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Transforming Paper Mill Waste into Green Boiler Fuel: Advancing Circular Economy and Decarbonization in Papermaking

Jagdeep Hira *
CEO-Operations

*Suresh Babu**
Vice President, Process Excellence

*Sudhanshu Ranjan Singh**
Assistant Manager, Process Excellence

*Adwitiya Gaurav**
Sr. General Manager
Engineering Utility)

* Kuantum Papers Ltd

Abstract: *The pulp and paper industry utilizes combustible residues generated during raw material preparation, screening, chip washing, debarking, board manufacturing, and wastewater treatment operations. Traditionally, this waste is treated as disposal material, leading to environmental challenges, land use issues, transport costs, and additional operational work. At Kuantum Papers, we have developed a combined method to convert these residues including veneer chip dust, woody chip dust, wheat straw dust, wet chip washing dust, white board sludge, and chip fines into an alternative boiler fuel. This innovation enables partial replacement of coal, generating steam sustainably. Based on characteristics such as calorific value, moisture susceptibility, ash properties, coal replacement potential, and CO_2 generation, we determined that the calorific value of straw and wood waste is 2,500–3100 kcal/kg, while that of white board sludge is 1,000–1,200 kcal/kg.*

Kuantum Paper operates with a production capacity of 540 TPD and requires 450 TPD of bleached pulp, consuming approximately 160,000 TPA of wheat straw and 165,000 TPA of woody material. From this furnish, 110–120 TPD of recoverable residue(7.0% from wheat straw &13% from Wood) can replace 72.68 TPD of coal, thereby reducing 177.35 TPD of CO_2 emissions. Over the course of one year, this substitution would eliminate the use of 23,985.8 tons of coal and prevent the release of 58,525.3 tons of fossil CO_2. Additionally, generating 40,000–45,000 tons of energy annually from biomass increases the share of green fuel in boiler operations from 33% to 45%, thereby supporting a circular economy in paper production.

Keywords: *Industrial waste; Biomass fuel; Combustible waste, Carbon reduction; Sustainability, Circular economy.*

1. Introduction

The pulp and paper industry is inherently energy-intensive, with steam required across pulping, chemical recovery, washing, evaporation, drying, and paper machine operations. Steam generation directly impacts energy costs, boiler efficiency, fossil fuel consumption, and environmental performance. Since most paper mills rely on coal-fired boilers, the sector contributes significantly to fossil carbon emissions, accounting for nearly 2% of total industrial emissions in 2022. [1] Globally, fossil fuels such as coal, oil, and natural gas supply almost 80% of energy demand, amounting to more than 400 EJ annually. [2] However, these finite resources drive global warming, acid rain, urban smog, and greenhouse gas accumulation. Reducing reliance on fossil fuels, while improving energy efficiency, is therefore critical for industrial sustainability. A process-integrated waste-to-energy model has been developed for paper mills, focusing not only on coal replacement but also on industrial waste management through energy recovery. Fuel suitability is evaluated based on gross calorific value, moisture sensitivity, combustion behavior and ash formation, coal substitution potential, and CO_2 mitigation capacity. The GCV of woody waste typically ranges between 2,500–2,800 kcal/kg, while that of white board sludge lies between 1,000–1,200 kcal/kg, compared to coal at 3,600–4,000 kcal/kg. [3] A case study at Kuantum Papers shows that 110–120 TPD of recoverable waste can substitute approximately 72.68 TPD of coal, avoiding 177.35 TPD of CO_2 emissions. Over 330 working days, this results in annual savings of 23,985.8 tons of coal and a reduction of 58,525.34 tons of CO_2, thereby promoting a circular economy and enabling sustainable steam generation.

2. Integrated Waste-to-Wealth Pathways in Paper Mill Operations

In the integrated waste-to-wealth system, internal conversion of paper mill waste into thermal energy is achieved by channeling combustible residues into boiler operations. Waste materials such as dust from raw material screening, chip-washing residues, and white board sludge are systematically collected, conditioned, and utilized as auxiliary boiler fuel for steam generation.

While the acceptable fraction of raw materials proceeds through the traditional pulping process, segregated residues including wood chip dust, veneer dust, wheat straw dust, wet dust, and sludge are directed to the boiler for controlled combustion.

