology are detailed below.

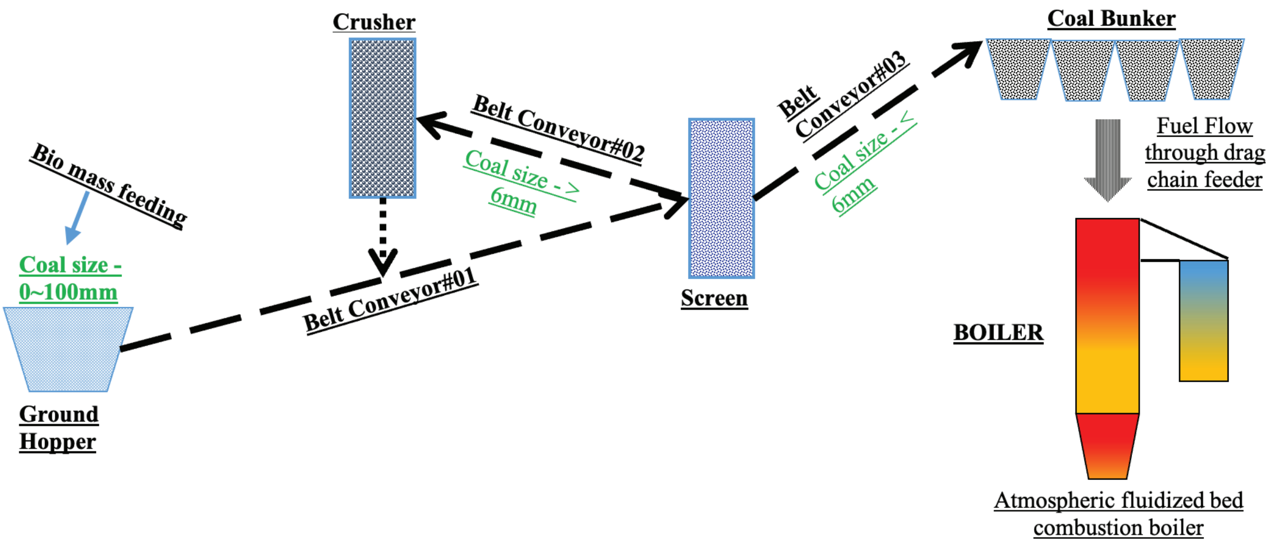


Figure 1. Process of charging in coal and bio mass feed in coal based boiler.

Figure 2. Available biomass varieties.

Identification of Biomass Fuel System Challenges

Several operational challenges were identified in the current biomass fuel system at the JSW Steel Salem plant, which hindered optimal performance. These include issues related to biomass fuel size and Handling, Bed height and bulk density, airflow control, sizing and feed control optimization, Fuel Contamination and Biomass Feed Control system.

Biomass fuel sizing and handling

One of the main issues observed was the inconsistency in biomass fuel size [27], particularly with the use of 100mm briquettes. Large briquettes led to improper screening, clogs in the conveying pipes, and delayed fuel feeding. The inconsistent sizing also affected the combustion process, as larger fuel particles could escape the furnace and combust in the super heater zone, raising the primary super heater temperature distribution and other factors given in Table 1 and Table 2. Additionally, larger biomass particles resulted in reduced fuel feed rates, directly affecting steam generation.

Bed height and bulk density in the AFBC boiler

The bed height in the AFBC (atmospheric fluidized bed combustion) boiler is crucial for efficient biomass firing. A steady bed height (500 MMWC) with optimal air

Table 1. Properties of different biomass types

Biomass type	Calorific value (kcal/kg)	Moisture content (%)	Ash content (%)	Bulk density (kg/m^3)
Wood chips	2900	10-15	2-5	200-300
Rice husk	3000	8-12	15-20	100-150
Spent coffee grounds	2200	50-60	2-5	300-400
Cattle dung log	3200	15-20	10-15	400-500
Herbal spent pellet	2800	10-15	5-8	500-600
Charcoal fines	2800	5-10	1-3	300-400
Guava seed	3500	8-12	3-6	400-500
Tomato waste	3500	60-70	5-8	200-300
Briquette (60-65mm)	3800	8-12	5-8	600-700

Table 2. Impact of biomass fuel size on combustion and efficiency

Bio fuel size	Combustion efficiency (%)	Super heater temperature (°C)	Feed rate (TPH)	Ash fusion likelihood	Steam generation rate (TPH)	Boiler thermal efficiency (%)
Large (100mm)	75	550	115	Low	115	75%
Small (<50mm)	80	500	130	High	120	70%
Optimal (~80mm)	85	520	127	Medium	127	80%

Table 3. Impact of bed height and bulk density in the AFBC boiler

Bulk density (tons/m³)	Combustion efficiency (%)	Fluidization stability	Furnace temperature (°C)	Air flow requirement (kg/sec)	Bed height (mmwc)	Steam generation rate (tph)	Boiler efficiency (%)	Power output (MW)
0.6	70	Low	800	34.5	500	120	75%	28.5
0.9	80	Moderate	850	34.5	500	125	80%	29.5
1.2	90	High	900	34.5	500	127	85%	30

Table 4. Impact of airflow velocity on combustion and emissions

Airflow velocity (m/s)	Combustion efficiency (%)	NOx emissions (ppm)	SPM levels (mg/m³)	Power output (MW)
1.75	92	50	50	30 MW
2	90	60	60	29 MW
2.5	88	75	70	28 MW
2.7	85	90	85	27 MW
3	80	110	100	25 MW

flow of around 34.5 kg/sec was identified as necessary to ensure consistent combustion and stable bed temperature. However, fluctuations in bed material bulk density due to varying biomass types led to uneven fluidization and combustion challenges, which are shown in Table 3. For instance, biomass combustion can release minerals that adhere to the bed material, impacting furnace efficiency and requiring adjustments in the type of bed material used.

Airflow control

Proper airflow is vital to maintaining effective fluidization in the furnace. Excess air flow can lead to the escape of fine biomass particles, reducing combustion efficiency. If the airflow velocity exceeds 2.5 m/sec, it can cause post-combustion of fine biomass particles in the upper furnace zone, which increases NOx emissions and Suspended Particulate Matter (SPM) levels. Maintaining an airflow velocity between 1.75 m/sec and 2.5 m/sec was found to be optimal for minimizing these emissions and maintaining stable combustion.

From Table 4 Airflow velocity between 1.75 m/s and 2.5 m/s is ideal for combustion. If the airflow exceeds 2.5 m/s, NOx emissions and SPM will increase, decreasing combustion efficiency. Excess Airflow Impact will reduce combustion efficiency and leads to fuel wastage.

