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SMART, CIRCULAR, AND CARBON-NEUTRAL: THE NEXT GENERATION OF SUGAR MILLS

Gaurav Chandra
Principal Consultant, Department of Cooperation, Haryana, India
gauravongc4@gmail.com

ABSTRACT

India's sugar sector, one of the largest agro-based industries globally, faces mounting pressures from volatile sugar prices, rising production costs, environmental regulations, and climate uncertainties. The conventional linear production model is increasingly inadequate for ensuring long-term sustainability. This paper examines the transition toward a circular-economy framework in India's sugar mills, where by-products such as bagasse, press mud, molasses, and wastewater are converted into valuable resources.

Within this circular framework, the paper also explores the establishment of bagasse-based briquette manufacturing as a complementary pathway for clean-energy production and agro- industrial waste management. With India's commitment to sourcing 50% of its electricity from non-fossil sources by 2030 and achieving net-zero emissions by 2070, biomass briquettes can serve as a viable coal substitute in industrial and power-generation sectors.

The study analyses technical, economic, and environmental aspects of circular sugar mills, including resource valorization, bioenergy integration, nutrient recycling, water circularity, and digital transformation. It also reviews market trends, policy incentives, and operational feasibility of integrated biomass-energy projects. The findings suggest that circular sugar mills can diversify revenue streams, reduce emissions, enhance soil and water sustainability, and strengthen rural livelihoods—positioning the sugar sector as a cornerstone of India's low-carbon development pathway.

Keywords: *Circular economy; Sugar industry; Bagasse; Biomass briquetting; Bio-refinery; Ethanol; Cogeneration; CBG; Renewable energy; Agro-waste; Climate change mitigation; Sustainable development.*

1. INTRODUCTION

India is undergoing a major energy and industrial transformation driven by rapid economic growth, increasing energy demand, and rising environmental concerns. The sugar industry, deeply embedded in the rural economy and supporting millions of farmers and workers, plays a crucial role in this transition. However, the sector faces structural challenges such as fluctuating global sugar prices, rising input costs, climate-induced variability in cane yields, and stricter environmental regulations.

The traditional linear production model—where sugarcane is processed into sugar and the remaining residues are either underutilized or discarded—has proven economically fragile and environmentally unsustainable. In contrast, the circular-economy model promotes resource efficiency by ensuring that all by-products are converted into valuable inputs for energy, agriculture, and industry.

In India's sugar sector, circularity can be achieved through:

- Cogeneration using bagasse for renewable power.
- Ethanol production from molasses and cane juice.
- Compressed biogas (CBG) from press mud and distillery waste.
- Nutrient recycling through compost and bio-fertilizers.
- Wastewater treatment and reuse under ZLD systems.
- Solid biofuel production through bagasse briquetting.

Among these pathways, bagasse-based briquetting represents a practical and scalable solution for converting surplus biomass into high-density solid fuel, often termed "white coal." Briquettes offer higher energy density, easier transport, and cleaner combustion compared to loose biomass, making them suitable substitutes for coal in industrial boilers and thermal power plants.

Integrating briquette manufacturing with sugar mills enhances resource utilization, reduces waste, creates new revenue streams, and supports India's clean-energy goals. This paper therefore examines the circular-economy transformation of sugar mills, while also assessing the feasibility and role of bagasse-based briquetting within this broader framework.

2. LITERATURE REVIEW

Existing literature highlights the environmental and economic potential of circular practices in the sugar industry and biomass-based energy systems.

Studies on sugar-industry circularity have shown that by-products such as bagasse, press mud, and molasses can be effectively converted into energy, fertilizers, and bio-based materials. Research indicates that bagasse-based cogeneration is one of the most mature renewable-energy pathways in the sector, contributing significantly to India’s renewable-power capacity.

In the context of biomass briquetting, Kumar et al. (2020) demonstrated that bagasse briquettes can reduce greenhouse-gas emissions substantially when used as a substitute for coal. The International Energy Agency’s Bioenergy Task 32 reported improved combustion efficiency and reduced particulate emissions in thermal plants using biomass briquettes.

Indian policy frameworks have increasingly supported biomass utilization. The National Bio- Energy Mission and MoEFCC guidelines encourage biomass co-firing in coal-based power plants, creating a growing market for briquettes and pellets. Ethanol blending programmes and SATAT initiatives for bio-CNG also reinforce the circular bioenergy ecosystem around sugar mills.

However, literature also identifies several barriers:

- Seasonal availability of biomass feedstock.
- Technological adaptation in older industrial systems.
- Financing constraints for rural projects.
- Limited market awareness and supply-chain infrastructure.

These challenges indicate the need for integrated policy support, financial incentives, and technological upgradation to scale circular-economy solutions in the sugar sector.

3. OBJECTIVES OF THE STUDY

The study is guided by the following objectives:

1. To analyse the circular-economy transformation of India’s sugar mills.
2. To propose a commercially viable model for integrated resource-valorization systems, including bagasse-based briquette production.
3. To evaluate the technical, financial, and operational feasibility of circular sugar-mill operations.
4. To assess market demand for bioenergy and biomass-based products.
5. To align circular-economy interventions with India’s climate, energy, and rural- development goals.

4. METHODOLOGY

This research adopts a mixed-method approach, combining primary and secondary data sources.

4.1 Data Sources Primary data:

- Interactions with sugar-mill operators.
- Consultations with biomass-energy and briquette manufacturers.
- Market assessments of industrial fuel demand.

Secondary data:

- Government policy documents.
- Industry reports and energy statistics.
- Academic research papers and case studies.