This integrated approach not only reduces the volume of disposed material but also ensures efficient utilization of waste, decreases coal consumption for steam production, and advances the principles of the circular economy by turning waste into a valuable energy resource.

2.1 Veneer Chip Residue Recovery Pathway

Veneer chips is a lignocellulosic feedstock, which is passed through screens to separate dust, fines, sand and over-and-under-size fractions. The good fraction is passed onto chip washing and then digester feed and the dry dust is collected and used as combustible wood-based waste after screening (Fig. 1). It is presumed that veneer chip dry dust can be used as wood-based biomass since the feedstock is of a woody nature and known GCVwet values for biomass chips and wood chips are approximately 2500-2800 kcal/kg. [4,5,6]

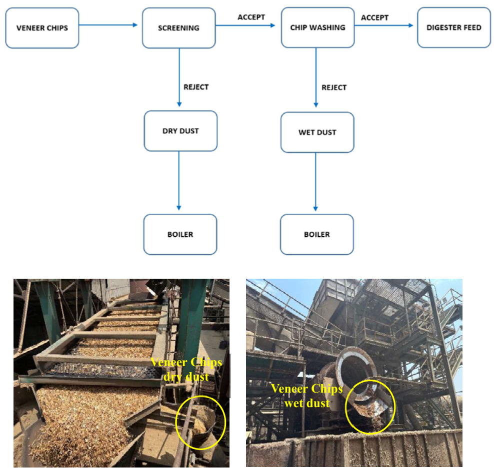

Fig. 1: Veneer chip residue recovery for use in boiler

2.2 Wood Chip Screening Dust Recovery Pathway

Wood chips are screened before entering the digester feed system. The accepted chips are retained for pulping, while dry dust, fines, bark fragments, and undersized particles are separated. Wood chip dust has high fuel value and is one of the most suitable paper mill residues for boiler integration (Fig. 2). Reported values show wood chips at approximately 2500-2800 kcal/kg, [8] while dry woody biomass generally has heating values in the range of 18.7–21.9 MJ/kg depending on species and composition. Moisture strongly affects usable energy; practical wood chip fuel at 30% moisture has lower net calorific value than oven-dry wood. [6]

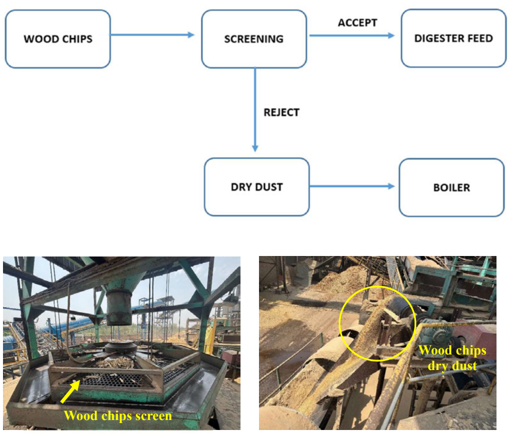

Fig. 2: Wood chip screening and dust recovery for use in boiler

2.3 Wheat Straw Dust Recovery Pathway

Wheat straw is processed through screening and washing before being routed to digester feed. Screening produces dry straw dust, while washing produces wet fines and dust. Wheat straw dust has significant thermal value but requires special attention due to its ash chemistry (Fig. 3). Reported biomass data indicates that wheat straw (GCV) is around 3100-3400 kcal/kg, wheat straw HHV of 17.19 MJ/kg as received and 19.10 MJ/kg on dry basis. [7] Wheat straw also contains ash, chlorine, potassium, and silica-bearing compounds, with chlorine around 1530 mg/kg as received and potassium around 6300 mg/kg on dry basis for one wheat straw sample. These constituents are important because alkali metals and chlorine can contribute to slagging, fouling, and corrosion in boilers. [8]