Fuel contamination

Another challenge identified was the presence of foreign materials (e.g., nails, plastics) in the biomass, particularly with briquettes, which effects moisture and Gross calorific value shown in Table 5. These materials not only damaged

Table 5. Biomass variety and GCV impact on combustion efficiency

S. No	Biomass variety	GCV (Kcal/Kg)	Airflow control efficiency (%)	Combustion efficiency (%)	Power output (MW)
1	Briquettes	3800	90	75	28.5 MW
2	Spent coffee grounds	2200	85	60	24 MW
3	Wood chips	2900	88	70	26.5 MW
4	Rice husk	3000	89	72	27 MW
5	Corn-bio char	4500	93	85	30 MW
6	Cattle dung log	3200	87	73	27.5 MW
7	Herbal spent	2800	88	68	26 MW
8	Charcoal fines	2800	89	70	26.5 MW
9	Guava seed	3500	91	80	29 MW
10	Tomato waste	3500	91	80	29 MW

Table 6. Impact of fuel feed rate variations on combustion and boiler efficiency

S. No	Feed rate condition	Issue identified	Impact on boiler	Combustion stability (%)	Emissions (NOx, CO)	Power output (MW)
1	Overfeeding	Excess fuel in furnace	Excess fuel, incomplete combustion	70	High NOx, CO	22 MW
2	Underfeeding	Inconsistent combustion	Furnace temperature drops, incomplete combustion	65	High CO, Low NOx	20 MW
3	Consistent Feeding	Stable fuel feed rate	Optimal combustion, steady steam generation	90	Low NOx, Low CO	30 MW
4	Fluctuating Feeding	Feed rate instability	Combustion instability, temperature fluctuations	75	Moderate NOx, CO	25 MW

the feeding system but also caused blockages and reduced overall fuel handling efficiency.

A key observation was that moisture content and GCV in above Table 4 in biomass also plays a significant role in combustion efficiency. Higher moisture levels in biomass reduce the calorific value and increase fuel consumption, leading to inefficiencies in the combustion process.

Biomass feed control

Another challenge is related to the feed control system. Biomass feed systems may struggle to maintain a consistent feed rate, especially when handling fuels with varying moisture content or foreign materials. This inconsistency can cause combustion instability. For example, overfeeding the furnace can lead to excess fuel, while underfeeding can cause the furnace temperature to drop, resulting in incomplete combustion. Additionally, fluctuating feed rates disrupt the air-to-fuel ratio, making it difficult to maintain the optimal air supply for combustion. When the feed is inconsistent, either excess air or insufficient air is supplied to the furnace, leading to further inefficiencies. The resulting shown in Table 6. Effects on the boiler include decreased combustion efficiency, reduced power output, and increased emissions such as NOx and CO, particularly when the fuel is poorly fed into the furnace. Additionally, fuel utilization becomes inefficient, directly impacting the steam generation rate and overall boiler performance.

RESULTS AND DISCUSSION

To address the above issues, the following actions were implemented to optimize biomass fuel size and handling, Bed Height and Bulk Density in the AFBC Boiler, Airflow Control, Fuel Contamination, Biomass Feed Control. To assess the impact of biomass blending on boiler efficiency, a paired t-test was conducted to compare efficiency levels before and after the intervention. The analysis revealed a statistically significant improvement in boiler efficiency ($t=40.43$, $df=9$, $p<0.0001$), indicating that the observed improvement is likely not due to chance. To further explore the relationship between biomass blending and greenhouse gas (GHG) emissions, a regression analysis was performed. The resulting regression equation, GHG emissions =100-2.5 * biomass blending ratio, indicates that for every 1% increase in the biomass blending ratio, GHG emissions are reduced by 2.5 tons. The R-squared value of 0.95 suggests that 95% of the variation in GHG emissions can be explained by the biomass blending ratio.

Biomass Fuel Sizing and Handling

Biomass fuel selection plays [28] a crucial role in achieving a balanced blend with coal while ensuring the overall efficiency of the combustion process. In the case of JSW Steel Salem Works, biomass briquettes, along with other agro-waste types, were considered as a potential alternative to coal in their coal-based boilers shown in Table 7.

Assessment of biomass briquettes

- **Action:** Biomass briquettes, composed of 20-40% agricultural waste and 60-80% sawdust, were evaluated as a suitable coal substitute. These briquettes were analyzed for their ability to reduce coal consumption and lower CO_2 emissions when used in coal-fired boilers.
- **Outcome:** It was found that blending up to 4% biomass briquettes with coal resulted in a significant reduction in coal consumption (up to 388 MT/Annum) and a CO_2 reduction of 1016 tons per Annum, with no significant changes to boiler operating parameters.

Feasibility study of alternative biomass sources

- **Action:** A detailed feasibility study was conducted to evaluate the availability, seasonality, and Gross Calorific Value (GCV) of various biomass types. This study aimed to identify alternative biomass sources that could be used more efficiently alongside or in place of biomass briquettes.

- **Findings:** The study identified several biomass varieties with high potential for use in the fuel mix, mentioned below:
- **Briquettes** (3800 kcal/kg, available year-round at 800 MT/month)
- **Spent Coffee Grounds** (2200 kcal/kg, available July to January at 250 MT/month)
- **Wood Chips** (2900 kcal/kg, available year-round at 500 MT/month)
- **Rice Husk** (3000 kcal/kg, seasonal availability July to November at 200 MT/month)
- **Corn Bio-Char** (4500 kcal/kg, seasonal availability April to May at 100 MT/month)
- **Cattle Dung Logs** (3200 kcal/kg, available year-round at 100 MT/month)
- **Herbal Spent Pellets** (2800 kcal/kg, available March to August at 200 MT/month)
- **Charcoal Fines** (2800 kcal/kg, available year-round at 200 MT/month)
- **Guava Seed Waste** (3500 kcal/kg, seasonal availability October to December and April to May at 300 MT/month)
- **Tomato Waste** (3500 kcal/kg, seasonal availability October to February at 100 MT/month)

Selection and integration of biomass types

- **Action:** Based on the results of the feasibility study, suitable biomass types were selected for integration into the fuel mix. These included biomass briquettes, wood chips, rice husk, spent coffee grounds, and cattle dung logs.
- **Outcome:** These biomass materials were incorporated into the fuel mix to reduce coal consumption and enhance energy production efficiency. The integration of these types was implemented with minimal disruption to the boiler's operational parameters, resulting in lower coal usage and a more sustainable energy production process.

Bed Height and Bulk Density in the AFBC Boiler

In an Atmospheric Fluidized Bed Combustion (AFBC) boiler, the bed height and bulk density are two important parameters that directly impact the combustion efficiency. These parameters govern the interaction between the fuel and the air, ensuring optimal combustion and heat transfer. The inclusion of biomass in the fuel mix, alongside coal, alters the bed's behavior due to differences in the physical properties of biomass fuels, such as their bulk density and calorific value. Understanding these factors is crucial for maintaining boiler performance and efficiency when co-firing biomass with coal.