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4.2 Technical Analysis

Technical feasibility is assessed based on:

- Availability and characteristics of sugarcane by-products.
- Existing mill infrastructure.
- Energy and material balances.
- Briquetting and bioenergy technologies.
- Operational benchmarks.

4.3 Financial Analysis

Financial viability is evaluated using standard DPR-based models, including:

- Capital investment.
- Operating costs.
- Revenue projections.
- Payback period.
- Internal Rate of Return (IRR).
- Net Present Value (NPV).

4.4 Market and Policy Analysis

Market demand is analysed through:

- Industrial fuel consumption patterns.
- Biomass co-firing mandates.
- Price comparisons with coal.

Policy alignment is assessed against:

- Renewable-energy targets.
- Ethanol blending programmes.
- Bio-CNG and waste-to-energy initiatives.
- Circular-economy and climate policies.

5.0 Introduction: The Need for a Circular Economy in India's Sugar Sector

India's sugar sector stands as one of the largest agro-based industries in the world, deeply embedded in the rural economy and supporting millions of livelihoods. However, the industry today is at a crossroads. Increasing production pressures, fluctuating global sugar prices, and rising input costs have highlighted the fragility of the current linear model of "produce–use–discard." In this backdrop, embracing a **circular economy** is not just desirable but essential for long-term sustainability.

The circular economy framework moves industries away from wasteful, extractive practices and towards regenerative systems that mirror natural cycles. In nature, nothing goes to waste—every output becomes an input for another process. Applying this philosophy to the sugar sector means redesigning processes so that by-products like bagasse, press mud, molasses, and wastewater are not treated as waste, but as **valuable resources** that can fuel energy production, soil enhancement, bio-fertilizers, and green chemicals.

Adopting circularity can address some of the most persistent challenges facing the sugar industry today. Issues such as **resource scarcity, environmental degradation, and economic inefficiency** can be significantly mitigated by reusing materials, optimizing energy consumption, and reducing pollution loads. For a developing country like India, this transition also carries broader socio- economic benefits—lower dependence on raw material imports, increased rural employment, and opportunities for new green enterprises built around bioenergy, bio-fertilizers, and sustainable chemicals.

The sugar industry's own challenges—price volatility, unpredictable cane yields due to climate change, and increasing environmental compliance requirements—have created a fertile ground for innovation. By integrating circular economy principles, sugar mills can transform into multi- product bio-refineries, generating diversified revenue streams while minimizing waste. Technologies such as cogeneration, ethanol production, compressed biogas (CBG), and composting have already begun to demonstrate significant potential in enhancing sustainability and financial resilience.

With over **525 operational mills producing more than 30 million tonnes of sugar annually**, India is the world's largest producer and consumer of sugar. The sector supports an extensive ecosystem of **50 million farmers and millions of rural workers**, making it central to India's agrarian economy. As the nation accelerates its transition to cleaner energy and sustainable industrial practices, implementing a full circular economy model within sugar mills presents a ransformative opportunity—one that strengthens rural livelihoods, boosts environmental stewardship, and secures the future of the industry.

A circular economy in sugar mills begins with **resource optimization**, where every component of sugarcane—juice, bagasse, molasses, and press-mud—is converted into value-added products rather than waste. This enables a shift from a single-product sugar factory to a **multi-product bio-refinery**, maximizing output from the same biomass resource. The next major component is **waste-to-value conversion**, where by-products like vinasse, CO_2 emissions, bagasse ash, and distillery effluents are repurposed to generate **CBG, compost, bricks, industrial CO_2**, and other secondary products, creating industrial symbiosis within and around the mill.

Energy circularity forms another critical part, as sugar mills use **bagasse-based cogeneration** to meet internal energy needs and supply surplus power to the grid, while supporting the production of **bio- hydrogen and green hydrogen**. Alongside this, **circular nutrient cycling** ensures that digestate from CBG plants, press-mud compost, and treated effluents return to the fields as **bio-fertilizers**, reducing chemical fertilizer dependence and enhancing soil health. Finally, **economic and carbon circularity** complete the loop: diversified revenue streams from ethanol blending, power sales, CBG contracts, and carbon credits strengthen mill finances, while CO_2 capture, renewable fuels, and waste minimization significantly reduce the carbon footprint, positioning sugar mills as engines of sustainable and climate-resilient rural development.

6.0 Resource Valorization: Efficient Utilization of Bagasse, Press Mud, and Cane Trash

A crucial component of circularity in the sugar sector is the systematic conversion of solid by- products—particularly **bagasse ash**, **press mud**, and **cane trash**—into valuable resources. Bagasse, when incinerated in boilers for heat and power generation, produces **sugarcane bagasse ash (SCBA)**, which is often dumped as waste despite its significant value. Research indicates that SCBA contains **high levels of phosphorus** and can act as an excellent soil amendment, enhancing soil fertility and microbial activity (James & Pandian, 2017). Studies have shown that its application improves soil pH, increases available organic carbon, and boosts essential macronutrients like potassium, calcium, and magnesium, contributing to improved soil health and productivity.

Beyond agriculture, bagasse ash has promising industrial applications. Its **amorphous alumino- silicate composition** makes it a potent **pozzolanic material**, suitable for sustainable construction. When combined with calcium hydroxide and water, SCBA forms cementitious compounds, enabling its use as a partial replacement for cement in concrete. Several studies (Yadav et al., 2020; Li et al., 2022) highlight that SCBA can be integrated into **geopolymer concrete**, offering an environmentally friendly alternative to traditional cement. This also aligns with global efforts to reduce the carbon footprint of cement production. Moreover, bagasse fly ash has been reported to effectively **adsorb distillery wastewater**, demonstrating potential in wastewater treatment applications (Patel, 2022).

