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Holistic Utilisation of Renewable Bio-Resources in Pulp & Paper Manufacturing: An Industrial Case Study from TNPL


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Abstract: *The pulp and paper industry provides considerable opportunities for the integrated utilisation of renewable bio-resources through efficient use of raw materials, energy streams, and process by-products. This paper presents an industrial case study from Tamil Nadu Newsprint and Papers Limited (TNPL), demonstrating the holistic utilisation of renewable bio-resources in paper manufacturing and allied operations. Bagasse and waste paper are utilised as renewable raw materials for paper production, supporting sustainable fibre sourcing and reducing reliance on virgin forest-based resources. Bagasse cleaning water is treated through anaerobic digestion to produce biogas, which is utilised as a renewable energy source. Bagasse pith generated during fibre preparation is effectively fired in the power boiler for steam and power generation. In addition, causticizing sludge from the chemical recovery process is gainfully utilised in cement manufacturing, promoting circular material utilisation and eliminating landfill disposal. Food waste generated from canteen operations is processed through bio-methanation to produce gobar gas, which is utilised as a cooking fuel within the facility. The integrated utilisation of these renewable bio-resources contributes to fossil fuel substitution, waste reduction, and improved resource efficiency. The study demonstrates that systematic bio-resource integration can significantly enhance environmental performance and sustainability in pulp and paper manufacturing.*

Keywords: *Bagasse, Waste paper, Biogas generation, Pith firing, Sludge utilisation.*

Introduction

Rapid population growth and continuous improvements in quality of life are placing increasing pressure on finite natural resources, both organic and inorganic. At the same time, challenges related to waste generation during manufacturing, product use, and end-of-life disposal are intensifying [1]. These issues are largely driven by the predominance of the linear economy model, which follows a conventional "take–make–dispose" approach. In contrast, the circular economy offers a sustainable alternative by addressing critical global challenges such as resource scarcity, waste management, greenhouse gas (GHG) emissions, and climate change [2]. By promoting resource efficiency, material circularity, and waste valorisation, the circular economy enables decoupling of economic growth from resource consumption [3]. The pulp and paper industry are uniquely positioned to adopt renewable bio-resources both as raw materials and as energy carriers [4]. Effective integration of diverse fibre sources, process residues, and waste-derived energy streams plays a vital role in improving environmental sustainability, reducing dependence on fossil fuels, and enhancing overall resource efficiency [5].

Utilisation of Bio-Resources in Pulp Production

TNPL operates with a well-diversified and strategically balanced fibre mix comprising bagasse pulp, recycled fibre, and hardwood pulp, reflecting its strong commitment to sustainability and resource efficiency. TNPL produces approximately 500 MT/day of bagasse pulp, 300 MT/day of recycled pulp, and 330 MT/day of hardwood pulp, resulting in a total pulp production in which non-wood and secondary fibres play a dominant role (Table 1).


Figure 1 Bagasse Yard

Figure 2 Waste Paper Storage

Bagasse, an agro-residue derived from the sugar industry (Figure 1), forms the backbone of TNPL's fibre strategy. Its large-scale utilisation not only provides a reliable and renewable raw material source but also converts an agricultural by-product into a high-value industrial input [6]. This significantly reduces pressure on forest resources and supports circular economy principles by linking the agro-industrial and pulp & paper sectors. Recycled fibre, sourced from waste paper (Figure 2), constitutes another major component of the fibre mix. The use of recycled pulp contributes to conservation of natural resources, reduction in landfill burden, and lower overall environmental footprint. By integrating recycled fibre into mainstream production, TNPL enhances material recovery and promotes sustainable consumption patterns.