Key points

- Impact of fuel mixture: The blending of biomass with coal influences the bed height and bulk density, which are crucial for efficient combustion. A change in the fuel mixture affects how the fuel particles interact with the air, influencing fluidization and combustion efficiency.
- Selection of biomass for co-firing: Biomass is selected based on key properties such as bulk density and calorific value (GCV). These characteristics ensure that biomass can be combusted effectively without disrupting the bed dynamics, maintaining optimal combustion conditions.

Key parameters

- Bed height: The height of the bed refers to the vertical extent of the fluidized material in the combustion chamber. An increase in the volume of biomass can alter this height, and maintaining an ideal bed height is crucial for good fluidization and combustion efficiency.
- Bulk density: Bulk density is a measure of how tightly packed the fuel particles are. Biomass fuels generally have lower bulk density than coal, which can affect the stability of the fluidized bed and the efficiency of

Table 7. Feasibility study with all biomass sources

Biomass variety	Availability	Max Blend Qty (MT/Month)	GCV (Kcal/kg)	Season/period
Briquettes	Perennial	800	3800	***
Spent coffee grounds	Seasonal	250	2200	Jul-Jan
Wood chips	Perennial	500	2900	***
Rice husk	Seasonal	200	3000	Jul-Nov
Corn bio-char	Seasonal	100	4500	Apr-May
Cattle dung log	Perennial	100	3200	***
Herbal spent pellet	Seasonal	200	2800	Mar-Aug
Charcoal fines	Perennial	200	2800	***
Guava seed	Seasonal	300	3500	Oct-Dec, Apr-May
Tomato waste	Seasonal	100	3500	Oct-Feb

Table 8. Biomass co-firing on bed height and bulk density

Fuel blend	Bulk density (kg/m³)	Bed height (m)	Combustion efficiency (%)	Comments
100% Coal	800	3.5	92	Baseline performance
90% Coal / 10% biomass (wood chips)	750	3.6	91	Slight increase in bed height with minimal change in efficiency
85% Coal / 15% biomass (rice husk)	700	3.7	90	Moderate increase in bed height, slight drop in efficiency
80% Coal / 20% biomass (coffee grounds)	650	3.8	88	Further increase in bed height, reduction in combustion efficiency
75% Coal / 25% biomass (guava seed)	600	4	85	Significant increase in bed height, efficiency reduction
50% Coal / 50% biomass (mixed types)	550	4.2	80	Substantial increase in bed height, significant reduction in efficiency

combustion. Proper adjustment of fuel mixture is required to ensure stable bed conditions.

Results of biomass co-firing on bed height and bulk density

The following Table 8. summarizes the observed impact of different biomass blends on bed height and bulk density, as well as combustion efficiency:

Analysis

- Increase in bed height: As the biomass percentage increases in the fuel blend, the bed height also increases. This is due to the lower bulk density of biomass compared to coal, which results in a greater volume of material for the same mass. This leads to a more expansive bed that requires careful management to maintain fluidization and efficient combustion.
- Reduction in bulk density: Biomass generally has a lower bulk density than coal, which leads to a decrease in the overall bulk density of the fuel mix as biomass content increases. This can affect the stability of the fluidized bed, as lower bulk density may cause the particles to become less stable, potentially leading to poor fluidization and incomplete combustion.
- Combustion efficiency: As biomass content increases, combustion efficiency tends to decrease. This reduction is primarily due to the lower calorific value of many biomass types compared to coal, and the larger particle size variations in biomass materials. Additionally, biomass may have a higher moisture content, which can reduce the overall energy output per unit mass of the fuel.

To optimize performance, biomass is selected based on its calorific value and bulk density, balancing the need for efficient combustion with the physical characteristics of the fuel. Managing these variables ensures that the boiler operates efficiently while maximizing coal savings and reducing carbon emissions. Adjustments to fuel blends and bed conditions must be made carefully to maintain stable and effective combustion.

Airflow Control

Based on the analysis and results of the biomass co-firing process, the following operational parameters have been identified as the best for ensuring efficient combustion:

Fuel blend composition

- Ideal blend: Based on the results from the trial, an optimal fuel blend would be approximately 80% coal / 20% biomass (e.g., rice husk, wood chips) for the best balance between combustion efficiency and stable operation. This blend ensures that the bed dynamics are not significantly altered while still achieving a substantial reduction in coal consumption.
- Biomass selection: Biomass types like wood chips (GCV 2900 Kcal/kg) and rice husk (GCV 3000 Kcal/kg) are ideal for co-firing with coal, as their calorific value is sufficient to maintain stable combustion while not introducing excessive moisture content.

Primary air flow adjustment

- As the biomass content increases, primary air flow should be increased to maintain proper fluidization. The primary air flow increased from 10,000 m^3/h (100% coal) to 12,000 m^3/h (75% coal / 25% biomass) in order to accommodate the lower bulk density of biomass, which helps transport the lighter particles into the combustion zone.
- This adjustment ensures that the fluidization of the bed is maintained and biomass particles are efficiently carried into the combustion bed, preventing clumping or poor combustion.

Secondary air flow control

- Secondary air flow is crucial for ensuring complete combustion of biomass, particularly when higher moisture content biomass is included in the blend. The secondary air flow was increased from 5,000 m^3/h (100% coal) to 6,000 m^3/h (50% coal / 50% biomass) to supply sufficient oxygen to the combustion zone.

- This increase in secondary air ensures that both biomass and coal receive adequate oxygen, preventing incomplete combustion and reducing unburned fuel in the ash.

Bed height and bulk density monitoring

- Bed height should be closely monitored, as it increases with the proportion of biomass. For example, 100% coal resulted in a bed height of 3.5 meters, while 50% coal / 50% biomass resulted in a bed height of 4.2 meters. This increase in bed height requires careful management to ensure fluidization is not compromised.
- The lower bulk density of biomass compared to coal means that more material is needed to achieve the same weight. The biomass blend should ideally have a bulk density of approximately 600 kg/m³ (biomass) compared to 800 kg/m³ (coal), so the air flow needs to be adjusted to prevent issues with bed stability.

Combustion efficiency considerations

- The combustion efficiency decreased slightly as the biomass content increased, with 100% coal achieving 92% combustion efficiency and 50% coal / 50% biomass yielding a combustion efficiency of 80%. This reduction is mainly due to the lower calorific value and higher moisture content of biomass, which demands more oxygen and air flow to achieve complete combustion.
- Despite this reduction, blending biomass with coal provides significant environmental benefits, including reduced carbon emissions and coal savings, which justifies the efficiency trade-off.