Press mud, another major by-product generated during cane-juice clarification, also plays a significant role in resource valorization. Chemically rich in **humic acid (~19%), fiber (15–30%), crude protein (5–15%), and essential minerals**, press mud has long been used as a soil conditioner or in composting with distillery spent wash. However, recent analyses show that press mud may contain **elevated concentrations of heavy metals**, such as **Fe (6169 µg/g), Mn (288 µg/g), Zn (115 µg/g), and Al (2233 µg/g)**, which poses risks of long-term heavy-metal accumulation in soils if applied repeatedly (Kumar et al., 2011). This raises the need for stricter quality checks, optimized composting processes, and safe-use protocols to ensure that its agricultural benefits are realized without compromising soil quality.

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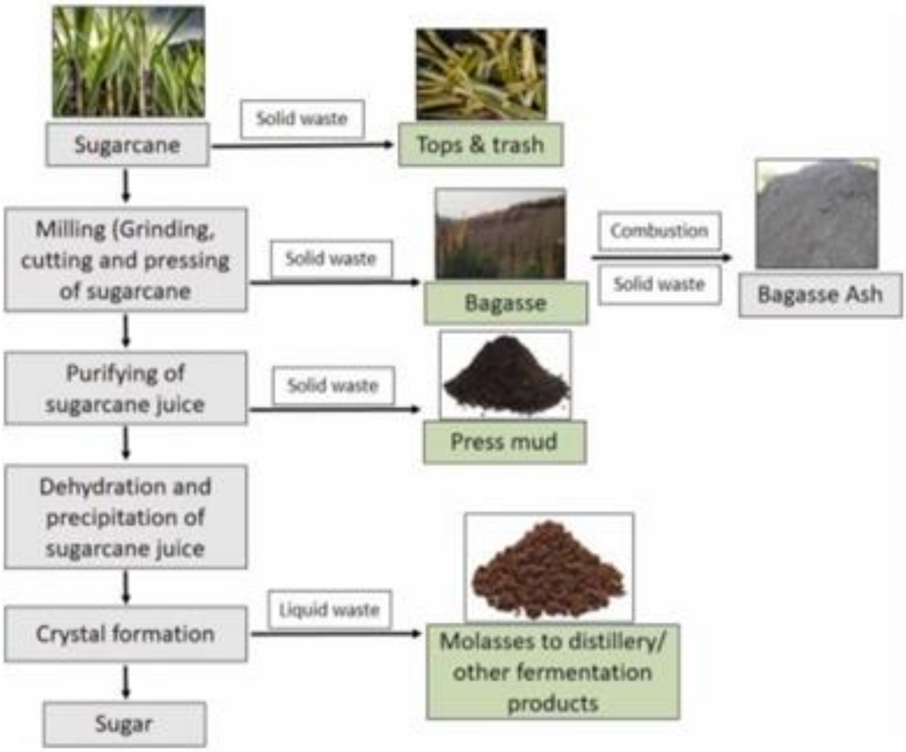

Despite the inherent value of these by-products, waste management practices in sugar mills remain inadequate. **Unregulated dumping** of bagasse ash continues to occupy large land areas, causing air pollution through airborne particulates and posing fire hazards due to residual unburnt carbon (Singh et al., 2020; Roy, 2021). Similarly, **field burning of cane trash**, still prevalent in many regions, contributes significantly to particulate emissions, soil degradation, and loss of organic matter (Gebretatios et al., 2022). These practices contradict the principles of a circular economy and highlight the urgent need for waste-to-resource interventions.

Molasses, a high-sugar by-product of sugar manufacturing, is a critical feedstock for **2G/1G bioethanol** production. It undergoes **fermentation → distillation → dehydration** to produce **fuel-grade ethanol (99.9%)** used in India's **E20 ethanol blending mandate**. The availability of ~**3 million tonnes of molasses annually** makes it ideal for large-scale biofuel programs. Its use reduces reliance on fossil fuels, boosts domestic farmers' incomes, and supports **carbon-neutral transport solutions**.

Recent research and industry pilots have demonstrated the viability of transforming sugarcane waste streams into **value-added products**, such as bio-fertilizers, bio-CNG substrates, construction materials, adsorbents, and soil enhancers (Chouhan et al., 2022). However, the key challenge lies in scaling these innovations, standardizing product quality, and integrating them into existing mill operations. Studies (Xu et al., 2021) emphasize that despite technological feasibility, adoption barriers remain due to limited awareness, lack of infrastructure, and insufficient policy support.

A circular economy approach can convert these challenges into opportunities by enabling mills to evolve into **multi-product biorefineries**. By fully valorizing bagasse ash, press mud, and cane trash, sugar mills can reduce waste, generate new revenue streams, enhance soil health, and minimize environmental impacts—laying the foundation for a more sustainable and resilient sugar industry.

7.0 Bioenergy Integration: Ethanol, CBG, and Cogeneration as Growth Drivers

The integration of bioenergy systems in sugar mills forms the backbone of a circular economy model in India's sugar sector. By converting process residues such as bagasse, molasses, press mud, and distillery spent wash into renewable energy, mills can diversify income, enhance resource efficiency, and significantly reduce environmental emissions. Today, sugar mills are evolving from conventional processing units into **multi-product bio-refineries**, generating electricity, ethanol, and compressed biogas (CBG) alongside sugar. This shift is central to India's renewable-energy transition and its broader climate-mitigation strategy.