Table 1 Pulp Production Details in MT

S. No	Particulars	2020-2021	2021-2022	2022-2023	2023-2024	2024-2025
1.	Hardwood Pulp Production	100877	101465	103525	84872	91316
2.	Bagasse Pulp Production	124739	150657	151095	139332	147539
3.	Deinked Pulp Production	42453	52088	57937	68745	62170

Table 2 Pulp Production Details in %

S. No	Particulars	2020-2021	2021-2022	2022-2023	2023-2024	2024-2025
1.	Wood Based Pulp Production	38	33	33	29	30
2.	Non-Wood Based Pulp production (Bagasse + DIP)	62	67	67	71	70

Together, bagasse and recycled fibre account for nearly 70% of total pulp production, classifying the majority of TNPL's raw material input as non-wood based renewable bio- resources (Table 2). This fibre mix substantially reduces dependence on forest-based virgin fibres, mitigates supply-side risks associated with wood availability, and stabilises raw material costs. At the same time, the diversified fibre strategy offers high process flexibility, allowing the mill to adapt to variations in raw material quality and availability without compromising operational efficiency or product quality. Overall, TNPL's fibre management approach demonstrates an effective integration of renewable bio-resources into large-scale industrial operations, aligning economic performance with environmental stewardship and long-term sustainability.

Utilisation of Bio-Waste from Fibre Preparation

All bio-waste generated during fibre preparation operations, including bagasse pith from both dry and wet depithing systems (Figure 3) and chipper dust from the chipper house (Figure 4), is effectively utilised as a renewable energy source within the mill. These materials, which are by-products of the fibre preparation process, possess significant calorific value and are therefore recovered and diverted for energy generation instead of being disposed of as waste (Table 3). The collected bagasse pith and chipper dust are appropriately dried and fired in the power boilers for the production of steam and electricity [7]. This practice enables partial to substantial replacement of fossil fuels, thereby reducing the mill's dependence on conventional energy sources. By integrating these bio-residues into the boiler fuel mix, TNPL strengthens its internal cogeneration capability, ensuring reliable energy supply for process operations while optimising overall energy efficiency.

Table 3 Bio-Waste Consumption Details in MT

S. No	Particulars	2020-2021	2021-2022	2022-2023	2023-2024	2024-2025
1.	Wet Pith	65090	105261	95370	79682	104260
2.	Dry Pith	33667	61616	73912	72211	44683

Figure 3 Dry Pith for Power generation

Figure 4 Saw dust for Power generation

Beyond energy recovery, this approach contributes significantly to environmental sustainability. The substitution of fossil fuels with biomass-derived fuels leads to a measurable reduction in greenhouse gas emissions, particularly carbon dioxide, as the biomass is considered carbon-neutral over its life cycle [8]. Moreover, systematic utilisation of fibre preparation bio-waste eliminates the environmental challenges associated with storage, handling, and disposal of these residues. Overall, the conversion of agricultural and process residues into renewable energy exemplifies an efficient waste-to-energy pathway. It transforms by-products of fibre preparation into valuable resources, supports circular economy principles, enhances energy self-sufficiency, and reinforces the mill's commitment to sustainable and low-carbon pulp and paper manufacturing.

Utilisation of Biogas from Bagasse-Based Effluents

The high-rate bio methanation facility (Biogas Plant–1), consisting of two Up flow Anaerobic Sludge Blanket (UASB) reactors (Figure 5) along with associated auxiliary systems (Figure 6), was commissioned in 2003. With the subsequent backward integration of the CBP fibre line, wastewater generation increased significantly. In addition, a prolonged shutdown required for the replacement of three-phase separators necessitated further enhancement of anaerobic treatment capacity. Consequently, Biogas Plant–2 was commissioned in 2008, followed by Biogas Plant–3 in 2017 to meet the increased hydraulic and organic load.

Figure 5 Biogas Reactor

Figure 6 Biogas Collection Pipe line

Wastewater generated from the bagasse yard and bagasse washing operations contains high Chemical Oxygen Demand (COD) levels due to the presence of residual sugars that are not fully extracted in the sugar mill. Further, during wet pile storage, these sugars undergo fermentation, resulting in the formation of sugar acids, which further elevate the COD of the wastewater [9]. Prior to the installation of the bio-methanation plants, this high COD wastewater was treated in open anaerobic lagoons, where biogas generated through anaerobic digestion was not captured and was released to the atmosphere.