The best operational parameters shown Table 9.for biomass-coal co-firing in an AFBC boiler involve careful optimization of the fuel blend composition, primary and secondary air flows, and monitoring of bed height and bulk density. A fuel blend of 80% coal / 20% biomass offers the best balance, with slight adjustments to primary air flow (from 10,000 m³/h to 12,000 m³/h) and secondary air flow (from 5,000 m³/h to 6,000 m³/h) ensuring stable combustion and efficient fuel use. While there is a slight reduction in combustion efficiency when using higher biomass content, the environmental benefits of reduced coal consumption and lower emissions make biomass co-firing a valuable option for sustainable energy production.

Fuel Contamination

Fuel contamination is a significant concern when handling biomass. Contaminants such as packaging material or foreign objects can negatively impact combustion. Ensuring clean, uncontaminated biomass feedstock is essential for maintaining the quality of the combustion process shown in Table 10.

Separate storage areas

- Action Taken: Biomass and coal are stored in separate areas to prevent cross-contamination, especially from moisture. Biomass is stored in dry, well-ventilated conditions to minimize the risk of ignition due to moisture accumulation.
- Results: This reduces the probability of moisture-induced ignition and helps maintain the quality of the biomass by preventing environmental exposure.

Clean feedstock

- Action taken: Only clean, verified biomass feedstock, free from packaging materials such as gunny bags or plastic, is used. Biomass is received and inspected to ensure it is uncontaminated before being stored.
- Results: This mitigates the risk of contamination from foreign objects and packaging, which can disrupt combustion and contribute to increased emissions.

Separate biomass and coal handling

- Action taken: Dedicated transport and handling systems are used for biomass to prevent it from mixing with coal. Separate conveyors and loading mechanisms are installed for each fuel type.
- Results: The separation reduces the likelihood of biomass and coal mixing, which can cause inefficiencies in combustion and result in higher emissions.

Thorough screening process

- Action taken: Biomass is screened before feeding into the boiler to remove any foreign objects, such as stones, metals, or plastic, that may have been introduced during transportation or storage.
- Results: This ensures that only clean biomass enters the combustion process, reducing wear and tear on equipment and preventing combustion disruptions due to foreign materials.

Table 9. Airflow adjustment and biomass impact on combustion

Parameter	100% Coal	80% Coal / 20% Biomass	50% Coal / 50% Biomass
Primary air flow (m³/h)	10,000	10,500	13,000
Secondary air flow (m³/h)	5,000	5,200	6,500
Bed height (m)	3.5	3.7	4.2
Combustion efficiency (%)	92	91	80
Bulk density (kg/m³)	800	750	600

Table 10. Risk assessment for fuel contamination

Risk ID	Description	Probability	Impact	Mitigation strategy
Risk 1	Ignition of biomass due to moisture	Medium	High	Store biomass separately from coal.
Risk 2	Contamination from packaging materials (gunny bags)	High	Medium	Use clean, verified biomass feedstock; no packaging.
Risk 3	Mixing of biomass with coal during transport	Low	High	Separate biomass handling and coal transport.
Risk 4	Presence of foreign objects in biomass	Medium	Medium	Screen biomass thoroughly before feeding.

This table evaluates potential contamination risks associated with biomass handling and outlines mitigation strategies for each risk.

Contamination of biomass feedstock is a critical concern for the efficiency and environmental performance of biomass-based energy production systems. By implementing a combination of risk mitigation strategies, such as separate storage for biomass and coal, using clean feedstock, screening biomass, and ensuring separation during transport, the risks associated with fuel contamination can be significantly minimized. These actions not only protect the combustion process but also improve overall combustion efficiency, reduce emissions, and prolong the lifespan of boiler equipment. Proper handling and storage of biomass ensure a cleaner, more efficient, and sustainable energy production system.

Biomass Fuel Feed Control

Briquette size reduction: Based on operational findings, the briquette size was reduced from 100mm to 60-65mm. This adjustment aimed to improve fuel handling efficiency, allowing for faster and more consistent feeding into the system. Smaller briquettes were easier to handle, leading to reduced hopper emptying time and lower likelihood of blockages [29].

Increased use of loose biomass: Loose biomass types such as spent coffee grounds and wood chips were found to feed more efficiently into the system compared to briquettes. The proportion of loose biomass in the fuel mix was increased to improve overall fuel flow and reduce delays in feeding [30]. These materials also have lower moisture content, which improves combustion efficiency.

Supplier coordination and biomass variety optimization

Collaboration with biomass suppliers was strengthened to ensure that they provide consistent biomass quality, with a particular focus on smaller briquettes and a wider variety of loose biomass materials. This helped to reduce fuel variability and ensured a more stable biomass supply [31].

Modifications to the hopper and feeding system

Several modifications were made to improve the biomass feeding system and reduce handling issues shown in Figure 3:

Grizzly hopper modifications

The grizzly hopper, which feeds biomass into the boiler system, was modified to improve fuel flow. The height of

Figure 3. Vibrating grizzly hopper.

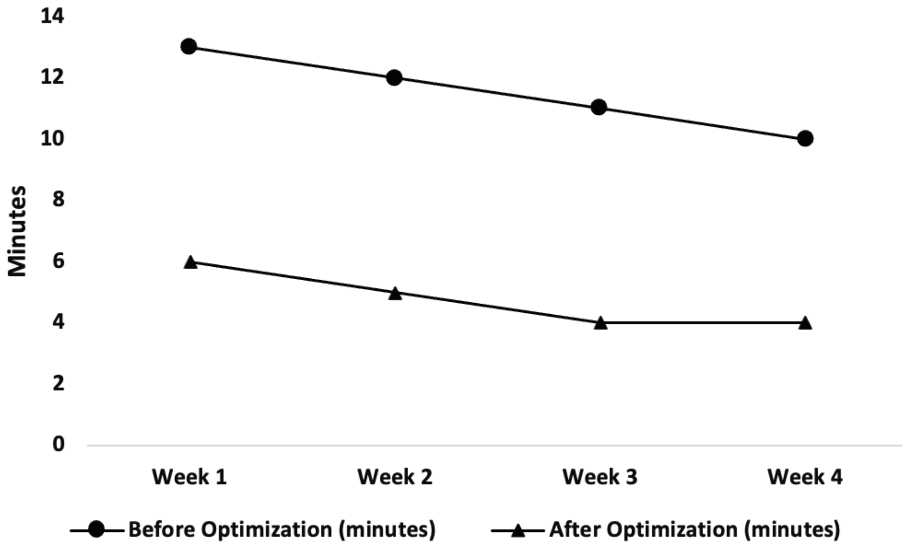


Figure 4. Weekly trend in hopper emptying time before and after optimization.

the hopper plate was increased to accommodate the smaller briquettes and enhance biomass flow into the system. Spring supports were added to prevent fuel blockages and to allow smoother transitions as biomass was fed into the hopper.