Cogeneration from bagasse remains one of the most mature and economically viable pathways. Bagasse-based high-pressure boilers can simultaneously generate steam and electricity, enabling mills to meet internal demand while exporting surplus power. On average, one metric tonne of bagasse can generate around **450 kWh** of electricity, contributing to India's renewable energy capacity. As of recent assessments, **over 147 sugar mills** in India operate cogeneration plants with a combined capacity exceeding **3,000 MW**, supplying nearly **1,900 MW** of surplus power to the grid. This reduces dependence on coal-based electricity and ensures steady non-seasonal income for mills.

Ethanol has emerged as another critical growth driver, especially after policy reforms allowed the use of **sugarcane juice, syrup, B-heavy molasses, and damaged food grains** as alternate feedstocks. Mills now have flexibility to switch between sugar and ethanol based on market conditions, helping stabilise industry revenues. With the government's push for **20% ethanol blending (E20)**, demand for fuel-grade ethanol has increased sharply. Ethanol production has become more profitable than sugar in several seasons, strengthening the case for integrated bio- refineries within mills.

A rapidly expanding opportunity lies in **compressed biogas (CBG)** production using press mud, distillery effluents, and other organic residues. Experts highlight that press mud is one of the **best feedstocks** for CBG because it contains **100% organic material**, unlike municipal waste which requires costly segregation. Biofuel expert Rohit Pathania notes that unused press mud decomposes anaerobically, releasing methane and other GHGs; its conversion into bio-CNG therefore provides both climatic and economic benefits. **Press-mud**, rich in organic matter, and **bagasse**, rich in lignocellulosic biomass, are excellent substrates for **Compressed Bio-Gas (CBG)**. Through **anaerobic digestion**, they can yield **60–70 m^3 of biogas per tonne of press- mud**, which is then purified and compressed to produce **CBG (≥95% methane)**. Bagasse after enzymatic pretreatment can significantly enhance gas yield. This supports India's **SATAT (Sustainable Alternative Towards Affordable Transportation)** initiative and provides decentralized clean fuel for transport and industry.

Sugar mills possess unique advantages in bio-CNG production: ready availability of feedstock, uninterrupted supply chains, and proximity to rural transport corridors. Experts recommend blending press mud with segregated municipal waste to ensure year-round plant utilisation, enabling cities and mills to co-manage waste. Cities such as **Pune and Indore** already operate bio- CNG-fuelled public buses, demonstrating the viability of this pathway. However, scaling CBG requires aligning plant locations with existing CNG demand hubs such as **Delhi-NCR and Gujarat**, where gas distribution networks are more developed.

Recent research also highlights the expanding technological potential of sugar industry residues. A study by IIT-Bombay, Queen's University Belfast, and the University of Limerick found that bagasse could also serve as a feedstock for CBG production. The cost of producing 10 tonnes/day of bio-CNG from bagasse was estimated at **₹87 per kg**, but could drop to **₹37 per kg** if bagasse and electricity were provided free—showcasing the cost-reduction potential of integrated mill operations. The same study noted that replacing fossil fuels with bio-CNG could reduce emissions by **up to 3.96 kg of CO_2 per kg** of bio-CNG used as transport fuel.

Government support continues to strengthen the sector. In a 2022 parliamentary statement, the Union Minister for New and Renewable Energy confirmed that bio-CNG plants are being promoted under the **Waste-to-Energy Programme** and **SATAT**, along with priority-sector lending and customs-duty concessions on equipment imports. This comprehensive policy ecosystem positions sugar mills as central nodes in India's green-energy transition—boosting income stability, decarbonising fuel consumption, and maximising value from agro-industrial by- products.

8.0 Bio-Hydrogen and Green Hydrogen Pathways in the Sugar Industry

Bio-hydrogen and green hydrogen offer a major technological leap for transforming sugar mills into integrated **clean-energy biorefineries**. **Bio-hydrogen** can be produced from carbohydrate- rich by-products such as molasses, press-mud hydrolysates, and distillery wastewater through microbial pathways like **dark fermentation** and **photo-fermentation**. Dark fermentation uses anaerobic bacteria to convert sugars into hydrogen, volatile fatty acids, and CO_2, achieving yields of about **1.5–3 mol H_2/mol glucose**, while integrated DF–PF systems can further enhance recovery. Bagasse, after enzymatic pretreatment, also becomes a viable hydrogen substrate. These processes not only generate hydrogen but also produce valuable co-products such as **VFAs for bioplastics**, CO_2 for industrial use, and nutrient-rich residues that can be converted into **bio-fertilizer**, thereby supporting circular economy principles.

In parallel, sugar mills are well positioned to produce **green hydrogen** using renewable power generated from **bagasse-based cogeneration** systems. Bagasse-fired high-pressure boilers generate surplus electricity that can run **alkaline or PEM electrolyzers**, splitting water into hydrogen and oxygen at >99.9% purity. The oxygen by-