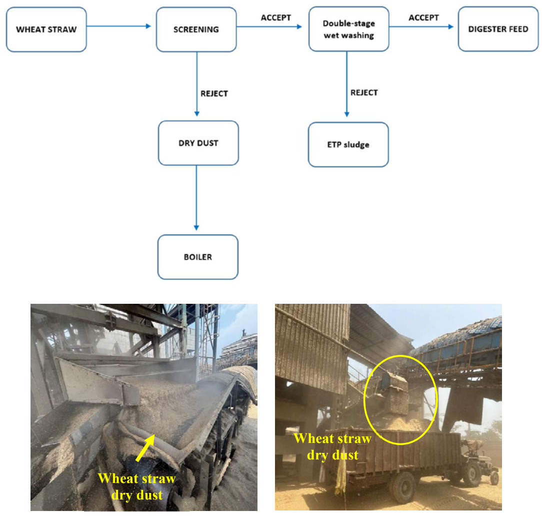

Fig. 3 Wheat straw dust recovery for use in boiler

2.4 White Board Sludge-to-Energy Pathway

White board sludge is generated from board manufacturing, recovered fiber processing, centri-cleaner loss recovery, filler loss, and wastewater treatment (Fig. 4). It typically contains short fibers, fines, fillers such as calcium carbonate and clay, coating pigments, and biological solids. Paper sludge has lower calorific value than dry biomass because it contains high moisture and inorganic material. Paper sludge reported an average (GCV) of 1000-1200 kcal/kg for undried paper sludge. The same work reported that increasing paper sludge content reduces calorific value and increases ash content, but increases ash melting temperatures, which can be useful when co-combusting with biomass that has low ash fusion temperature. [9]

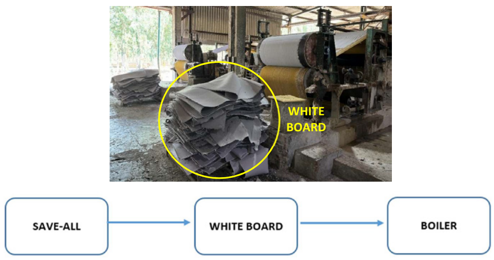

Fig. 4: White board sludge recovery for use in boiler

3. Materials, Fuel Properties based on the Internal & External Lab testing

3.1 Fuel Inputs Considered

The study considers coal as the baseline boiler fuel alongside five internally generated waste-derived alternatives: veneer chip dry dust, wood chip dry dust, wheat straw dry dust, chip-washing wet dust, and white board sludge. These residues, produced during raw material screening, chip washing, and board/effluent treatment, are not treated as disposal streams. Instead, they are recovered, conditioned, and utilized as supplementary fuels in line with the waste-to-energy approach for sustainable steam generation.

The selected fuel streams vary significantly in calorific value, moisture content, ash behaviour, and combustion performance. Woody residues such as veneer chip dust and wood chip dust exhibit relatively high energy value and stable combustion. Wheat straw dust offers moderate energy potential but requires careful handling due to ash-forming constituents like silica, potassium, and chlorine. Chip-washing wet dust has diminished heat value because of its high moisture content, while white board sludge is limited by both moisture and inorganic filler load (Table 1). Nevertheless, when blended with higher-GCV biomass residues, wet dust and sludge play a crucial role in waste mitigation and contribute meaningfully to overall fuel sustainability.

Table 1. Fuel properties and data inputs used for waste-to-wealth evaluation

Fuel input	Source/Origin	Moisture %	Ash %	GCV- kcal/kg
Coal	Reference boiler fuel	15-18	35-40	3800
Veneer chip dry dust	Veneer chip screening	25-30	22-26	2500-2800
Wood chip dry dust	Wood chip screening	18-22	6.5-8.5	2500-2800
Wheat straw dry dust	Wheat straw screening	15-18	12-16	3100-3400
Chip washing wet dust	Chip washing rejects	40-45	4-5	1800-2000
White board sludge	Board manufacturing/ETP sludge	35-38	28-32	1000-1200

Study boundary

The study boundary covers the complete waste-to-energy pathway from residue generation to boiler utilization. It includes waste generation during raw material screening, chip washing, and white board sludge handling; segregation of combustible residues; conditioning through dewatering or blending; boiler integration; steam generation; coal-equivalent replacement; waste diversion; and fossil CO_2 avoidance.