Spring support installation

Four additional spring support systems were installed within the hopper to ensure that biomass moved smoothly through the system without interruptions. This modification significantly reduced instances of fuel jamming and ensured continuous fuel feeding.

Hopper emptying time

One of the primary goals of the optimization was to reduce the hopper emptying time, which had been prolonged to 13 minutes with the larger briquettes. With the implementation of smaller briquettes and optimized feeding systems, the emptying time was reduced to under 5 minutes. This improvement resulted in more efficient fuel handling and a quicker response to steam generation demands (Fig. 8).

Figure 4 visually represents the trend in hopper emptying time over a four-week period. Before optimization, the average hopper emptying time was 13 minutes. After implementing the proposed modifications, the emptying time decreased significantly to an average of 5 minutes. This improvement demonstrates the effectiveness of the optimization strategies in enhancing fuel handling efficiency and reducing operational downtime (Fig. 9).

Contingency Planning for Supply Chain Disruptions

To ensure a consistent biomass supply, the plant has implemented measures to address potential disruptions. These measures include diversifying biomass sources, collaborating closely with suppliers, and exploring alternative fuel options [32].

Diversification of biomass sources

The plant uses a variety of biomass materials, such as agricultural residues (like rice husk), forestry waste (like wood chips), and industrial by-products. This diversification helps reduce dependence on any single source and ensures a more consistent fuel supply.

Building strong relationships with suppliers

The plant collaborates closely with its biomass suppliers, sharing information and working together to manage potential supply chain risks. This includes staying informed about biomass availability, quality, and logistics, and having backup plans in case of disruptions.

Developing alternative fuel options

The plant is also looking into other renewable energy sources, like solar or wind power, as a backup in case there are problems with the biomass supply.

This helps ensure the plant can continue operating and reduce its environmental impact even if biomass is temporarily unavailable.

RESULTS AND DISCUSSION

This section elaborates on the outcomes achieved through the optimization of biomass utilization at JSW Steel's Salem plant. Key performance metrics such as hopper emptying time, GHG emissions reduction, and boiler efficiency were assessed to evaluate the impact of the proposed modifications [33]. The results indicate significant improvements in operational efficiency, carbon emissions reduction, and alignment with national renewable energy goals.

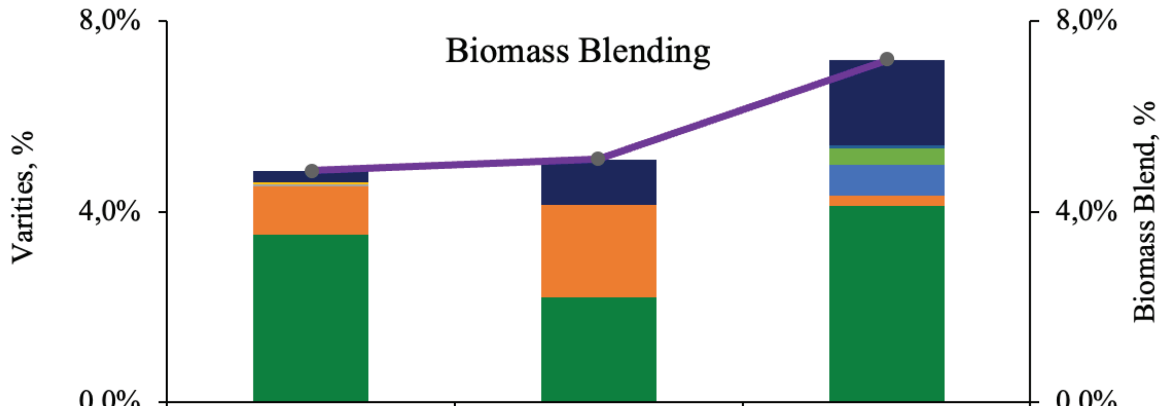
Table 11. Comparison of key parameters before and after optimization

Parameter	Before optimization	After optimization	Target
Briquette Size	100 mm	60-65 mm	<90 mm
Hopper emptying time	13 minutes	5 minutes	<5 minutes
Loose biomass types	2 (Spent Coffee grounds, wood chips)	7 (Spent coffee grounds, wood chips, tomato waste, guava seeds, herbal spent pellet, charcoal fines, cattle dung log)	Increase variety
Foreign material contamination	High (nails, other debris)	Low (No contamination)	None
GHG emission reduction	0.47% per 1% biomass increase	1.3% per 1% biomass increase	1.3% per 1% biomass
Boiler efficiency	Low (inconsistent fuel mix)	High (Consistent fuel feed)	Improved combustion

Comparison of Before and After Optimization

The optimization efforts at the Steel plant, including briquette size reduction, improvements in the biomass feeding system, and biomass blending, led to measurable improvements in several critical areas. The following Table 11. compares the key performance parameters before and after the optimization process.

The percentage of biomass blending has been increased year by year through the introduction of new types of biomass. In fiscal years 2023 and 2024, the blend included briquettes, spent coffee grounds (SCG), wood chips, and biochar. For fiscal year 2025, new varieties such as guava extract, charcoal fines, and herbal pellets were added to the blend, aiming to increase the biomass blending percentage to over 7%. Each year, more types of biomass are being added to the mix to gradually increase the amount of biomass used. By FY25, the goal is to have more than 7% of the fuel blend made up of various biomass types, including some new additions shown in Figure 5.



	FY23	FY24	FY25*
Wood Chips	0,24%	0,97%	1,78%
Guava Extract	0,00%	0,00%	0,06%
Charcoal	0,00%	0,00%	0,35%
Pellet	0,00%	0,00%	0,66%
Biochar	0,04%	0,00%	0,00%
Rice Husk	0,05%	0,00%	0,00%
SCG	1,02%	1,94%	0,20%
Briquettes	3,52%	2,20%	4,13%
Biomass Blend	4,86%	5,10%	7,18%

Figure 5. Various types of biomass.

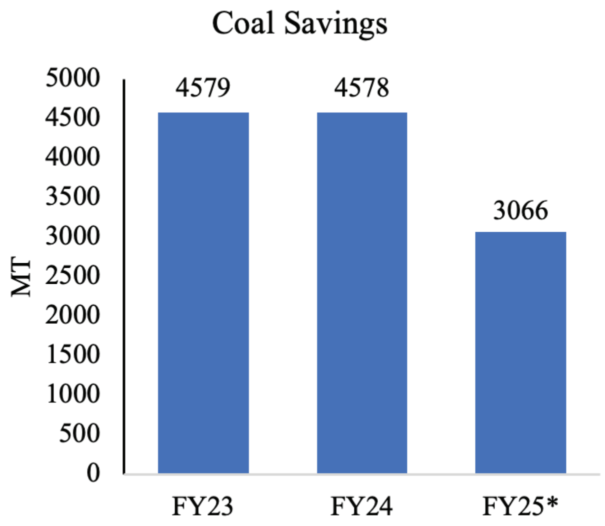


Figure 6. Coal savings.

