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Unlocking Next-Generation Energy & Innovative Raw Material Bio-Resources for The Pulp & Paper Industry

Abstract: *The pulp and paper sector is prompting urgent shifts toward sustainability in the face of climate challenges. This paper investigates, using renewable bioresources as versatile resources in pulp & paper industries for on-site energy and other uses, embracing circular economical strategies. It assesses the technical and financial viability of deploying these in pulp mills facing resource-shortage, where fuel imports amplify ecological harm.*

The industry is increasingly transitioning toward renewable bioresources in response to sustainability mandates, regulatory requirements, and circular economy goals. Rising constraints related to fiber availability, energy efficiency, and carbon emissions have necessitated a shift away from conventional inputs. Renewable bioresources, including sustainably sourced fibers, agricultural residues, recycled materials, and biomass-based energy, offer viable solutions to these challenges. Ongoing research and innovation within the industry are enabling improved resource utilization, enhanced circularity, and reduced environmental impact. This paper highlights the strategic role of renewable bioresources in supporting sustainable and resilient pulp and paper operations.

Keywords: *Green Fuels, Turpentine, Liquid Gold, Lignosulfonates, Bio-ethanol & Gelidialian red algae.*

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Introduction

Pulp & paper industry is undergoing a strategic shift as sustainability, resource security, and energy transition become central to long-term viability. Increasing constraints on conventional fiber sources, coupled with rising environmental and regulatory expectations, have accelerated the adoption of renewable bioresources as alternatives for both raw materials and energy.

Renewable bioresources—including sustainably managed plantations, agricultural residues, and recycled fibers—offer viable pathways to enhance fiber availability while strengthening circularity and reducing environmental impact. Simultaneously, biomass-based energy streams such as black liquor, mill residues, emerging biofuels etc. are enabling reduced reliance on fossil fuels and improved energy efficiency. The substantial national availability of surplus biomass further reinforces the potential of bioresources as scalable industrial inputs.

As climate change intensifies resource scarcity, the traditional focus on paper production is expanding toward the "valorization" of waste streams. A systemic mapping of residues across the five primary manufacturing stages—wood preparation, pulping & washing, chemical recovery, wastewater treatment, and power generation—reveals untapped potential for the production of biofuels, biochemicals, and sustainable construction materials.[1]

By adopting an integrated approach, mills can minimize landfill dependency while simultaneously generating new revenue streams from materials like lignin, sludge-derived biogas, and fly ash.[2] This paradigm shift not only enhances the economic resilience of the industry but also aligns it with the global goals of a carbon-neutral bioeconomy.

However, variability in feedstock quality, technical processing requirements, supply-chain limitations, and economic considerations pose challenges to widespread adoption. Addressing these issues through focused research, technological advancement, and integrated resource management is essential. Effective utilization of renewable bioresources can support sustainable growth, improve economic resilience, and position the pulp and paper sector for a low-carbon future.

From Debris to Decarbonization: Closing the Energy Loop in Wood Preparation Zone

The pulp & paper industrial journey begins at the wood yard, where raw logs or non-wood stalks (such as sugarcane) are prepared for downstream chemical processing. Mechanical debarking and depithing generate substantial solid residues, including bark, sawdust screening dust, and pith. Historically, these were considered low-value debris, often posing a disposal challenge. However, in an integrated biorefinery, these materials are redefined as high-calorific "green fuels."

Lignocellulosic residues possess a unique chemical profile, often containing higher concentrations of extractives (tannins, phenols, and resins) compared to the inner white wood.[3] Bark and pith have a high carbon-to-oxygen ratio, providing a stable base-load for thermal plants.[3] When diverted to boilers, these residues provide the necessary thermal energy to generate high-pressure process steam and electricity. Furthermore, advanced pre-treatment methods like torrefaction can be applied at this stage to increase the energy density of these residues by up to 30%, making them a carbon-neutral alternative to sub-bituminous coal.[3] Utilizing wood yard waste reduces the "Gate-to-Gate" carbon footprint of the paper manufacturing process by replacing grid electricity with self-generated green power.[1] By maximizing the energy recovery from these "botanical skins," the mill significantly offsets its fossil fuel dependency and achieves a high degree of thermal self-sufficiency, effectively closing the energy loop at the very start of the production line.[1] Efficient wood yard management ensures that 100% of the incoming biomass is utilized, adhering to the "Zero-Waste" strategy.[2]

Bark and sawdust generated in pulp and paper mills are widely available biomass residues, but their direct use as fuel is limited by poor handling characteristics and uneven combustion. Briquetting these materials using gypsum or any other natural or chemical binders, as shown in Fig 1, offers a practical solution by improving mechanical strength, shape stability, and ash cohesion. Gypsum acts as an inorganic binding and fluxing agent, enhancing briquette durability and reducing fines generation during storage and transport. The resulting briquettes provide a more uniform and controllable solid fuel compared to loosen biomass.