Table 4 Biogas Details

S. No	Particulars	2020-2021	2021-2022	2022-2023	2023-2024	2024-2025
1.	Biogas Generation, m^3	7468494	9567079	8985683	8305983	7970544
2.	Biogas Consumption at Lime Kilns, m^3	6440597	8455302	8481501	7440402	7269700
3.	Biogas Consumption at Power Boiler's, m^3	444599	183161	243967	396039	645644
4.	Furnace Oil Saved, m^3	3863	5074	5088	4464	4363

With the implementation of closed anaerobic digesters in the form of UASB reactors, the biogas produced is effectively captured and utilised as a supplementary fuel in the lime kiln, thereby partially replacing fossil fuels (Table 4). This system also prevents the uncontrolled release of methane into the atmosphere, methane being the second-largest contributor to greenhouse gas emissions and climate change. In addition to renewable energy generation, efficient COD degradation in the UASB reactors substantially reduces the organic load on the downstream treatment units, namely the activated sludge process, leading to improved treatment efficiency and reduced overall energy consumption.

Utilisation Of Renewable Resources In Cement Production

TNPL being an agro-based integrated pulp and paper mill, it utilises nearly one million tonnes of sugarcane bagasse annually as its primary raw material. The black liquor generated from bagasse pulping presents unique challenges to the chemical recovery system due to its distinct characteristics. In particular, the high concentration of non-process elements such as silica and potassium, along with unfavourable thermal and rheological properties, adversely affects recovery plant performance [10]. Among these, silica poses the most critical operational issue, impacting almost every stage of the chemical recovery cycle. To address these challenges, TNPL has successfully adopted a two-stage causticizing process in place of the conventional single-stage system. In a conventional causticizing reaction, sodium carbonate reacts with burnt lime and water to form sodium hydroxide and calcium carbonate:

$$Na_2CO_3 + CaO + H_2O \rightarrow 2NaOH + CaCO_3$$

In the two-stage causticizing process, the first stage is designed specifically to target silica removal. The primary reaction occurring in this stage involves sodium silicate reacting with burnt lime and water to form sodium hydroxide and calcium silicate:

$$Na_2SiO_3 + CaO + H_2O \rightarrow 2NaOH + CaSiO_3$$

Figure 7 First Stage Sludge Drum Washer

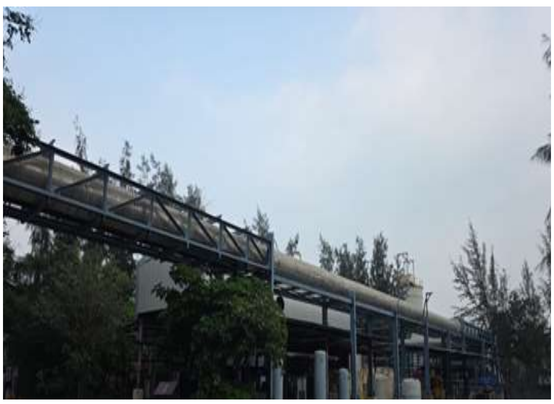

Figure 8 First Stage Sludge to Cement Plant

The main objective of the first-stage slaking is to reduce the silica content in the green liquor by selectively precipitating it as calcium silicate [7]. Typically, about 35–40% of the total burnt lime requirement is added in the first stage, depending on the silica concentration in the green liquor. The reaction between burnt lime and sodium silicate proceeds at a faster rate than the reaction with sodium carbonate, leading to preferential formation and precipitation of calcium silicate. If silica is not removed at this stage, it interferes with the causticizing reaction, resulting in reduced causticizing efficiency and poor-quality lime mud. By allowing the preferential reaction of calcium oxide with silica in the first stage, silica is effectively separated as high-silica lime sludge [10]. This sludge is removed through settling, and the clarified liquor, along with the remaining lime, is forwarded to the second-stage causticizing. The second stage produces low-silica lime mud, which is subsequently calcined in the lime kiln to regenerate burnt lime for white liquor preparation, thereby improving kiln operation and overall recovery efficiency.