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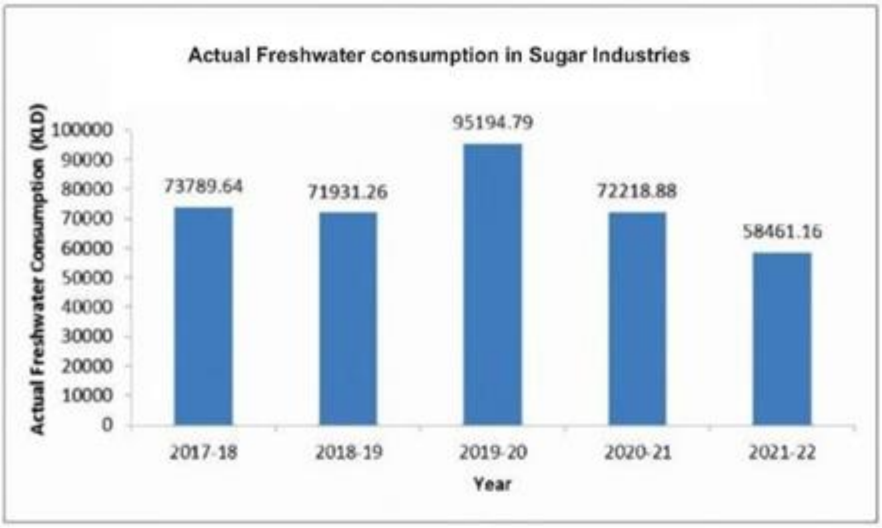
product can be reused in distillery aeration or wastewater treatment, while thermal integration of electrolyzers improves mill energy efficiency. This hydrogen can fuel **fuel-cell vehicles**, support fertilizer production, or contribute to refinery blending under the National Green Hydrogen Mission. Together, bio-H_2 and green-H_2 pathways create a synergistic model where biological and electrochemical processes complement each other—converting waste into energy, reducing emissions, and positioning sugar mills as decentralized hydrogen hubs in India's clean-energy transition.

9.0 Water Circularity: Wastewater Treatment, Reuse, and Zero-Liquid Discharge (ZLD)



In the sugar industry, water is an indispensable input — used at multiple stages including cane washing, juice extraction, equipment cleaning, cooling, and auxiliary processes. Naturally, this intensive use also leads to large volumes of **wastewater**. Research shows that crushing one tonne of sugarcane typically consumes **1.5– 2 cubic metres** of fresh water and

generates roughly **1 cubic metre (≈ 1,000 litres)** of wastewater. This wastewater is not benign: it carries high concentrations of dissolved and suspended organic and inorganic pollutants. Typical parameters for untreated sugar-mill effluent include **Chemical Oxygen Demand (COD)** of **1,800–3,200 mg/L**, **Biochemical Oxygen Demand (BOD_5)** between **720–1,500 mg/L**, and total suspended solids often in thousands of mg/L — making direct discharge hazardous for water bodies or soil.

Given this pollution load, traditional practices of discharging untreated or minimally treated effluent into nearby rivers, drains, or onto land have caused severe environmental degradation. Aquatic ecosystems get damaged due to oxygen depletion, soil fertility suffers, and water bodies around mills — often vital for rural communities — become unfit for use. In many regions, the discharge of untreated effluent has also triggered regulatory actions and public outcry, underlining the environmental and social untenability of the conventional "use-and-dispose" model.

Recognizing these challenges, a growing number of sugar mills are pivoting toward **water circularity**, through a combination of wastewater treatment, internal reuse, and adoption of **Zero- Liquid Discharge (ZLD)** frameworks. Under ZLD, all effluents — including spent wash from distilleries tied to sugar mills — are treated, purified, and recycled internally, eliminating any external liquid discharge. A prominent example is Harinagar Sugar Mills Ltd. (Bihar), which after implementing a sophisticated ZLD system (involving degasification, multiple-effect evaporation, condensate polishing, and bio-methanation) now **recycles approximately 800,000 litres of water**

per day. The recycled water is reused for boiler feed, cooling-tower makeup, fermentation, and other industrial processes — significantly reducing freshwater demand.

Beyond conserving water, ZLD offers other tangible benefits. By recovering and reusing process water, mills drastically cut down on freshwater withdrawal — a critical advantage in regions with water stress or seasonal scarcity. The reduction in wastewater discharge also means lowered environmental pollution and risks to

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aquatic ecosystems. Further, advanced ZLD systems often enable recovery of valuable by-products from the residual waste — such as potash salts or nutrients

— which can be repurposed as fertilizers or soil amendments, thereby contributing to a circular bio-resource economy rather than simple waste disposal.

At a broader scale, the adoption of wastewater reuse and ZLD in the sugar sector has yielded noteworthy results. According to a 2023 assessment of mills in the Central Pollution Control Board (CPCB)'s Ganga-Basin charter programme, **specific freshwater consumption fell by 53%** and **wastewater discharge decreased by 17%** between 2017-18 and 2021-22 — despite overall production increasing during the same period. This saved over **2,452.55 million litres** of fresh water. Such data demonstrates that water circularity is not just an idealistic goal but a **practical and scalable solution**.

However, moving to full ZLD and water reuse across India's sugar mills is not devoid of challenges: it requires **substantial capital investment**, **technical expertise**, and **consistent operation and maintenance**. Advanced treatment systems — including anaerobic/ aerobic treatment, membrane filtration, evaporation, crystallization and polishing — must be integrated carefully to handle the high organic and chemical load of the effluent. Further, regulatory enforcement, incentives, and capacity-building among mill owners and managers are critical to scale adoption and ensure long-term compliance and environmental safety.

In sum, integrating wastewater treatment, reuse, and ZLD presents a **transformative opportunity** for India's sugar sector — enabling large freshwater savings, preventing water-body pollution, generating by-products (like potash fertilizers), and steering mills toward sustainable, circular bio- refinery models. Investing in such water circularity today could pay off in enhanced environmental sustainability, regulatory compliance, and long-term viability of the sugar industry.

10.0 Nutrient Cycling: Converting Sugarcane By-products into Bio-fertilizers and Soil Enhancers

In the circular economy model for sugar industries, nutrient cycling plays a central role by transforming waste streams into valuable agricultural inputs. By-products such as **press mud, bagasse, and sugarcane trash**—once considered disposal burdens—are now recognized as powerful organic resources capable of restoring soil fertility, reducing chemical fertilizer dependence, and supporting sustainable sugarcane cultivation. This shift is particularly relevant as India's soils face depletion due to continuous, intensive, high-input agriculture and declining organic matter levels.