The accepted raw material fractions that proceed toward pulping or digester feed are excluded from the energy recovery calculation. Only the separated combustible residue streams—veneer chip dry dust, wood chip dry dust, wheat straw dry dust, chip washing wet dust, and white board sludge—are considered for boiler fuel utilization. This boundary is consistent with the objective of the study, which is to evaluate industrial waste mitigation through sustainable biomass-based fuel integration rather than only direct coal replacement.

3.2 Fuel Characterization Framework

The suitability of each residue stream for boiler utilization was evaluated through a fuel characterization framework. The key parameters considered include moisture content, gross calorific value (GCV), net calorific value (NCV), ash content, volatile matter, fixed carbon, sulphur, nitrogen, chlorine, alkali metals, silica content, ash fusion temperature, bulk density, and particle size distribution. These parameters are important because paper mill residues differ widely in combustion behavior, energy content, ash generation, and handling characteristics.

Calorific value testing is especially important for paper-making biomass, paper by-products, sludge, and packaging-related residues, as the energy recovery potential depends strongly on moisture and inorganic content. Bomb calorimetry is commonly used for determining GCV and NCV of such fuel materials. [10] For sludge-based fuels, Lab testings reported that dried paper sludge may have a GCV of approximately 1000-1200 kcal/kg.

Woody residues such as veneer chip dust and wood chip dust have comparatively higher calorific value and better combustion stability. Inhouse and external lab analysis for biomass chips and wood chips are around 2500-2800 kcal/kg, [4,5] making these streams suitable as high-energy supplementary fuels. Wheat straw dust has moderate calorific value, around 3100-3400 kcal/kg but requires careful monitoring because wheat straw contains ash-forming constituents such as silica, potassium, and chlorine, which may influence slagging, fouling, and corrosion behavior in boilers. [8]

3.3 Coal-Equivalent Replacement Calculation

Coal-equivalent replacement was calculated using the heat-equivalent method. This method compares the useful heat input supplied by each waste-derived fuel with the heat input supplied by coal. [3]

$$\textbf{Coal saved (t/day)} = \frac{\textbf{Waste fuel used}\left(\frac{t}{\textbf{Day}}\right) \times \textbf{GCVwaste}}{\textbf{GCV coal}}$$

For the base calculation, coal GCV was considered as 3800 kcal/kg, representing a moderate-grade industrial boiler coal. The actual coal saving may vary depending on boiler efficiency, fuel moisture, combustion completeness, excess air, furnace temperature, and feeding stability. [11]

3.4 Carbon Footprint Calculation

Fossil CO_2 avoidance was calculated based on avoided coal combustion. The daily CO_2 reduction was estimated using the following equation:

CO_2 avoided (t/day) = Coal saved (t/day) × Coal emission factor

A coal emission factor of 2.44 tCO_2/t coal was used for the model case, consistent with Indian carbon accounting references reporting coal emission factors around 2.44–2.46 tCO_2/t coal [12].

For plant-specific reporting, CO_2 emissions should preferably be calculated from ultimate analysis of coal using the carbon fraction:

$$\mathbf{CO_2 = Coal\ saved \times C \times \frac{44}{12}}$$

where C is the carbon fraction of coal. The IPCC stationary combustion methodology supports fuel-based emission calculations using activity data, calorific value, emission factor, and oxidation factor.

4. Literature-Normalized Industrial Model Case

A normalized industrial model case was developed to quantify the technical potential of the proposed waste-to-energy pathway. The model considers internally generated combustible residues that are recovered, conditioned, and utilized as supplementary boiler fuel. The selected streams include veneer chip dry dust, wood chip dry dust, wheat straw dry dust, chip washing wet dust, and white board sludge.

A total residue recovery of 110-120 t/day (Table 2), which is shifted from disposal or low-value handling toward boiler-based thermal utilization. [13,14] The assumed quantities are representative values used for calculation and may be replaced with actual plant data during mill-level implementation.

Table 2. Assumed daily waste recovery model

Waste stream	Assumed recovered quantity, t/day	GCV used, kcal/kg
Veneer chip dry dust	20	2650
Wood chip dry dust	30	2650
Wheat straw dry dust	28	3250
Chip washing wet dust	15	1900
White board sludge	12	1100
Total waste diverted	115	2511 (weighted average)

5. Results and Discussion

5.1 Daily Waste Mitigation Potential

A total of 110-120 t/day of waste was internally generated paper mill residues from disposal toward boiler-based energy recovery. At 330 operating days/year, this corresponds to 36,300 t/year of waste mitigation. Waste diversion is especially important for chip washing wet dust and white board sludge because these streams usually require handling, dewatering, storage, transport, or disposal if not beneficially utilized.