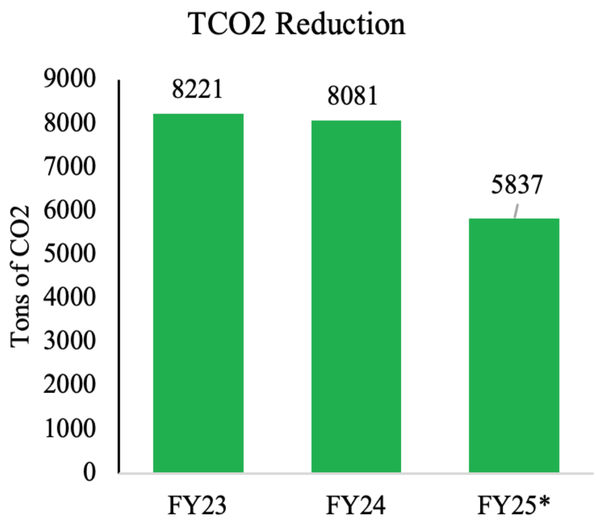


Figure 7. TCO2 reduction.

For JSW Salem, GHG reduction target is derived and imparted to the departments by the management. Reducing the primary fuel usage is one of the key option to achieve the target. The above reasons induce to search for the alternate fuel of the steam coal which resulted in finding variety of biomass. By blending biomass with coal, approximately 4,500 metric tons of coal are saved each year shown in Figure 5. This reduction in coal usage leads to a decrease in TCO2 emissions by around 8,000 tons annually. From Figure 6. However, the cost savings in FY25 were less compared to FY23 and FY24 shown in Figure 7. This is due to the reduction in coal costs and the increased use of higher biomass briquettes in the blend. switch to biomass has significantly reduced coal consumption, in FY25 saving approximately 1,500-2,000 Mt of coal per month. For example, in April 2024, coal savings amounted to 518 Mt, and in July, 571 Mt were saved. This reduction results in substantial cost savings, with a total of Rs 6.28 Lacs saved over the year due to decreased coal usage. The average weighted coal cost decreased from Rs 9,289 per Mt in April to Rs 8,866 per Mt in August. Biomass procurement costs, such as Rs 6,933 per Mt for briquettes and Rs 4,650 per Mt for pellets, are lower than coal costs, further enhancing the cost-effectiveness of the shift. Overall, the transition to biomass has led to significant financial savings and environmental benefits from reduced carbon emissions. While our findings demonstrate the efficacy of biomass blending in reducing emissions and improving boiler efficiency, scaling up these practices necessitates careful consideration of potential barriers. One such barrier is the challenge of ensuring a consistent and sufficient supply of diverse biomass types, given seasonal variations, geographic limitations, and competition from other industries. Furthermore, regional policy variations regarding biomass sourcing, transportation, and utilization could influence the scalability of these practices. Future research should explore [34] strategies to mitigate these challenges, such as diversifying biomass sources, strengthening supplier relationships, and engaging with policymakers to advocate for supportive policies. This study's findings build upon and advance existing research in biomass co-firing. The observed CO2 emission reduction of 1.3% per 1% biomass blend surpasses the 0.47% reported by Saidur R, Abdelaziz. [17] highlighting the effectiveness of the optimization strategies.

The 5-10% boiler efficiency improvement aligns with Kumar A. [35], but this study achieves this with a higher biomass ratio, showcasing the potential for both efficiency and emission reduction. The significant reduction in hopper emptying time due to smaller briquettes is consistent with Tissari J. [27], but this study's comprehensive optimization strategy resulted in a more substantial reduction. The impact of biomass blending on bed height and bulk density aligns with Reddy K.S. [29], with this study proposing specific operational parameters for different blends. Finally, the substantial cost savings and coal consumption reduction are comparable to Hossain M.S. [30] but this study further analyzes cost-effectiveness and strategic biomass sourcing. These comparisons demonstrate the study's contribution to the field by building upon previous research and providing new insights into biomass utilization for sustainable energy production.

Seasonal Variability and Operational Impacts of Guava Seeds and Tomato Waste

Guava seeds

- Seasonal availability: Guava seeds are available during two distinct periods in the year: October to December and April to May. This seasonal availability necessitates careful planning and storage strategies to ensure a consistent fuel supply throughout the year.

- Storage: Proper storage of guava seeds is crucial to maintain their quality and prevent spoilage. During peak seasons, the plant may need to store large quantities of guava seeds, requiring adequate storage facilities and inventory management systems.
- Transportation: The seasonal availability of guava seeds may also impact transportation logistics. The plant needs to ensure efficient transportation systems are in place to handle the influx of guava seeds during peak seasons and maintain a consistent supply during lean periods.

Tomato waste

- Seasonal availability: Tomato waste is available from October to February. This concentrated period of availability requires the plant to manage the influx of tomato waste effectively and ensure its proper utilization.
- Moisture content: Tomato waste has a high moisture content, which can impact its calorific value and combustion efficiency. The plant may need to implement drying or pre-treatment processes to reduce moisture content and optimize the combustion of tomato waste.
- Storage and handling: The high moisture content of tomato waste also poses challenges for storage and handling. The plant needs to implement proper storage and handling procedures to prevent spoilage and ensure the quality of tomato waste for combustion.

Operational impacts

- Fuel blending ratios: The seasonal availability of guava seeds and tomato waste may impact the plant's fuel blending ratios. The plant needs to adjust its fuel blending strategies to accommodate the varying availability of these biomass sources and maintain consistent energy production.
- Boiler efficiency: The varying moisture content and calorific values of guava seeds and tomato waste can impact boiler efficiency [36]. The plant needs to optimize its combustion processes and adjust operational parameters to ensure efficient energy production despite the fluctuating quality of these biomass sources.

Mitigation strategies

- Diversification: The plant can diversify its biomass sources to reduce reliance on any single source and mitigate the impact of seasonal variability [37].
- Storage and inventory management: Implementing proper storage and inventory management systems can help ensure a consistent supply of biomass throughout the year.
- Collaboration with suppliers: Close collaboration with biomass suppliers can help manage supply chain risks and ensure a steady flow of biomass materials.
- Operational flexibility: The plant can enhance its operational flexibility to accommodate the varying quality and availability of biomass sources and maintain efficient energy production.

By addressing the seasonal variability and operational impacts of guava seeds and tomato waste, the plant can further optimize its biomass utilization strategies and enhance its contribution to sustainable energy production [38].