Sugarcane itself is a **heavy nutrient-demanding crop**, requiring large amounts of nitrogen, phosphorus, and potassium (NPK). Continuous extraction of nutrients without adequate replenishment has led to nutrient imbalances, micronutrient deficiencies, and deterioration of soil structure (Shukla et al., 2016). Excessive reliance on chemical fertilizers has also become economically unsustainable due to rising prices, seasonal scarcity, and adverse impacts on soil health. In this context, **recycling sugarcane processing residues back into sugarcane fields** emerges as a scientifically validated and economically viable strategy.

Researchers across regions have demonstrated that sugarcane by-products such as **press mud and bagasse** can significantly improve soil fertility and crop productivity (Bhattacharyya et al., 2003; Dotaniya, 2013). Press mud is rich in organic matter, humic substances, micronutrients, and beneficial compounds, improving soil structure, water-holding capacity, and microbial activity. When composted or vermicomposted, press mud provides balanced macro-, secondary-, and micro-nutrients, reducing the need for chemical fertilizers. Its role in enhancing soil physio- chemical properties—bulk density, porosity, pH buffering, and cation exchange capacity—makes it valuable for long-term soil regeneration.

Bagasse and sugarcane trash also play a crucial role in nutrient cycling. During microbial decomposition, these residues generate **organic acids** that enhance **phosphorus use efficiency (PUE)** by reducing phosphorus fixation in soils. Organic acids derived from decomposing sugarcane residues promote phosphorus availability through three well-established mechanisms (Shukla et al., 2013; Dotaniya et al., 2014):

1. **Competition for P adsorption sites** on soil surfaces, preventing P immobilization.
2. **Dissolution of Fe, Al, and Ca-based adsorbents**, releasing bound phosphorus.
3. **Modification of soil surface charge**, reducing the affinity of soil particles for phosphate ions.

This enhanced P availability is particularly important in tropical and subtropical regions—where sugarcane predominates—because these soils are often phosphorus-fixing and nutrient-deficient. As many studies show, complex formation between organic acids and metal ions (Fe, Al, Ca) mobilizes phosphorus, improving its uptake and boosting crop yield and quality. The presence of sugars in cane residues further stimulates microbial populations, accelerating decomposition and nutrient release.

Beyond phosphorus, the incorporation of sugarcane residues stimulates soil biological activity, increases soil organic carbon, and improves overall soil resilience. Crop residues have historically been vital to sustaining soil productivity, and sugarcane by-products are among the most readily available organic resources for nutrient recycling in cane-growing regions (Dotaniya & Kushwah, 2013). Their use in fields helps address multiple challenges simultaneously:

- **Waste disposal** problems in sugar mills,
- **Nutrient depletion** in intensively cultivated soils,
- **Rising costs and scarcity** of chemical fertilizers, and
- **Demand for organic and residue-free agricultural practices**.

Adopting nutrient cycling from sugarcane by-products thus supports agricultural sustainability, reduces environmental pollution, and enhances circular-resource efficiency in the sugar sector. By establishing systematic composting facilities, quality monitoring of organic amendments, and farmer outreach programs, sugar mills can close the nutrient loop while reducing their ecological footprint—strengthening both soil health and the economic viability of sugarcane production.

11.0 Technological Upgradation and Digitalization for Process Optimization

The contemporary sugar industry — especially in India — is witnessing a gradual but definite shift from conventional, labor-intensive methods to **modern, technology-driven processes**. This transformation, grounded in automation, process control, digital data management, and precision agriculture, aims to enhance efficiency, improve yields, reduce resource intensity, and make sugar production more sustainable. Several technologies and digital tools now enable sugar mills and associated farming operations to optimize every stage — from field to factory.

A core pathway of upgradation lies in **automation and industrial control systems** in sugar mills. Companies such as Fuji Gemco — a joint venture combining global technology and Indian market knowledge — supply AC/DC motor drives, PLC (Programmable Logic Controller) systems, SCADA control panels, and other automation modules that handle high-torque, heavy-duty operations like cane crushing, juice extraction, clarification, evaporation, and crystallization. Such systems ensure precise control over speed, pressure, temperature and other critical parameters, helping maximize juice extraction, improve sugar recovery, and reduce process losses.

Automation also improves **energy efficiency and resource management**. Advanced motor drive systems and energy-efficient boilers reduce electricity consumption during intensive processes; continuous control of operations minimizes wastage of steam, water, and power. Integration of sensors, real-time monitoring, and feedback mechanisms allows mills to detect inefficiencies or maintenance needs early, reducing downtime and avoiding costly breakdowns — essential given the seasonal nature of sugarcane crushing.

On the digitalization front, mills are increasingly adopting **Enterprise Resource Planning (ERP) systems**, often integrated across departments — cane procurement, inventory management, production planning, logistics, accounting, and human resources. For instance, one modern mill described how a fully integrated Oracle-based ERP replaced fragmented data systems: MIS reports are generated automatically, redundant data entry is eliminated, inter-departmental coordination improves, and management gains real-time visibility into operations and costs. Such holistic digitization enhances decision-making, transparency, and responsiveness, especially crucial for large mills dealing with vast supplies, multiple by-products, energy co-generation, ethanol/distillery operations, and supply-chain logistics.

Beyond factory automation, the sugar sector is increasingly using **digital agriculture and precision-agriculture tools** to optimize sugarcane cultivation itself. Through satellite imagery, IoT sensors, geospatial mapping and AI-based yield forecasting (as deployed by solutions like RMSI Cropalytics), mills and associated agencies can monitor field boundaries, crop types (plant vs. ratoon cane), soil moisture, nutrient status, and irrigation patterns. This helps plan procurement zones more efficiently, reduce resource wastage (water, fertilizers), and ensure timely harvesting — which ultimately increases overall cane yield and quality while reducing environmental footprint.