The briquetting process begins with collection and screening of bark or sawdust, followed by moisture adjustment to achieve optimal compaction conditions. The binding material is then blended in controlled proportions with the biomass to ensure uniform binding. The mixture is fed into a briquetting press, where high pressure consolidates the material into dense briquettes. During compaction, the combined effect of pressure, frictional heat, and binder action produces briquettes with improved structural integrity and consistent dimensions.

In pulp and paper mills, biomass briquettes prepared with gypsum can be utilized as supplementary or primary fuel in biomass boilers and power boilers. Their higher bulk density allows stable fuel feeding and predictable combustion behavior. While gypsum contributes to slightly higher ash content, it can also improve ash handling characteristics when managed properly. Overall, this approach enables effective conversion of in-house residues into a usable energy source, supporting fuel diversification, waste reduction, and sustainable energy management within the mill.

Pulping Stage: Transitioning From Fiber Extraction To A Biochemical Hub

The pulping and washing phase constitute the primary chemical transformation within a mill, where the lignin-carbohydrate matrix is deconstructed to liberate cellulose fibers. To maintain high standards of fiber homogeneity, the mill integrates a screening phase immediately after cooking to extract knots and dense woody fragments. These components are then reprocessed, ensuring that the final pulp remains consistent and free of debris. The resulting black liquor is no longer viewed solely as an internal energy source, but as a "platform stream" for a diversified bioeconomy. Integrating membrane filtration during the washing stage, mills can recover specific hemi-cellulosic fractions before they are degraded in the recovery boiler.[4]

By integrating advanced separation technologies, modern mills can transition from traditional fiber extraction to a sophisticated valorization model. Molecular richness of black liquor enables recovery of high-value aromatic compounds and advanced energy carriers, offering a renewable alternative to

Fig 1. Different technically viable binders for briquetting sawdust or bark

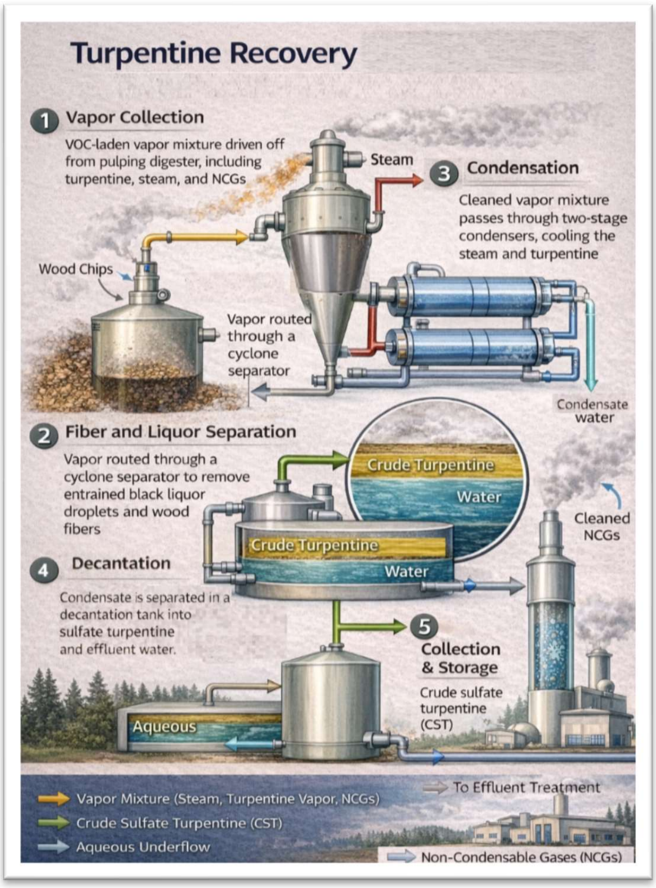

Fig 2. Turpentine Recovery Process in Pulp Mills

petroleum-derived intermediates. This capability is transforming pulp mills into integrated, multi-product biochemical platforms.

