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Bio-Based Resources and Energy Recovery in Kraft Paper Manufacturing

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Abstract: *The pulp and paper sector, particularly Kraft paper mills, generates large volumes of wastewater rich in organic matter, posing significant environmental challenges. This study investigates the potential of converting such effluents into compressed biogas (CBG) through anaerobic digestion followed by gas upgrading. Research was conducted at a semi-Kraft paper mill with a production capacity of 350 TPD, discharging approximately 3,500–4,000 m³ of wastewater daily. Biogas produced from the anaerobic treatment system was upgraded via pressure swing adsorption to comply with IS 16087:2016 standards. Monthly monitoring confirmed stable yields of 1.99–2.82 tonnes of CBG, corresponding to reductions of 15.8–22.3 tCO_2e emissions per month. The findings highlight that wastewater-to-CBG conversion in the paper industry is both technically feasible and environmentally beneficial, offering a reliable pathway to substitute fossil fuels while mitigating greenhouse gas emissions.*

Keywords: *Kraft paper wastewater, Anaerobic digestion, Compressed biogas (CBG), Renewable energy recovery, Carbon emission mitigation.*

Introduction:

The pulp and paper industry is one of the largest industrial sectors worldwide, with Kraft-based mills dominating production due to their efficiency in extracting cellulose fibres. However, the process generates substantial volumes of wastewater enriched with lignin, hemicellulose, and other organic compounds. These effluents, if untreated, contribute to high COD, BOD, and colour pollution, posing serious environmental risks to aquatic ecosystems and regulatory compliance [1, 2].

Wastewater management remains a critical challenge, as conventional treatment methods often struggle to balance cost-effectiveness with sustainability. Integrating anaerobic digestion offers a promising solution by converting organic-rich effluents into biogas, which can be upgraded to CBG. The application of biogas plants within paper mills not only mitigates wastewater pollution but also provides renewable energy, reduces greenhouse gas emissions, and substitutes fossil fuels [3, 4].

Kraft Paper Manufacturing Process

The Kraft pulping process begins with debarking and chipping softwood logs—commonly pine or spruce—into uniform fragments. These wood chips are subjected to high-temperature (150–170 °C) and high-pressure cooking in a digester using white liquor, a chemical mixture of sodium hydroxide (NaOH) and sodium sulphide (Na_2S). This treatment dissolves lignin, liberating cellulose fibres to form brown pulp. The residual black liquor, containing dissolved organic and inorganic substances, is separated and routed to the recovery system [1].

Subsequent stages involve pulp washing, screening, and optional bleaching using chlorine dioxide or oxygen-based agents to achieve the desired brightness. The refined pulp is then processed on a paper machine, where it undergoes pressing, drying, and finishing to produce paper sheets. A cornerstone of sustainability in this process is the black liquor recovery boiler, which facilitates chemical recycling and steam generation for energy. Nonetheless, wastewater discharged from pulping, bleaching, and washing operations continues to present significant environmental challenges due to its high organic load, colour, and COD [2, 5].

Wastewater Generation in the Kraft Process

Water consumption in Kraft paper manufacturing is substantial, with modern integrated mills typically requiring 20–60 m³ of water per metric ton of paper, depending on process integration and recycling efficiency. In older facilities, usage levels were historically much higher, reaching up to 227 m³ per ton. Advances in closed-loop systems have significantly reduced this demand, with chemical pulp and paper mills now operating in the range of 9–27 m³ per ton [1, 6]. Wastewater generation is distributed across key stages of production: wood preparation (10–15%), pulping and washing (40–50%), bleaching (20–30%), and paper machine operations (10–20%). For unbleached Kraft pulp, effluent volumes range between 15–38 m³ per ton, while bleached processes produce higher flows due to additional rinsing requirements [5].

Sustainable Treatment: Anaerobic Digestion and Biogas Production

Anaerobic digestion offers a promising solution for managing Kraft mill wastewater while simultaneously recovering renewable energy. In this process, microorganisms degrade organic matter under oxygen-free conditions, generating biogas composed of 50–75% methane, which can be upgraded to BioCNG for use in boilers or as a transport fuel. Typical yields range from 0.3–0.5 m³ of biogas per kilogram of COD removed, with COD reductions of 80–85% achievable in tank reactors.

Anaerobic coupled with aerobic treatment systems provide additional polishing, ensuring effluent quality meets discharge standards (COD <250 mg/L, BOD <30 mg/L), while methane capture generates carbon credits. This integrated approach transforms wastewater into a valuable bioresource, reducing fossil fuel dependence by 20–30% in energy-intensive mills and creating new revenue streams through BioCNG.