Another emerging frontier is **data-driven process optimization using AI and predictive analytics**. A recent academic study proposes using deep-learning based control strategies (e.g. LSTM — Long Short-Term Memory networks) to optimize sugarcane crushing processes. By modeling the crushing system's dynamics, such strategies can adapt operations to changing raw- material quality or load, optimizing energy input, juice extraction efficiency, and overall throughput under varying conditions. In mills with high variability (e.g. seasonal shifts in cane quality, moisture, fiber content), such adaptive control promises better consistency, higher sugar recovery, and lower wastage — enhancing both economic and environmental performance.

At a broader policy-industry level, the legacy of Sugar Technology Mission (STM) — launched in the early 1990s — continues to undergird modernization efforts across the Indian sugar sector. Recognizing technological deficits in many older mills, STM facilitated horizontal transfer of proven, cost-effective technologies, evaluated new processes, and supported modernization in energy conservation, productivity improvement and capital-output efficiency. Through such initiatives, several mills have upgraded boilers, juice extraction setups, crystallization, distillation and distillery operations — laying the foundation for current automation and digitalization trends.

In sum, technological upgradation and digitalization can transform sugar mills into **smart, efficient, data-driven bio-refineries** — reducing resource use (energy, water, manpower), increasing sugar and by-product yields (bagasse, ethanol, molasses), enhancing energy and bio- fuel generation, ensuring better product quality, and improving economic viability even amid volatility. As climate pressure, resource scarcity and sustainability demands grow, such transformation becomes less optional and more imperative — offering a clear pathway toward a modern, resilient, and circular sugar sector.

12.0 Environmental and Economic Advantages of Circular Sugar Mills

Adopting a circular-economy model transforms sugar mills from waste-heavy factories into efficient, resource-optimizing bio-refineries — with clear **environmental and economic advantages**. By systematically valorizing by-products such as bagasse, press mud, molasses, and other residues, mills can dramatically reduce solid, liquid and gaseous waste streams. Instead of discarding these wastes or letting them generate pollution, they become inputs for energy generation, bio-fertilizers, compost, and even bio-based materials — which reduces environmental burden and preserves natural resources.

One of the most significant environmental gains comes from **renewable energy generation**. For instance, bagasse — the fibrous residue after sugarcane juice extraction — when burnt in high- pressure boilers, can produce steam and electricity. This allows mills to meet their own energy needs and even export surplus power to the grid.This reduces dependence on fossil fuels, curbs greenhouse-gas emissions, and builds energy self-reliance. Indeed, a mature circular pathway for sugar-industry waste valorization identifies electricity production from bagasse as one of the most established routes.

From an **economic** standpoint, circular mills benefit significantly by diversifying their revenue streams. Rather than depending solely on sugar — a commodity subject to price volatility — mills can earn from energy sales, biofuels (e.g., ethanol, biogas), organic fertilizers, compost, and other by-products. This diversification stabilizes income, mitigates risk tied to fluctuating sugar markets, and increases overall financial resilience. Moreover, by using in-house residues as fuel or inputs, mills effectively reduce production costs, lower fuel expenses and depend less on external raw materials.

Another major advantage lies in **soil health and sustainable agriculture**. When by-products like press mud and bagasse-based compost are applied to fields, they improve soil structure, increase soil organic matter, and supply essential macro- and micronutrients. Research indicates that recycling all available press mud can supply substantial quantities of N, P, K, and micronutrients (Fe, Zn, Mn, Cu), reducing the need for costly chemical fertilizers. This not only helps maintain long-term soil fertility but also supports sustainable crop yields, closing the loop between industrial production and agriculture.

Finally, circular practices bring **social and rural-economy benefits**. The sugar industry in India supports millions of farmers and workers; shifting to a circular model — with energy generation, waste valorization, bio-fertilizer production, and diversified outputs — creates new employment opportunities in rural and semi-urban areas, including in processing, maintenance, transport and supply chains. At the same time, reduced environmental pollution and waste burdens help communities around mill areas, improving public health and ecological sustainability.

In sum, circular sugar mills deliver a **win-win combination** — they reduce environmental footprint, conserve resources, support rural livelihoods, and increase economic resilience. As the global push for sustainable development intensifies, transforming sugar mills into circular bio-refineries offers a promising pathway for both environmental sustainability and long-term industrial viability.

13.0 Key Challenges Hindering Circular Economy Adoption in Sugar Mill.

Adopting a circular economy in sugar mills faces multiple challenges, which hinder its widespread implementation in India and other sugar-producing countries. One of the major obstacles is the **complexity of waste valorization and the lack of technological maturity**. While technologies like bagasse-based cogeneration are well-established, more advanced methods — such as converting residues into biofuels or high-value chemicals — remain expensive and technically challenging. Downstream separation and purification processes are often inefficient, and by- products like press mud can contain heavy metals or waxy components, limiting their safe use in agriculture due to potential soil toxicity.

Infrastructure and investment constraints further restrict circular practices, particularly for small and medium-sized mills. Transforming a conventional mill into a circular-economy-ready bio-refinery requires significant capital investment in waste-treatment plants, anaerobic digesters, composting infrastructure, storage facilities, and zero-liquid discharge systems. Smaller mills often lack access to the necessary funds or credit, and even when infrastructure is installed, the seasonal variability in sugarcane crushing and effluent load complicates operation, increases costs, and reduces reliability.