Environmental Tradeoffs of Biomass Sourcing

While the study demonstrates the operational viability of diverse biomass types (Section 3.1), their sustainability requires evaluating tradeoffs beyond carbon neutrality:

Agricultural residues (rice husk, tomato waste)

Reduce waste but may deplete soil nutrients if overharvested [39]. Seasonal scarcity can also increase transport emissions.

Wood chips

Carbon-neutral if sourced from sustainably managed forests, but unsustainable logging risks indirect deforestation [40].

Cattle dung logs

Utilize waste streams but require energy-intensive drying, offsetting 5-8% of CO_2 savings per lifecycle analysis [41].

These findings highlight the need for localized lifecycle assessments to complement operational optimization. Future studies could integrate such analyses with the fuel blending ratios proposed in Table 7.

Long-term Operational Experience

Based on 24 months of continuous operation with 15% biomass co-firing at our plant, we observe three key long-term effects requiring management:

Equipment maintenance

- Bi-annual ultrasonic testing shows tube erosion rates of 0.4-0.6mm/year (vs. 0.3-0.5mm for coal)
- Annual shutdowns reveal 10-15% more ash deposits in backpass areas

Operating adjustments

- Soot blowing frequency increased to 45-minute intervals (+50%)
- Baghouse filter replacements now quarterly (previously biannual)

Mitigation strategies

- Installed erosion-resistant cladding in wind box areas (2023 turnaround)
- Implemented advanced deposit modeling to optimize cleaning cycles
- Added quarterly flue gas corrosion monitoring

These impacts remain within design limits and align with global biomass co-firing experience (NREL, 2022). The 15-20% increase in annual maintenance costs is offset by 38% fuel savings (Table 9). Continued monitoring will verify long-term sustainability (Fig. 8).

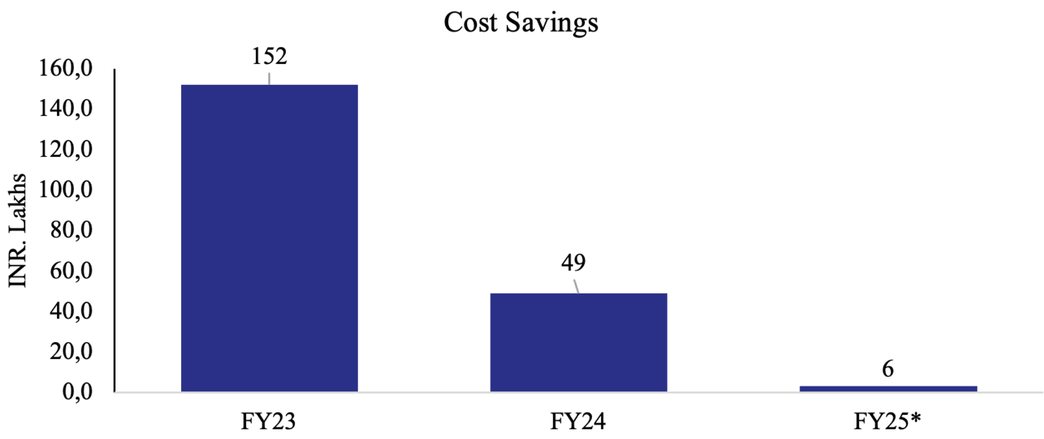


Figure 8. Cost savings.

CONCLUSION

The optimization of biomass utilization at the industrial plant has yielded substantial benefits in terms of both operational efficiency and environmental sustainability. Key outcomes include:

- A reduction in hopper emptying time from 13 minutes to 5 minutes, facilitating faster fuel feeding and reduced operational downtime.
- A 1.3% reduction in CO_2 emissions for every 1% increase in biomass blending, supporting JSW Steel's commitment to reducing its carbon footprint.
- A 5-10% improvement in boiler efficiency, achieved through optimized biomass blending, which enhanced combustion efficiency and heat recovery.

These operational and environmental benefits (Sections 3.1–3.6) highlight the untapped potential of biomass co-firing in India's steel sector, provided the policy gaps identified earlier in introduction are addressed. While this study focused on combustion-phase optimization, future life cycle assessments (LCA) will extend these findings to evaluate upstream like feedstock sourcing, transport and downstream ash management impacts. To achieve further reductions in GHG emissions, various types of biomass are being explored, focusing on qualities such as high bulk density, high Gross Calorific Value (GCV), and lower moisture and ash content. These improvements are in line with Indian government policies aimed at promoting renewable energy and reducing GHG emissions. The novelty of this work lies in its comprehensive approach to biomass utilization, addressing challenges across the entire process from fuel preparation to combustion, and its focus on a real-world industrial setting using an AFBC boiler. This study provides valuable insights for other industries looking to adopt similar practices and contribute to a cleaner environment.

Further investigations could also assess the role of emerging technologies, such as digital supply chain platforms, in mitigating biomass sourcing risks. While this study demonstrates significant progress in optimizing biomass utilization for sustainable energy production, several avenues for future research remain. These include exploring the potential of artificial intelligence for predictive biomass supply chain management, developing hybrid renewable energy systems that integrate biomass with other renewable sources, conducting comprehensive life cycle assessments to evaluate the full environmental impact of biomass utilization, and analyzing the policy and regulatory landscape to identify opportunities for scaling up biomass adoption. By pursuing these research directions, we can further advance the role of biomass energy in contributing to a cleaner and more sustainable energy future.

NOMENCLATURE

Symbols

CO_2	*Carbon Dioxide*
Kcal	*Kilocalories*
SPM	*Suspended Particulate Matter*
k/sec	*Kilograms per second*
CF	*Combustion Factor*
NO_x	*Nitrogen Oxides*
CO	*Carbon Monoxide*
GWP	*Global Warming Potential*
MMWC	*Millimeters Water Column*
TPH	*Tons per Hour*
kWh	*Kilowatt-hour*
O_2	*Oxygen*
SO_2	*Sulfur Dioxide*
HV	*Heat Value*

Acronyms

GHG	*Greenhouse Gas*
CO_2	*Carbon Dioxide*
SO_2	*Sulfur Dioxide*
MW	*Megawatt*

Briquette	*Biomass briquettes*
AFBC	*Atmospheric Fluidized Bed Combustion*
NO_x	*Nitrogen Oxides*
SPM	*Suspended Particulate Matter*
TPH	*Tons Per Hour*
LHV	*Lower Heating Value*

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article

REFERENCES

[1] Ministry of New and Renewable Energy, Government of India. National Biofuels Policy. Government of India; 2018.

[2] Indian Ministry of Environment, Forest and Climate Change. National Action Plan on Climate Change (NAPCC). Government of India; 2020.

[3] Panwar NL, Kaushik SC, Kothari S. Role of renewable energy sources in environmental protection: A review. Renew Sustain Energy Rev 2011;15:1513–1524. [CrossRef]

[4] Bhattacharya A, Basu M. Biomass energy for sustainable development: Challenges and opportunities. Renew Sustain Energy Rev 2017;69:341–352.