Materials & Methods

KIS Group has done a project at Sainsons Paper Industries Pvt. Ltd., a leading semi-Kraft paper producer in North India (350 TPD capacity), a high-capacity anaerobic reactor was commissioned to treat 18,000 kg COD/day and 4,500 m³/day hydraulic load under mesophilic conditions. Pre-treatment included screening, equalization, and pH adjustment (6.8–7.2) to stabilize influent [1]. The upgraded biomethane consistently exceeded IS 16087:2016 specifications, achieving >98% methane, <1 mg/m³ moisture, and <2% CO_2 [7].

Wastewater Characterization and Sampling

The mill discharges approximately 3,500–4,000 m³ of effluent per day, with COD levels reaching ~6,000 mg/L as a result of concentrated organic loads from repeated water reuse during pulp washing and paper processing. Effluent samples were collected on a daily basis throughout the monitoring period and analysed for COD, BOD, TSS, and pH in accordance with APHA standard methods. Each parameter was measured in triplicate to ensure analytical accuracy and precision.

Below are the operational parameters of the running plant i.e. digestor inlet, digestor outlet & final outlet (Table 1).

Table 1: Operational Parameters

Parameters	UOM	Digestor Inlet	Digestor Outlet	Final Outlet
pH		5.6-5.8	7.2-7.3	6.8-7.0
Temp	^{0}C	37	36	29
TSS	ppm	350-400	450-500	6-8
TDS	ppm	1900-2000	1900-1950	1950-2000
COD	mg/L	4500-5000	1200-1500	170-180
BOD	mg/L	1500-1600	700-750	10-15
Calcium	ppm	350-400	350-400	350
Chloride	ppm	800-1000	750-800	600-700
Color	Pt-Co unit	7000-7500	7000-7500	180-200
VFA	meq/L	31.2	BDL	-
Alkanity	meq/L	6.78	32.74	-

Design Data (Inlet Parameters) for BioCNG Plant

Below are the inlet parameters for the BioCNG plant i.e. flow rate and gas content (Table 2).

Table 2: Inlet parameters

Sr.No	Paramteres	Unit	Value
01	Biogas flow rate	m3/day	7200
02	Pressure	mmwc	<40
03	Temperature	^{O}C	Amb
04	CH_4	%	60-70
05	H_2S of raw Biogas	ppm	20000
06	CO_2	%	30-40

Anaerobic Treatment Configuration

A high-capacity anaerobic reactor was commissioned with a design capability to treat approximately 18,000 kg COD per day and a hydraulic load of 4,500 m³/day under mesophilic conditions (30–38 °C).

Key operating parameters include:

- Reactor type: Anaerobic system tailored for high-strength industrial wastewater.
- Hydraulic Retention Time (HRT): Optimized between 2 – 4 days.
- Temperature: Maintained at 30–38 °C to support microbial activity.
- Organic Loading Rate (OLR): Adjusted according to influent characteristics (less than 6 kg COD/m3/day).

This configuration was selected for its ability to handle high organic loads while ensuring stable treatment performance under the variable conditions typical of paper mill effluents. In addition to effective COD reduction, the system enables significant biogas generation, thereby integrating wastewater treatment with renewable energy recovery.

Figure 1: Overview of Sainsons Plant

Pre-Treatment Steps

Prior to anaerobic digestion, the wastewater from the paper mill was subjected to essential pre-treatment measures to ensure stable reactor performance and safeguard downstream biological processes. The raw effluent was first passed through coarse and fine screens to remove fibres, plastics, and other floating solids commonly present in paper mill discharges. The screened wastewater was then directed to an equalization tank, where controlled mixing minimized hydraulic and organic load fluctuations. pH adjustment was also carried out in the equalization tank to maintain influent values within the optimal range of 6.8–7.2, thereby creating favourable conditions for anaerobic microbial activity. These pre-treatment steps enhanced wastewater uniformity, reduced shock loading, and improved the overall efficiency and stability of the anaerobic digestion process.

Monitoring and control

Online sensors for critical parameters (pH, temperature, biogas flow) and recurring laboratory testing for organic load reduction were used to track reactor performance. To make sure that upgrading systems continuously produced CBG that complied with vehicle fuel regulations, biogas output was tracked every day and quality criteria were assessed.

Biogas Collection and Upgrading to Compressed Biogas (CBG)

The raw biogas from the anaerobic digester was collected in double-membrane gas holders under gas-tight conditions. CBG plant located in the current Sainsons paper mill is shown in figure 1.

To improve its quality, the biogas went through purification and upgrading steps.