Environmental and health risks associated with by-product reuse also pose significant barriers. Untreated or inadequately treated residues, such as press mud or vinasse, can degrade water bodies, harm ecosystems, and contaminate soil. High levels of BOD, COD, suspended solids, salts, and other toxic components in effluents can affect human health and local ecology if not properly managed. Moreover, repeated application of composted press mud containing heavy metals may lead to accumulation of toxins over time, further restricting safe use.

Logistical challenges in **handling, storage, and transportation of bulky residues** add another layer of difficulty. By-products such as bagasse, press mud, and filter cakes have high moisture content and low bulk density, making storage and transport costly and complicated. Even where there is potential economic value, these logistical burdens can negate benefits, especially for mills located far from farms or processing centers.

Regulatory and compliance gaps also limit circular economy adoption. While environmental regulations exist for water discharge, air emissions, and waste disposal, enforcement is often weak or inconsistent, particularly for smaller or older mills. Traditional practices such as open-field burning of cane trash or indiscriminate dumping of ash continue, contributing to pollution and undermining circular practices. Without strong enforcement or incentives, adoption remains uneven across the sector.

The **seasonality of the sugar industry** compounds these challenges. Limited crushing seasons result in off-season idleness of mills and irregular generation of by-products, making it difficult to operate bio-gas plants, composting units, and effluent treatment systems year-round. This irregularity affects the consistency and economic viability of circular operations.

Finally, **market and demand uncertainties for value-added products** act as a deterrent. Even when mills successfully produce bio-fertilizers, bio-CNG, compost, or biochemicals, limited or irregular demand, particularly in rural areas, may prevent them from realizing expected returns. Additionally, economic trade-offs between short-term profitability and long-term environmental benefit can discourage mills from investing in circular practices, especially when conventional sugar production remains the dominant and predictable source of revenue.

14.0 Strategic Solutions & Policy Interventions to Accelerate Circular-Economy Adoption in Sugar Mills

To unlock the full potential of circular models in sugar mills, a combination of **policy support, financial incentives, regulatory mandates**, and **industry-level strategic planning** is required. Below are key solutions and interventions:

A major enabler is **targeted financial support and subsidies**. For example, under the programme of the Ministry of New and Renewable Energy (MNRE), sugar mills that set up biomass-based cogeneration projects — especially bagasse cogeneration — can avail **Central Financial Assistance (CFA)** to the tune of ₹ 25 lakh per MW for bagasse cogeneration, and higher for non- bagasse biomass projects. Such subsidies reduce upfront capital barriers, making it more attractive for mills — including small and medium ones — to invest in waste-based energy generation infrastructure.

Regulatory mandates and environmental norms also play a critical role. For instance, governing bodies have increasingly required sugar mills and distilleries to implement **Zero-Liquid Discharge (ZLD)** systems for effluent and wastewater, ensuring no untreated wastewater is released outside the premises. Compliance with such norms forces mills to invest in wastewater treatment, water recycling, and resource recovery — a precondition for circular water use.

Beyond energy and water, policy facilitation for **diversification of industrial output** can help. Encouraging sugar mills to set up downstream units — for example, bio-based materials, biodegradable packaging or bio-plastics — can turn by-products like bagasse into high-value materials, thereby creating new revenue streams. A recent example is a large sugar company that is investing in a sugar-to-PLA (polylactic acid) facility to manufacture bio-based packaging using sugarcane feedstock under renewable energy, aligning industrial diversification with sustainability goals.

Another strategic lever lies in **linking sugar-sector operations with national bioenergy and biofuel policies**. The push for ethanol blending under the Ethanol Blended Petrol Programme (EBP) creates demand for ethanol derived from sugarcane by-products or juice, offering an alternate revenue model to mills beyond sugar alone. Similarly, under national initiatives encouraging biomass power and biofuels, mills can leverage existing incentives to build cogeneration, bio-CNG, or bio-fertilizer production capacity — thereby embedding circular practices into mainstream business strategy.

On the ground, **industry collaboration, capacity-building and integrated operations** can drive circular models. Sugar mills can partner with agribusinesses, waste-management firms, and rural industries to set up common infrastructure — for bio-CNG plants, composting units, waste collection systems, and bio-product manufacturing facilities. Such collaborative clusters reduce individual burden, share investment costs, and foster efficient resource flows. This kind of cluster-based rural industrialization — anchored by sugar complexes — is increasingly being proposed under long-term industry visions.

Finally, integrating **sustainability metrics and carbon-credit mechanisms** could provide long-term incentives. By producing renewable energy (from bagasse cogeneration or bio-CNG), recycling waste, and reducing environmental pollution, sugar mills can position themselves as net-zero or low-carbon enterprises — potentially participating in carbon-credit markets or accessing green financing. This can significantly improve the business case for circular investments, making them more attractive even under market volatility.

16. CONCLUSION

The transition from conventional sugar factories to circular bio-refineries represents a structural transformation of India’s sugar sector. By integrating resource valorization, bioenergy generation, nutrient recycling, water circularity, and digital technologies, sugar mills can significantly reduce waste, lower emissions, and enhance economic resilience. Circular practices enable diversified revenue streams through ethanol, cogeneration, CBG, briquettes, and bio-fertilizers, reducing dependence on volatile sugar markets.

However, scaling this transformation requires coordinated policy support, financial incentives, technological upgrades, and industry collaboration. With appropriate regulatory frameworks, investment mechanisms, and market development for bio-products, the sugar sector can emerge as a cornerstone of India’s green economy. A fully circular sugar industry has the potential to strengthen rural livelihoods, enhance soil and water sustainability, and contribute meaningfully to national climate and energy goals.

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