Paper sludge management is widely recognized as a challenge for pulp and paper mills due to economic, environmental, and social costs associated with disposal. [15] Thermal utilization provides an opportunity to reduce waste volume and recover useful heat for steam generation.

5.2 Coal Conservation Potential

At a reference coal GCV of 3800 kcal/kg, the coal-equivalent replacement was calculated using the heat-equivalent method. The model indicates that 110-120 t/day of recovered residues can theoretically replace approximately 72.68 t/day of coal (Table 3).

Table 3. Coal-equivalent replacement potential

Waste stream	Quantity, t/day	GCV, kcal/kg	Coal equivalent, t/day
Veneer chip dry dust	20	2650	13.95
Wood chip dry dust	30	2650	22.32
Wheat straw dry dust	28	3250	23.95
Chip washing wet dust	15	1900	9.00
White board sludge	12	1100	3.47
Total	115	—	**72.68**

The highest contribution comes from dry biomass streams because wood chip dust, veneer chip dust, and wheat straw dust have much higher calorific values than sludge. Wood and veneer dust are particularly attractive because their GCV values are comparable to lower- and medium-grade industrial boiler coals. [5,16]

At 330 operating days/year, the estimated annual coal conservation is:

$$72.68 \times 330 = 23{,}984.4 \text{ t/year}$$

Thus, the waste-to-energy pathway can theoretically conserve approximately 23,984.4 t/year of coal.

5.3 Carbon Footprint Reduction

Using a coal emission factor of 2.44 tCO_2/t coal, the daily fossil CO_2 avoidance is calculated as:

$$72.68 \times 2.44 = 177.34 \text{ tCO}_2\text{/day}$$

Annual fossil CO_2 avoidance at 330 operating days/year is:

$$177.34 \times 330 = 58{,}522.2 \text{ tCO}_2\text{/year}$$

This reduction represents avoided fossil CO_2 emissions from coal displacement. Biomass-derived CO_2 is generally treated separately from fossil CO_2 in greenhouse gas accounting because biomass carbon belongs to the short-term biogenic carbon cycle, whereas coal combustion releases fossil carbon. [2] IPCC inventory methods support fuel-based emission calculations using activity data, calorific value, emission factors, and oxidation factors. [12]

5.4 Steam Generation Relevance

The practical industrial benefit of residue utilization is not only fuel substitution but also sustainable steam generation. Recovered residues provide additional heat input to the boiler furnace, reducing the amount of coal required to generate the same steam load.

The primary operating performance indicator should be:

$$\textbf{Specific coal consumption} = \frac{\textbf{Coal consumed (kg)}}{\textbf{Steam generated (Tons)}}$$

A successful waste-to-energy trial should show a reduction in kg coal/t steam without deterioration in steam pressure, steam temperature, boiler load stability, furnace draft, oxygen control, CO level, ash behavior, or stack emissions. Waste-derived fuels can reduce fossil fuel consumption, but co-combustion may alter fly ash and bottom ash characteristics. Therefore, ash chemistry, unburnt carbon, clinker formation, and particulate emissions should be monitored during boiler operation. Studies on co-combustion of paper mill wastes with coal indicate that waste-derived fuel utilization can reduce carbon emissions but may significantly change ash characteristics, requiring proper ash evaluation. [8,17]

5.5 Boiler Operational Risks and Control Strategy

The major operational risks associated with paper mill residue utilization include high moisture, low GCV, ash loading, slagging, fouling, corrosion, feeding instability, and emission variation. Wet dust and sludge reduce net heat release because part of the combustion energy is consumed in evaporating moisture (Table 4).