During the pulping operation, especially in the early stages of heating and pressure release, volatile components are liberated from the wood matrix. These vapors mainly consist of turpentine vapors along with steam and non-condensable gases. The released vapor stream is extracted from the digester to prevent pressure buildup and to enable recovery of valuable volatile by-products.

The extracted vapor mixture is first directed through a separation device, commonly a cyclone or similar mechanical separator, to remove entrained fibers and traces of black liquor. Effective removal of these solids and liquor droplets is essential, as their presence can interfere with downstream phase separation and reduce turpentine recovery efficiency. After cleaning, the vapor stream is cooled in one or more condensers, where steam and organic vapors are converted into a liquid condensate containing both water and crude turpentine as shown in Fig 2. The condensate is then transferred to a settling or decantation system, where separation occurs based on density differences. Turpentine, being lighter, forms the upper layer and is withdrawn to a dedicated crude sulfate turpentine storage tank. The heavier aqueous phase is routed to effluent treatment or reused within the process where appropriate. Any remaining non-condensable gases are collected and treated through scrubbing or controlled combustion systems to ensure effective odor control and environmental compliance.

Crude turpentine oil is a high-value byproduct recovered during the digestion and subsequent degassing stages of the pulping process. After recovery, the turpentine is typically refined—most commonly via acid degumming—to meet commercial quality requirements. The purified product is then marketed across multiple downstream industries due to its versatile functional properties. Key end-use applications include:

- Use as an effective solvent in the formulation of paints, varnishes, and resin systems.
- Serving as a feedstock for the industrial synthesis of specialty chemicals such as camphor and menthol.
- Incorporation into fragrances, cosmetic formulations, and disinfectant products.
- Utilization as an active component in selected over-the-counter pharmaceutical preparations, including chest rubs, where it functions as a counter-irritant and expectorant.

This byproduct recovery pathway not only enhances overall process economics but also supports value maximization through integrated biorefinery concepts.

Transforming "Liquid Gold" Into Industrial Symbiosis: The Chemical Recovery Loop

Chemical recovery circuit represents the economic backbone of the Kraft process, centered on the transformation of concentrated black liquor—frequently dubbed the industry's "liquid gold." This moniker reflects the fluid's dual utility as both a potent biogenic fuel and a critical reservoir of inorganic reagents. At the center of this phase is the recovery boiler, where the thermal oxidation of organic matter generates high-pressure steam for mill-wide energy autonomy, while the resulting inorganic "smelt" is harvested to reconstitute the essential cooking chemicals.

The modern viability of a pulp mill is directly tethered to the efficiency of this "Liquid Gold" loop, which provides a cost-effective alternative to purchasing virgin chemicals. Beyond internal energy, this stage facilitates a broader "Industrial Symbiosis" by addressing external environmental needs. Byproducts such as Green Liquor Dregs (GLD) should be viewed as functional minerals rather than waste.[2] Due to their inherent alkalinity, these residues are uniquely suited for upcycling into carbon-sequestration media or for the stabilization of acidic mine tailings. By strategically valorizing these inorganic streams, the recovery cycle transitions from a closed-loop internal process to a vital environmental service provider.

While many conventional facilities still struggle with GLD management and rely primarily on land disposal, this traditional dumping practice represents a significant environmental liability and a loss of potential resources. Modern circular strategies propose repurposing these dregs as effective neutralizing agents in industrial wastewater treatment or as supplementary raw materials in the production of bricks and cement. By diverting GLD from landfills into these value-added applications, mills can mitigate soil contamination risks, lower disposal expenditures, and provide a sustainable mineral source for the construction and mining sectors.

The potential of black liquor as a source of lignosulfonates, emphasizing their recovery as high-value bio-based products within pulp and paper operations. It reviews the fundamental properties of black liquor and outlines practical separation and purification approaches that enable efficient lignosulfonate extraction. The extraction process is shown Figure 3. The work highlights the economic and environmental advantages of valorizing this stream, including reduced waste generation, improved process efficiency, and additional revenue opportunities.