Table 5 First Stage Sludge consumed in Cement Plant MT

S. No	Particlulars	2020-2021	2021-2022	2022-2023	2023-2024	2024-2025
1.	Lime sludge Consumption in Cement Plant	56895	53225	59892	54127	55742

While the two-stage causticizing process enables effective purging of silica through first-stage lime mud, it also necessitates an environmentally sustainable solution for managing this by-product. In line with circular economy principles, TNPL has developed an innovative and industrially proven approach by utilising the first-stage lime sludge (Figure 7), which contains biogenic carbonate (Table 5), as a raw material for cement manufacturing (Figure 8) in its Lime Sludge–based Cement (LSFM) plant. Through this route, the biogenic carbonate is beneficially transferred from the pulp and paper process to the cement production system, eliminating solid waste disposal concerns. TNPL is the first pulp and paper mill to successfully implement this concept at an industrial scale. An initial cement manufacturing facility with a capacity of 600 tonnes per day was established within the mill premises and commissioned in 2012. Subsequently, the plant capacity was expanded from 600 tpd to 900 tpd in 2015, further strengthening TNPL's position as a leader in sustainable chemical recovery and circular resource utilisation.

Utilisation of Biogenic Carbon Cycling Through Cement qnd PCC Production

During cement manufacturing, the biogenic carbon present in the carbonate component of lime sludge undergoes thermal decomposition in the cement kiln, in a manner analogous to the calcination's reactions occurring in a chemical recovery lime kiln. The calcium carbonate ($CaCO_3$) present in the lime sludge [8], which contains biogenic carbon originating from renewable biomass, is converted into calcium oxide (CaO) and carbon dioxide (CO_2) at elevated kiln temperatures:

Figure 9 View of TNPL Cement Plant

Figure 10 CO2 Line to PCC Plant

$$CaCO_3 \rightarrow CaO + CO_2$$

The calcium oxide produced through this process becomes an integral raw material in cement clinker formation (Figure 9), thereby substituting conventional limestone-derived CaO. Simultaneously, the CO_2 released from the decomposition of biogenic carbonate exits the cement kiln through the stack. Instead of allowing this biogenic CO_2 to be discharged entirely into the atmosphere, TNPL has established a closed-loop carbon utilisation pathway by integrating cement manufacturing with Precipitated Calcium Carbonate (PCC) production (Table 6). The CO_2 emitted from the cement kiln stack is captured and routed to the PCC manufacturing plant (Figure 10), where it is reacted with calcium-bearing streams to produce high-purity PCC.

Table 6 Sequestration of CO_2 from Cement stack in PCC

S. No	Particulars	2020-2021	2021-2022	2022-2023	2023-2024	2024-2025
1.	CO2 Sequestered	4828	5768	6405	7019	7545

The PCC thus generated is subsequently utilised as a functional filler in the papermaking process, improving paper properties such as brightness, opacity, and printability while reducing fibre consumption [9]. Through this integrated approach, biogenic carbon released during cement production is effectively sequestered back into a solid mineral form and reintegrated into paper products [11]. This unique cross-industry integration establishes a practical example of industrial carbon looping, wherein biogenic carbon flows from biomass-based pulping to chemical recovery, cement manufacturing, PCC production, and finally into paper. This approach significantly reduces net greenhouse gas emissions, minimises dependence on virgin mineral resources, and demonstrates TNPL's leadership in implementing circular economy and carbon management concepts at an industrial scale.

Utilisation of Biogas for on-Site Cooking Energy

Food waste generated from the TNPL industrial canteen is systematically collected and treated through a dedicated bio methanation system (Figure 11). This organic waste, which would otherwise require disposal, is subjected to anaerobic digestion under controlled conditions, resulting in the generation of biogas commonly referred to as gobar gas (Figure 12). The biogas produced primarily consists of methane and is a clean, renewable source of energy. The generated biogas is efficiently utilised as a cooking fuel in the guest house kitchen, directly replacing conventional fossil-based fuels such as LPG [11]. This on-site utilisation ensures energy recovery at the point of waste generation, minimises fuel procurement from external sources, and reduces the overall carbon footprint associated with cooking energy requirements.