Wheat straw requires careful blending because chlorine, potassium, and silica-bearing ash constituents can influence slagging, fouling, and high-temperature corrosion. White board sludge must be dosed carefully because it has higher ash content and lower calorific value compared with woody biomass. [9]

Table 4. Technical risk-control matrix

Risk	Most affected stream	Control measure
High moisture	Wet dust, white board sludge	Dewatering, solar/waste-heat drying, blending with dry wood dust
Low GCV	White board sludge	Limit sludge fraction; co-feed with high-GCV wood/veneer dust
Slagging/fouling	Wheat straw dust	Monitor ash fusion temperature, K, Na, Si, Cl; maintain controlled blend ratio
Feeding instability	Dust and sludge	Use screw feeders, rotary feeders, controlled dosing, and bulk density monitoring
High ash loading	Sludge and wheat straw	Track bottom ash, fly ash, LOI, and clinker formation
Corrosion	Wheat straw	Monitor chlorine and alkali content; inspect super-heater and economizer zones
Emission variation	Mixed fuel	Monitor O_2, CO, NOx, SOx, PM, and unburnt carbon

Overall, it demonstrates that paper mill residues can be successfully converted into useful boiler fuel when supported by proper segregation, moisture management, optimized blending, controlled feeding, and continuous boiler performance monitoring. This creates a practical waste-to-wealth pathway that reduces disposal burden, conserves coal, lowers fossil CO_2 emissions, and supports sustainable steam generation.

6. Key Differences Between Biomass-Based Residues and Fossil Fuels

The utilization of biomass-based paper mill residues as boiler fuel provides both environmental and operational advantages over conventional fossil fuels. Table 5 summarizes the major differences between biomass fuels and fossil fuels relevant to industrial steam generation.

Table 5. Comparison of biomass-based residues and fossil fuels

Feature	Biomass-Based Residues	Fossil Fuels
Origin	Generated from recent organic materials such as wood dust, straw dust, bark, sludge, and paper mill residues.	Formed from ancient organic matter over millions of years.
Renewability	Renewable when sourced from sustainable process residues.	Non-renewable and finite.
Carbon Impact	Part of the short-term biogenic carbon cycle; helps reduce fossil CO_2 when replacing coal.	Releases fossil carbon stored underground, increasing greenhouse gas emissions.
Energy Density	Generally lower due to higher moisture and oxygen content.	Higher and more concentrated.
Operational Benefit	Reduces waste disposal, supports circular economy, and partially replaces coal.	Provides stable heat but increases fossil fuel dependency and ash burden.

7. Environmental and Economic Relevance

Using paper mill residues as boiler fuel reduces waste disposal, lowers coal consumption, and supports sustainable steam generation. However, biomass combustion still requires proper moisture control, blending, ash management, and emission monitoring. Woody residues provide better calorific value, while wet dust and sludge require conditioning before firing. Overall, biomass-based residue utilization converts waste into value and supports a practical waste-to-wealth pathway in paper mill operations. [14]

8. Conclusion

This study demonstrates that paper mill residues can be transformed from disposal liabilities into valuable energy assets through an integrated waste to energy framework. By utilizing veneer chip screening dust, wood chip screening dust, wheat straw dust, chip washing wet dust, and white board sludge, the mill achieves sustainable steam generation while simultaneously reducing the burden of waste disposal, lowering coal dependency, and mitigating fossil carbon emissions.

In doing so, the approach not only recovers energy from diverse residue streams but also advances circular resource management, turning operational by products into reliable supplementary fuels that support both environmental stewardship and energy efficiency.

Key Findings

- **Woody residues such as veneer chip dust and wood chip dust exhibit strong fuel potential, with gross calorific values (GCV) of 2,500–2,800 kcal/kg, making them reliable supplementary boiler fuels.**
- **Wheat straw dust provides moderate energy value of 3,100–3,400 kcal/kg and can significantly contribute to boiler heat input when blended appropriately.**
- **White board sludge, though limited to 1,000–1,200 kcal/kg, plays a vital role in waste mitigation when co fired with higher GCV biomass residues.**
- **A representative model of 110–120 tons/day of recoverable residues can divert approximately 36,300 tons/year of waste from disposal.**
- **On an energy equivalent basis, this utilization can replace about 72.68 tons/day of coal, equivalent to 23,985.8 tons/year of coal conservation.**
- **With a coal emission factor of 2.44 tCO_2/ton coal, the avoided fossil emissions are estimated at 177.35 tCO_2/day, or roughly 58,525.3 tCO_2/year.**

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