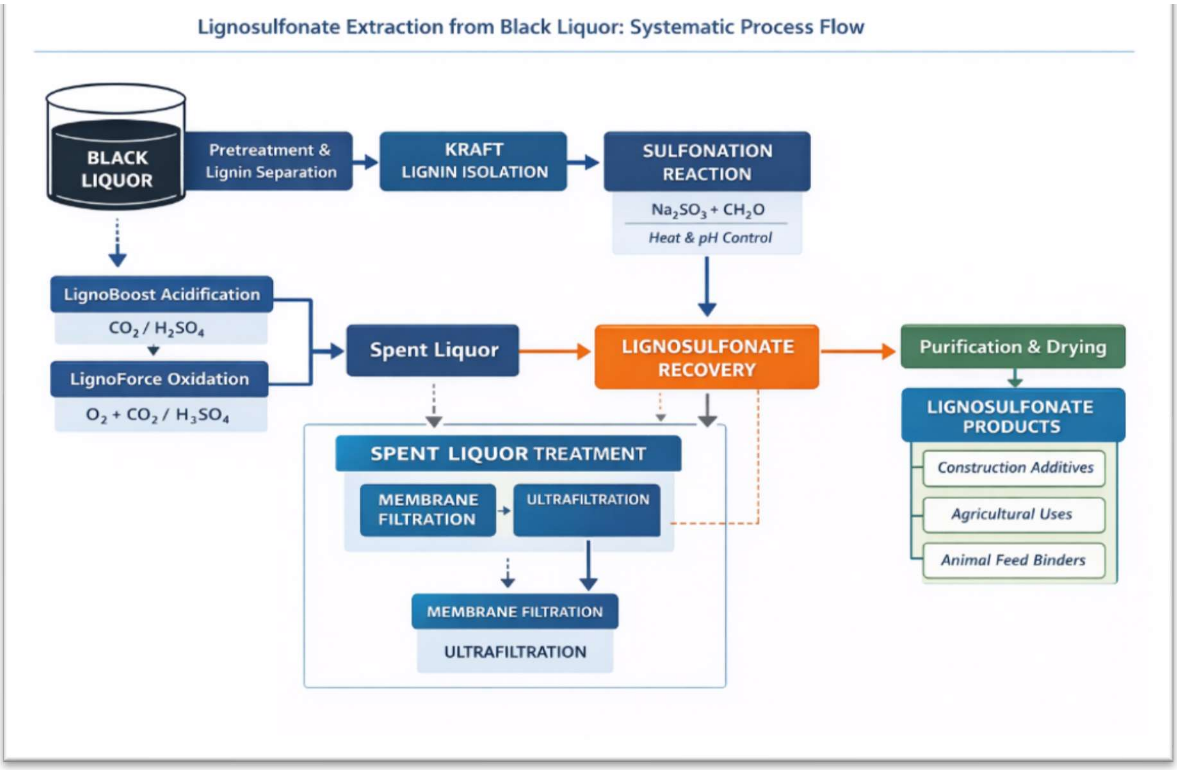

Fig 3. Process Flowsheet of the process of Extraction of Lignosulfonate.

Recovered lignosulfonates find wide application across several industrial sectors due to their dispersing, binding, and chelating properties. In the construction industry, they are commonly used as plasticizers and water-reducing agents in concrete admixtures, improving workability while lowering cement consumption. In agriculture, lignosulfonates serve as carriers and binders in fertilizers and pesticides, enhancing nutrient delivery and dust control. They are also utilized in animal feed as pellet binders to improve handling and mechanical strength. In specialty chemical applications, lignosulfonates function as dispersants in dyes, pigments, and ceramic formulations. These diverse uses illustrate how lignosulfonate recovery transforms a pulping by-product into a portfolio of bio-based materials, reinforcing circular resource utilization and value creation. This supports the evolution of mills into integrated, sustainable biorefinery systems.

Petroleum Coke functions as a high-enthalpy thermal stabilizer, bridging the gap between biomass and fossil fuels. With a superior calorific value (34–36 MJ/kg) and high fixed carbon, it ensures the consistent temperatures required for lime kiln operations.[5] Its integration optimizes syngas quality, mitigates biomass moisture fluctuations, and enhances overall gasification efficiency.