- Hydrogen sulphide (H_2S) was removal: Hydrogen sulphide was oxidized using a compressed air oxidation system, converting it into elemental sulphur and removing corrosive components from the gas (figure 2).
- CO_2 and moisture removal: The gas then passed through a multi stage Pressure Swing Adsorption (PSA) system to remove carbon dioxide and moisture, producing upgraded CBG with methane content exceeding 90%, compliant with IS 16087:2016 standards for automotive and energy use (figure 2).
- Carbon dioxide (CO_2) and moisture were removed using a multi-tower Pressure Swing Adsorption (PSA) system, producing upgraded compressed biogas (CBG) with over 90% methane, meeting the IS 16087:2016 automotive fuel standards.

Daily CBG production was approximately 3,000 kg, which was utilized for commercial sale under the SATAT initiative and internal energy use, demonstrating the dual benefits of pollution control and renewable energy generation. Produced CBG is selling at the nearby HP dispensing station and using as a transport fuel (Figure 3).

Figure 2: PSA and Scrubber System

Figure 3: Upgrading BIOCNG & dispensing station Overview

Outlet Parameters

The output after cleaning and up gradation is mentioned below (Table 3).

Table 3: Outlet Parameters

Sr.NO	Parameters	Unit	Value
01	BioCNG	kg/day	3100
02	CH_4	%	>96
03	H_2S outlet	ppm	<10
04	CO_2	%	<4

Technical Specifications of Compressed Biogas

The bio-methane produced at Sainsons CBG plant consistently meets and exceeds the quality requirements outlined in IS 16087:2016 as shown in the Table 4 [7]. Methane concentration is maintained above 98%, significantly higher than the minimum specification of 90%, ensuring high calorific value and suitability for automotive and industrial applications. Moisture content is reduced to below 1 mg/m³, well within the prescribed limit, while sulphur levels remain controlled under 20 mg/m³, minimizing corrosion and emissions. The combined concentration of CO_2, N_2, and O_2 is restricted to less than 2%, compared to the allowable 10%, reflecting efficient gas upgrading. Overall, the plant demonstrates robust compliance with national standards, delivering biomethane of superior purity and reliability.

Table 4: Biomethane specifications -
IS standards vs quality achieved at Sainsons plant

Characteristics	Spec as per IS16087:2016	Quality of Biomethane at Sainson's CBG Plant
Moisture (mg/m³)	<5	<1
Methane (%)	>90	>98
Total Sulphur (Including H_2S) (mg/m³)	<20	<20
$CO_2 + N_2 + O_2$ (%)	<10	<2
CO_2 (%)	<4	<1.5
O2 (%)	<0.5	<0.5

Typical R.O.I (Cost Economics) for Paper Mill BioCNG Project

Economics plays a major role in determining the viability of a project. In the case of RNG, economics is critical as the sector is just emerging.

Below (Table 5) is the typical R.O.I for Complete BioCNG Plant for the existing Biogas projects; in which Capex includes mainly the Scrubber System, Biogas Management System, PSA System & related equipments/ instruments.

Table 5: Typical R.O.I

Biogas	700 m³/day
BioCNG	3.09 tones/day
Capex	7.5 Crores
R.O.I	Less then 2 years

Environmental and Safety Considerations

Anaerobic treatment and biogas production present environmental and safety challenges that must be carefully managed to ensure regulatory compliance and secure plant operations. Under anaerobic conditions, biological treatment systems can generate odorous compounds such as hydrogen sulphide (H_2S), ammonia, and volatile organic compounds (VOCs), which may adversely affect air quality and pose health risks if uncontrolled. Effective odour management—through gas collection systems, scrubbers, and biofilters—is therefore essential to minimize environmental impacts at the facility boundary.

From a safety perspective, anaerobic digestion and biogas upgrading systems involve inherent risks associated with combustible gas mixtures and toxic exposures. Methane readily forms explosive mixtures with air, while hydrogen sulphide is highly toxic and can cause acute health effects at elevated concentrations. Ensuring safe operations requires strict adherence to engineering design standards, implementation of robust ventilation systems, continuous gas monitoring, and the use of appropriate protective equipment. These environmental and safety measures complement technical process controls, enabling sustainable plant performance while safeguarding both the surrounding environment and personnel [2, 4].

Results and Discussion

The month-wise performance analysis demonstrates a clear correlation between wastewater generation, biogas yield, and CBG output. Wastewater inflows ranged from 2,900 to 4,100 m^3/day, resulting in biogas production between 4,466 and 6,314 m^3/day (figure 4). Correspondingly, CBG generation varied from 1.99 to 2.82 tonnes per month. Higher wastewater volumes consistently translated into increased biogas and CBG output, with October recording the peak values (2.818 tonnes CBG and 22.3 tCO_2e emission reduction).