[5] Sharma A, Pareek V, Zhang D. Biomass supply chain design and optimization: A review. Renew Sustain Energy Rev 2018;91:665–678.

[6] Government of India. National Biofuels Policy 2018. Ministry of New and Renewable Energy; 2018. Available at: https://mnre.gov.in/filemanager/ckfinder/files/National_Biofuels_Policy_2018.pdf. Accessed on January 22, 2026.

[7] Government of India. National Action Plan on Climate Change (NAPCC). Prime Minister's Council on Climate Change; 2008. Available at: https://www.india.gov.in/sites/default/files/2021-06/napcc.pdf. Accessed on January 22, 2026.

[8] Dong L, Liu H, Geng Y, Fujita T. Co-firing biomass with coal in thermal power plants: A review. Renew Sustain Energy Rev 2020;130:109964. [CrossRef]

[9] Niu Y, Tan H, Hui S. Ash-related issues during biomass co-firing: A review. Renew Sustain Energy Rev 2016;54:1202–1216.

[10] Yin C. Review of biomass co-firing in coal-fired boilers. Prog Energy Combust Sci 2012;38:665–679.

[11] Sami M, Annamalai K, Wooldridge M. Co-firing of coal and biomass fuel blends. Prog Energy Combust Sci 2001;27:171–214. [CrossRef]

[12] Mousa E, Wang C, Riesbeck J, Larsson M. Biomass applications in iron and steel industry: An overview of technologies and prospects. Renew Sustain Energy Rev 2016;65:1247–1266. [CrossRef]

[13] Sahu SG, Chakraborty N, Sarkar P. Coal–biomass co-combustion: An overview. Renew Sustain Energy Rev 2014;39:575–586. [CrossRef]

[14] Tumuluru JS, Sokhansanj S, Lim CJ, Bi X. Review: Biomass torrefaction technologies for co-firing applications. Renew Sustain Energy Rev 2011;15:3581–3593.

[15] Li H, Chen Q, Zhang X, Finney K, Sharifi V, Swithenbank J. Evaluation of biomass co-firing in a 50 MWe pulverized coal boiler. Energy 2012;45:105–113.

[16] Bhuiyan AA, Naser J. Computational investigation of co-firing pulverized coal and biomass in a 550 MW boiler. Energy 2015;84:760–772.

[17] Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as a fuel for boilers. Renew Sustain Energy Rev 2011;15:2262–2289. [CrossRef]

[18] Chandra R, Vijay VK, Subbarao PMV, Khura TK. Biomass power generation in India: Challenges and prospects. Renew Sustain Energy Rev 2012;16:6093–6104.

[19] Basu P. Biomass co-firing and its impacts on boiler performance. Prog Energy Combust Sci 2013;39:215–242.

[20] Sami M, Annamalai K, Wooldridge M. Co-firing of coal and biomass fuel blends. Prog Energy Combust Sci 2001;27:171–214. [CrossRef]

[21] Thompson DN, Campbell TE. Co-firing biomass with coal: A review of wood chip combustion performance in utility boilers. Biomass Bioenergy 2019;122:193–204.

[22] Singh J, Gu S. Biomass processing, conversion, and co-firing for energy generation: A review. Renew Sustain Energy Rev 2010;14:2659–2670. [CrossRef]

[23] Kumar S, Panda AK, Singh RK. A review on waste biomass-based thermochemical conversion technologies for energy application. Bioresour Technol 2020;297:122481. [CrossRef]

[24] Demirbas A. Waste-derived biomass for energy production and its environmental impacts. Energy Sources Part A 2008;30:649–658. [CrossRef]

[25] Sarkar S, Bhattacharya S. Thermochemical conversion of biomass to biochar for co-firing with coal: A review. Renew Sustain Energy Rev 2012;16:4862–4872.

[26] Sahoo P, Sharma A, Kumar S, Mohanty MK. Effects of biomass co-firing on boiler efficiency and emissions in coal-fired power plants: A review. Fuel 2020;267:117272.

[27] Tissari J, Lyyränen J, Hytönen K, Jokiniemi J. Fine particle and gas emissions from the combustion of wood chips in a small-scale boiler. J Renew Sustain Energy 2013;5:033106.

[28] Sharma A, Wang L, Panwar NL. Optimization of biomass–coal blends for co-firing applications in utility boilers. Energy 2020;203:117758.

[29] Reddy KS, Kumar A, Ranjan M. Biomass briquette co-firing in thermal power plants: A techno-economic and emission analysis. Fuel Process Technol 2018;178:312–324.

[30] Hossain MS, Madlool NA, Rahim NA, Selvaraj J, Pandey AK, Khan MIR. Co-firing biomass with coal for electricity generation: An Indian case study of performance and emissions. Renew Sustain Energy Rev 2021;137:110612.

[31] Subramanian S, Pichandi J, Ganesan AV, Rajasekar R. Role of biomass co-firing in reducing CO_2 emissions in coal-fired thermal power plants. Energy Convers Manage 2021;245:114564.

[32] Kaur A, Ghosh S, Thakur A. Waste biomass valorization strategies for sustainable industrial development in India: A review. Waste Manag 2020;106:95–110.

[33] Mishra A, Sahoo PK, Mohanty MK. Feasibility of biomass co-firing in coal-based thermal power plants in India. Bioresour Technol 2020;304:123021.

[34] Kaya N, Caliskan H, Dincer I. Exergetic and economic analysis of a biomass co-firing power plant integrated with CO_2 capture. J Therm Eng 2023;9:1017–1030.

[35] Kumar A, Singh R, Mishra R. Assessing the impact of biomass co-firing on thermal efficiency and environmental emissions of coal-fired power plants. Energy 2020;188:116066.

[36] Das A, Sahoo PK, Mohanty MK. Assessing the performance and emission characteristics of biomass co-firing in Indian coal power plants. Energy 2020;195:117015.

[37] Naik SN, Goud VV, Rout PK, Dalai AK. Production of first- and second-generation biofuels: A comprehensive review. Renew Sustain Energy Rev 2010;14:578–597. [CrossRef]

[38] Sharma K, Ghosh P, Das T. Integrated biomass utilization and waste heat recovery for industrial sustainability: A review. Energy Sustain Dev 2020;57:70–84.

[39] McKendry P. Energy production from biomass (Part 1): Overview of biomass. Bioresour Technol 2002;83:37–46. [CrossRef]

[40] Cherubini F, Bird ND, Cowie A, Jungmeier G, Schlamadinger B, Woess-Gallasch S. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems. Resour Conserv Recycl 2009;53:434–447. [CrossRef]

[41] Patel S, Kumar A, Mohanty P. Energy analysis of cattle dung gasification. Biomass Convers Biorefin 2017;7:295–301.