Substituting wood with pine needles (Pinus roxburghii) enables pulp mills to achieve energy autonomy. Their high volatile content (72–75%) facilitates rapid conversion into syngas, providing a green alternative for lime kiln operations. Furthermore, co-gasification with black liquor utilizes internal alkali salts (e.g., Na2CO3) as catalysts. This "Catalytic Loop" lowers activation energy and increases hydrogen output, effectively replacing fossil fuels with a circular, waste-based system.

Although the transportation cost of pine needles may be higher due to their high-altitude growth and dispersed availability, dried pine needles exhibit a comparatively high calorific value among biomass fuels.[5] For instance, the calorific value of pine needles has been reported around 18.1–21.6 MJ/kg, which is similar to or higher than many common agricultural residues such as cotton stalks, wheat straw, rice husk and other loose biomass, making them a competitive feedstock for combustion and gasification applications as shown in table 1.[6]

Table 1. Specifications of different raw materials that can used as fuel for combustion process.[6-16]

Raw Material Feedstock	**CV (MJ/kg)**	**Ash Content (%)**	**Volatile Matter (%)**	**Fixed Carbon (%)**
Pet coke	34.1 – 36.3	0.5 – 0.75	13.5 – 15.2	83.2 – 85.2
Pine Needles (*P. roxburghii*)	18.1 – 21.5	2.5 – 4.5	72.0 – 75.9	18.0 – 21.0
Wheat Straw	17.0 – 18.5	6.0 – 9.0	70.0 – 74.0	15.0 – 17.0
Bagasse Residues	16.0 – 18.0	1.5 – 4.0	80.0 – 85.0	12.0 – 15.0
Eucalyptus Bark	16.5 – 18.0	3.0 – 5.0	68.0 – 72.0	20.0 – 24.0
Bamboo Residues	18.5 – 19.5	1.0 – 3.0	75.0 – 78.0	16.0 – 19.0
Coffee Husk	16.0 – 19.5	1.3 – 4.0	55.0 – 72.0	16.0 – 30.0
Saw Dust	10.0 – 15.0	0.20 – 2.2	67.0 – 73.0	13.0 – 27.0
Rice Husk	13.0 – 17.5	15.0 – 22.0	50.0 – 65.0	13.0 – 19.0

Incorporating bovine waste into the gasification stream introduces essential alkali minerals, such as potassium and calcium, which function as internal catalysts. These biogenic elements significantly reduce the activation energy required for thermal decomposition, promoting a more efficient carbon conversion rate. This catalytic effect allows for stable syngas production at reduced operating temperatures, optimizing the mill's overall energy recovery.

Beyond the use of pine needles, the feasibility of establishing a dedicated bark gasification plant offers a transformative opportunity for mill energy management. By converting waste bark into high-quality syngas for direct application in lime kiln operations, mills can drastically reduce their reliance on external fossil fuels. This strategic integration not only elevates overall thermal efficiency but also reinforces the circular economy by ensuring that even the most recalcitrant wood by-products are utilized as high-value energy carriers.

The implementation of comprehensive NCG collection systems—specifically targeting emissions from digester vents and evaporator vacuum units—is essential for modern sustainable pulping operations. This framework facilitates the reclamation of high-energy gaseous fractions, which are repurposed as auxiliary thermal inputs for the lime kiln. Beyond the economic benefits of fossil fuel displacement, the high-temperature environment of the kiln ensures the complete oxidation of recalcitrant sulfur compounds. Consequently, this integrated management strategy transforms potential pollutants into a functional energy stream, thereby fulfilling the dual objectives of odor mitigation and industrial decarbonization.

Steam and condensate recovery forms an integral part of energy and water optimization in the chemical recovery plant of a pulp and paper mill. The system is designed to maximize thermal energy utilization from the recovery boiler while minimizing freshwater consumption and operational losses.

In the chemical recovery cycle, high-pressure steam is produced in the recovery boiler during the combustion of concentrated black liquor. This steam is primarily routed through turbines for power generation and subsequently supplied to various process users such as evaporators, reboilers, and deaerators. Efficient pressure cascading ensures that steam energy is extracted to the maximum extent before final condensation.

Condensate is generated when steam releases its latent heat during process heating. Major sources include evaporator heating surfaces, turbine exhaust users, and indirect heaters. Depending on the level of contamination from volatile compounds and reduced sulfur species, condensate is segregated into pure and foul streams.