Carbon credit potential ranged from 15,791 to 22,325 tCO_2e per month, while fossil fuel substitution benefits were equally significant, with reductions between 1,683 and 2,380 tCO_2e (figure 5). Importantly, even during months of lower wastewater inflow (e.g., February and April), the system maintained stable CBG production above 1.9 tonnes, underscoring the robustness of the anaerobic digestion and upgrading process [3, 5].

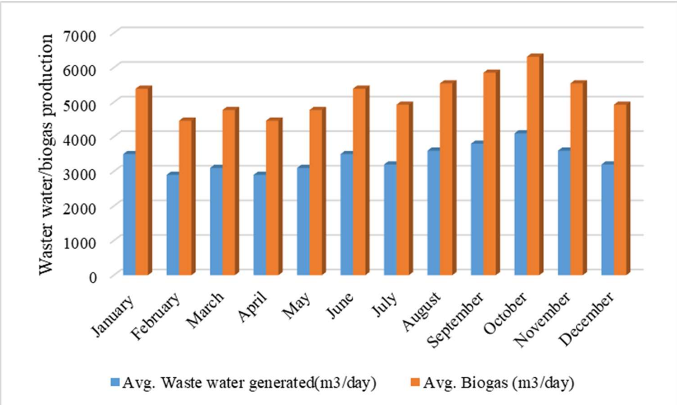

Figure 4: Waste water generation vs. Average biogas production

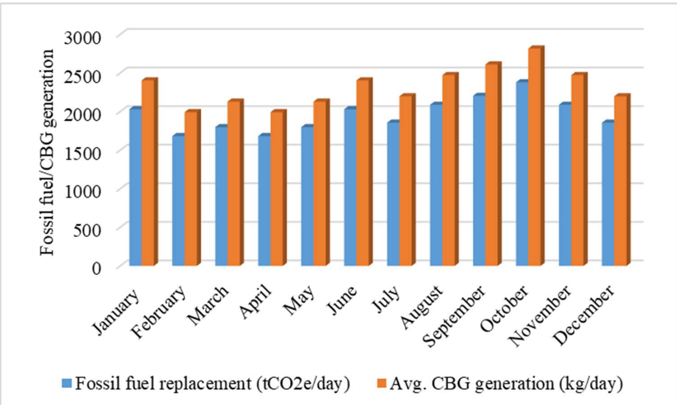

Figure 5: CBG generation vs Fossil fuel replacement

Comparatively, similar studies in Indian Kraft paper mills have reported CBG yields of 1.8–2.5 tonnes per month under comparable wastewater loads, with COD removal efficiencies of 80–85% [3]. The results from Sainsons Paper Industries not only align with these benchmarks but also demonstrate superior methane purity (>98%) and consistent emission mitigation, highlighting the scalability of wastewater-to-CBG conversion for semi-Kraft mills [4, 6].

Seasonal variations in wastewater inflow were observed, with higher volumes during monsoon months (August–October) due to increased process water usage. These months corresponded with peak biogas and CBG generation, as well as maximum carbon credit accrual. Conversely, drier months exhibited lower inflows but maintained steady output, confirming that the system can adapt to variable operating conditions without compromising performance.

Overall, the results validate wastewater-to-CBG conversion as a reliable and scalable solution for semi-Kraft mills. The integration of anaerobic digestion not only addresses wastewater treatment challenges but also provides renewable energy, reduces fossil fuel dependency, and generates tradable carbon credits. This positions the technology as a cornerstone of sustainable industrial operations in the pulp and paper sector [1, 4].

Conclusions

The study demonstrates that wastewater-to-CBG conversion in semi-Kraft paper mills is a technically feasible and environmentally beneficial approach. Consistent CBG production not only substitutes fossil fuel use but also delivers measurable reductions in CO_2 emissions, thereby contributing to industrial climate mitigation strategies. The results highlight the potential of integrating CBG systems into wastewater treatment frameworks as a reliable pathway for sustainable energy generation in the pulp and paper sector.

Future work should focus on incorporating advanced anaerobic digestion technologies, such as thermophilic and hybrid systems, to further enhance treatment efficiency and biogas yields. Additionally, comprehensive life-cycle assessments are recommended to evaluate long-term environmental benefits, economic viability, and scalability across diverse industrial contexts. By coupling wastewater management with renewable energy recovery, the pulp and paper industry can move toward a circular economy model that aligns with national and global sustainability goals.

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