Figure 11 Biogas Plant at Kitchen

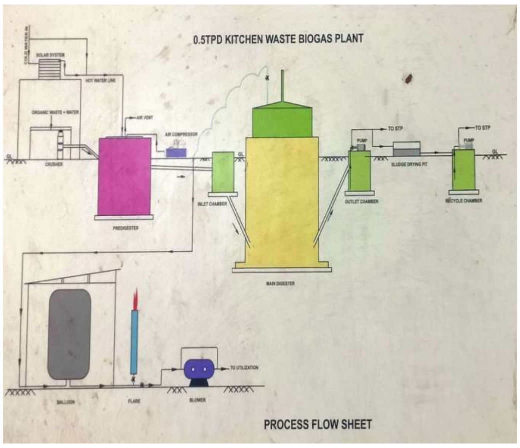

Figure 12 Process Flow of Biogas Plant

In addition to energy generation, this initiative contributes to effective waste minimisation by diverting biodegradable waste from landfills or other disposal routes. The process also yields digestate, which can be safely managed or utilised as a soil conditioner, further enhancing resource recovery. Overall, the integration of food waste bio-methanation into TNPL's operations exemplifies a small-scale yet impactful circular economy practice, reinforcing the organisation's commitment to sustainability, decentralised renewable energy generation, and responsible waste management (Table 7).

Table 7 Details of Biogas Plant in Guest House Kitchen

S. No	Parameters	Unit	Value
1	Organic solid waste collected &utilized from TNPL Canteen per day	kg	250
2	Volume of biogas used in the heating equipment per day	m^3	25

Results & Discussion

Substitution of wood with bagasse and recycled fibre conserved wood, reducing dependence on forest-based raw materials. Utilisation of bagasse pith, replacement of furnace oil with biogas in the lime kiln & boilers, conserved limestone by diversion of first-stage lime sludge to the cement industry, CO_2 sequestration in the PCC plant & utilization of food waste for generation of gobar gas resulted in significant resource conservation and GHG emission reduction (Table 8). Overall, the results demonstrate that holistic integration of bio-resources, waste-to-energy systems, and industrial symbiosis can substantially reduce fossil fuel consumption and carbon footprint while enhancing sustainability in the pulp and paper industry.

Table 8 Details of Raw material/Energy Conservation & GHG Emission

S. No	Particulars	Savings	GHG Emission reduction
1.	Equivalent Wood conserved by using Bagasse & Recycled paper	8.6 Lakhs MT/Annum	-NA-
2.	Thermal Energy Saved by Bagasse Pith	9.3 Lakhs GJ/Annum	89423 t CO2e/Annum
3.	Furnace oil Saving by using Biogas in lime kiln	4570 M^3/Annum	14837 t CO2e/Annum
4.	Lime Stone Conserved by Using First stage lime sludge in Cement Plant	55976 MT/Annum	28898 t CO2e/Annum
5.	Thermal Energy Conserved by CO2 Sequestration in PCC Plant	2.28 GJ/Annum	22000 t CO2e/Annum
6.	Volume of biogas used in the heating equipment	7300 M^3/Annum	6570 t CO_2e/Annum

Conclusions

This case study shows that holistic integration of renewable bioresources can substantially improve sustainability in pulp and paper manufacturing. At TNPL, the extensive use of bagasse and recycled fibre reduces dependence on forest-based raw materials, while conversion of bio-wastes and effluents into biogas and energy enables effective fossil fuel substitution and greenhouse gas reduction. Innovative circular practices such as two-stage causticizing, utilisation of lime sludge in cement manufacturing, and biogenic carbon looping through PCC production demonstrate successful industrial symbiosis and resource efficiency beyond the mill boundary. Overall, the TNPL model highlights a practical, scalable approach to circular and low-carbon manufacturing, offering valuable insights for the pulp and paper industry and allied sectors

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