Pure condensate, characterized by low conductivity and minimal organic load, is collected through dedicated headers and returned to the boiler feedwater system or deaerator. This practice significantly reduces the requirement for makeup water, lowers chemical dosing, and improves boiler efficiency due to higher feedwater temperature. Whereas, Foul condensate, typically originating from black liquor evaporation and stripping sections, is treated in condensate stripping systems to remove volatile organic compounds, methanol, and odorous sulfur compounds. After treatment, the condensate can be safely reused within the process or routed for further polishing as required.

Flash steam recovery is commonly incorporated through flash tanks, where high-temperature condensate releases low-pressure steam that can be reused for secondary heating applications. This further enhances overall energy recovery and reduces vent losses. An effective steam and condensate recovery system delivers measurable benefits in terms of energy conservation, water savings, reduced effluent load, and improved equipment reliability. Proper steam trap selection, leak prevention, condensate segregation, and real-time monitoring are essential for sustained performance.

Overall, steam and condensate recovery in the chemical recovery plant represents a critical synergy between energy efficiency, environmental compliance, and cost competitiveness. When managed systematically, it supports sustainable mill operation while strengthening the economic performance of the recovery cycle.

The Effluent Biorefinery: Harvesting Energy from Wastewater Residuals

Within the modern pulp mill, the Effluent treatment plant (ETP) has evolved from a liability into a vital energy-generating hub. This transformation is driven by the strategic diversion of organic residuals—primary and secondary sludges—into specialized biochemical recovery pathways. Primary sludge, which consists largely of rejected cellulosic fibers and wood fines, acts as a concentrated carbohydrate feedstock. Rather than being landfilled, this material undergoes enzymatic hydrolysis followed by fermentation, a process that breaks down the structural polysaccharides into fermentable sugars. These sugars are then distilled into bioethanol, providing the mill with a renewable liquid fuel that can either be used in internal logistics or refined as a green chemical commodity as shown in Fig 4.

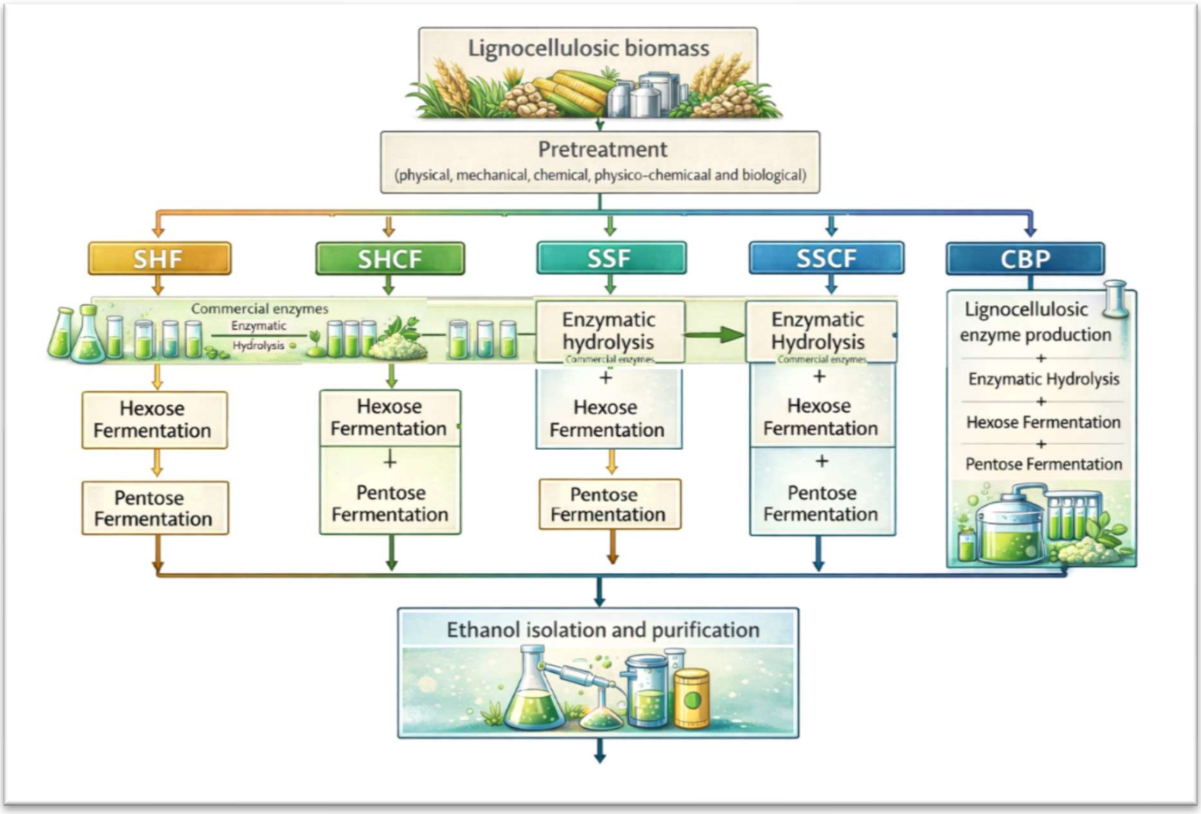

Fig 4. Bio-Ethanol Production Process

Simultaneously, the secondary sludge—the nutrient-dense microbial biomass produced during biological aeration—is optimized for gaseous energy recovery. To further maximize output, the mill integrates the collection of sewage water into the energy cycle, channeling these domestic and process-related organic fluids into the biogas system. Due to its high protein and microbial content, this stream is best suited for anaerobic digestion. Within sealed reactors, anaerobic consortia decompose the biomass to produce biomethane (CH4). This biogenic gas serves as a direct substitute for fossil-based natural gas, powering lime kilns or generating carbon-neutral steam for the facility.[17] By capturing sewage-derived organics for biomethane conversion, the mill not only enhances its renewable gas yield but also reduces the chemical oxygen demand (COD) in the final discharge. By integrating these dual recovery streams, mills effectively "close the loop" on water usage, transforming a traditional waste management cost into a source of operational autonomy and renewable revenue.

Next-Generation Sustainability Solutions for Pulp and Paper Industries

The increasing environmental impact of wood-based papermaking has intensified the search for alternative fibrous raw materials. Escalating deforestation pressures, volatile raw material costs, and tightening environmental regulations are challenging the long-term viability of conventional pulp sources. At the same time, the industry is under growing scrutiny to decouple production growth from ecological degradation while maintaining product performance and economic competitiveness. This has prompted a strategic shift toward non-wood and waste-derived biomass streams that support circular economy principles and resource efficiency. Exploring such alternatives not only reduces dependency on forest resources but also enables valorization of underutilized residues, positioning sustainable fibrous inputs as a critical lever for the future transformation of the paper and pulp sector.

A startup named ReLeaf Paper has devised a sustainable alternative to conventional paper manufacturing by transforming fallen leaves into usable paper products. Around 15 billion trees are cut down each year, with a significant portion used for paper production.[18] ReLeaf's process aims to reduce that impact.

Their approach repurposes urban leaf waste, which is often difficult and costly to manage. Rather than burning or landfilling fallen leaves, partner cities in Europe collect and send this biomass to ReLeaf's facility, where it is cleaned, combined with biological additives, dried, and processed into paper goods such as bags, notebooks, and packaging materials. One ton of cellulose can be generated from about 2.3 tons of leaves—an amount that would otherwise require felling about 17 trees if sourced from wood.[18]

ReLeaf's method significantly reduces environmental burdens: it uses considerably less water and emits much lower amounts of carbon dioxide than conventional paper production because it eliminates sulfur and chlorine chemicals.[18] Additionally, the leaf-based paper decomposes far faster in soil compared to standard paper, enhancing its end-of-life sustainability.

Currently based in Paris, ReLeaf processes thousands of tons of leaves annually and manufactures millions of paper bags monthly. Their products are already being supplied to several well-known brands, and the company plans to expand its operations globally, aiming to make leaf-derived paper widely available across continents.

Marine biomass, particularly red algae from the order Gelidiales, has emerged as a viable alternative to traditional wood fibers due to its specialized anatomical configuration. The genus Gelidium is characterized by a tripartite cellular arrangement consisting of cortical cells, medullary cells, and rhizoidal filaments. Research indicates that while the medullary region is rich in agar-based mucilaginous polysaccharides, the structural integrity of the resulting paper sheets is primarily attributed to the slender rhizoidal filaments. To utilize these fibers, a two-step refinement protocol is employed: initially, a hydrothermal treatment extracts the mucilage, followed by oxidative bleaching to remove the chromophores from the cortical cells. This methodology produces a high-reflectance pulp. Comparative evaluations involving G. amansii and G. corneum demonstrate that these algal fibers offer a sustainable substitute for wood-derived chemical pulps, specifically for high-end or specialty paper products.[19]

The specialized morphology of Gelidialian red algae, specifically the presence of ultra-fine rhizoidal filaments, enables the production of high-performance paper grades that surpass traditional wood-based alternatives. Because these fibers are roughly ten times narrower than timber tracheids, they form a dense, interwoven network that yields a Bekk smoothness index double that of conventional pulp and achieves over 90% opacity even in low-grammage sheets (60 g/m2) without mineral additives.[19] Consequently, this pulp is uniquely suited for premium applications such as lightweight, "no-bleed" printing paper for lexicons, high-definition photographic stationery, and reinforced recycled stocks. Furthermore, when processed into cellulose nanofibrils (CNF), these fibers serve as a sustainable, moisture-resistant barrier for biodegradable food packaging, offering a versatile and eco-friendly substitute for both synthetic coatings and forest-derived materials.

The utilization of Gelidiales in paper production facilitates a highly efficient circular bio-economy. Unlike conventional timber processing, the hydrothermal extraction phase in this workflow does not yield a waste stream; rather, it isolates agar-agar, a premium polysaccharide with extensive industrial utility. This byproduct is a critical resource in food science, where it functions as a plant-based stabilizer and texturizer (E406). Furthermore, the pharmaceutical and biomedical sectors rely on high-grade Gelidium extracts as the benchmark substrate for microbiological growth media and advanced hydrogel systems for targeted drug transport as shown in Table 2. By synchronizing the recovery of agar with the processing of structural rhizoidal filaments, the entire biomass is converted into value-added commodities. This zero-waste methodology significantly enhances the economic and environmental viability of marine-based papermaking.

Table 2. Industrial Versatility of Recovered Algal Mucilage.

Industrial Sector	Specific Functional Application
Laboratory & Medical Research	It is the primary solidifying matrix utilized for microbiological culture media (Petri dishes) and electrophoresis gels due to its high purity and thermal stability. [20]
Nutritional Science	Functioning as a plant-derived hydrocolloid (E406), it is widely employed in the food industry as a stabilizer in dairy products and a vegan gelling agent for confectionery.[21]
Pharmacology	Agar is integrated into the synthesis of biodegradable drug capsules and specialized matrices designed for controlled-release pharmaceutical delivery.[22]
Cosmeceuticals	In skincare, it acts as a natural rheology modifier, providing necessary viscosity to lotions and forming the structural base for hydrating facial treatments.[23]
Agricultural Biotechnology	It provides a nutrient-dense substrate for in-vitro micropropagation, particularly in the commercial cultivation of orchids and other ornamental species.[24]

Conclusion

The pulp and paper industry is uniquely positioned to evolve from a resource-intensive manufacturing sector into an integrated bioresource and energy platform. By systematically mapping material and energy flows across the wood preparation, pulping, chemical recovery, effluent treatment, and product diversification stages, the paper establishes that many so-called "waste" streams are, in fact, underutilized assets with significant economic and environmental value.

The valorization of lignocellulosic residues, black liquor derivatives, turpentine, lignosulfonates, sludge-based biofuels, and alternative biomass feedstocks highlights a clear pathway toward fossil fuel displacement, improved energy self-sufficiency, and reduced carbon intensity. When supported by appropriate separation technologies, energy recovery systems, and biorefinery concepts, these streams enable mills to transition from linear consumption models to closed-loop, circular operations without compromising process reliability or product performance.

The analysis further confirms that non-wood and unconventional bioresources—such as pine needles, urban leaf waste, and marine algae—can complement traditional fiber and fuel sources, particularly in regions facing wood scarcity or cost volatility. While logistical and technical challenges remain, targeted integration strategies and localized resource planning can unlock their full potential, strengthening both supply-chain resilience and sustainability outcomes.

Overall, the findings reinforce that the future competitiveness of the pulp and paper industry will depend not only on fiber efficiency, but on its ability to maximize total biomass utilization, recover high-value byproducts, and align energy systems with low-carbon objectives. Strategic adoption of renewable bioresources positions pulp mills as central contributors to the emerging bioeconomy—delivering environmental compliance, operational resilience, and diversified revenue streams in a single, integrated framework.

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