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Sugar industry waste as an alternate resource for sustainable waste management

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The sugar industry is one of the world's most significant agro-based sectors, but it traditionally carries a heavy environmental footprint due to high water consumption and massive waste generation. However, the modern industry is shifting from simple sugar production to a bio refinery model, where by-products are the key to achieving environmental sustainability which involves a circular economy approach that transforms traditional waste products such as bagasse, molasses, press mud, and wastewater into renewable energy, organic fertilisers, and eco-friendly materials. The article showcases the process of conversion of sugar industry waste into effective sustainable products along with their application in different sectors and challenges ahead. This transition not only mitigates the industry's environmental impact such as reducing effluent discharge into water bodies but also enhances economic resilience through resource efficiency.

Keywords: Bagasse, Press mud, Spent wash, Sugar industry by-products

INDIA has the world's second-largest sugar industry. According to USDA report, global sugar production has risen, where India contributes 2.1 million tonnes (mt) out of total (8.4 mt). However, it generates massive amounts of waste, including 1,000 L of wastewater, 300 kg of bagasse, and 30–40 kg of press mud per tonne of cane crushed. Though, these waste by-products threaten aquatic/terrestrial ecosystems if untreated, they are now increasingly repurposed for bio-CNG, fertiliser, and power. Sugar industry waste management focuses on converting high-volume solid wastes (bagasse, press mud) and liquid effluents into valuable resources like bioenergy, organic fertiliser, and biodegradable materials. Key practices include using bagasse for cogeneration, composting press mud, and applying biological/physicochemical treatments to wastewater to meet environmental regulations, promoting a circular economy. Spent wash is a highly organic, acidic, and dark-coloured liquid waste generated in distilleries attached to sugar mills. For every liter of alcohol produced, approximately 10–15 L of spent wash are generated. The Central Pollution Control Board (CPCB) classifies alcohol distilleries as 'Red' category industries. Since 2026, Zero Liquid Discharge (ZLD) has become the mandatory baseline, requiring that no liquid effluent leaves the facility boundary. By converting these by-products into valuable products, the industry not only mitigates environmental risks associated with waste disposal but also strengthens the economic viability of sugar production.

The sugar industries in India are characterised by their high cost of production where approximately 80% of the production cost goes towards raw material alone and producing sugar with outdated technologies. According to International Sugar Organisation, a tonne of sugarcane biomass (waste generated in sugar industry) has energy equal to one barrel of crude oil. Proper management of sugar industry waste can help reduce greenhouse gas emissions, better management of sugar industry waste and a sustainable ecosystem.

Key waste components and their uses

***Wastewater (Effluent)*:** Approximately 1,000 L of waste water are produced per tonne of sugarcane. It has a high Biochemical Oxygen Demand (BOD) (1,000–1,500 mg/L). Treatment methods include anaerobic, aerobic, and physico-chemical processes, which have reduced BOD loads in areas like the Ganges by 35–54%.

***Bagasse*:** It is the fibrous residue remaining after juice extraction. About 0.30 tonne is produced per tonne of cane. It is widely used as fuel in factory boilers, with potential for bio-CNG production.

***Press mud (Filter cake)*:** Approximately 100 lakh tonnes are produced annually in India. Rich in nutrients, it is utilised as organic fertiliser, in vermicomposting, and as a source for biogas.

***Molasses*:** A thick syrup leftover from sugar crystallisation, primarily used for alcohol/ethanol production, which in turn generates high-pollution wastewater known as 'spent wash'.

Standard treatment and disposal methods of spent wash

Indian sugar industries typically use a combination of technologies to manage spent wash. Biomethanation (Anaerobic digestion) which removes 60–80% of chemical oxygen demand, bio-composting, co-processing in cement kilns, advanced membrane systems (using technologies like RO and NF) and incineration to reduce the volume and concentrated in Multiple Effect Evaporators (MEE) to produce ash and valorise it to fertilisers or use it as a raw material in cement industries. Incinerated ash is highly valued for its high potash (K_2O) content, typically ranging from 21% to 37%. It contains significant amounts of magnesium (MgO ~9.3%), calcium (CaO ~4.6%), and sulphates (~7.3%). Traces of iron, manganese, and zinc are also present. Although the constraints do come along as CPCB guidelines discourage, its usage as manure during the rainy season and limit storage to a maximum of seven days of generation.

Risks and limitations of spent wash

***High toxicity in fresh form*:** Freshly generated ash can be highly toxic. It has been found that even at a 2% concentration, fresh ash can inhibit seed germination and damage plant roots due to its extreme alkalinity and high salt content.

***Contaminants*:** It may contain heavy metals (Nickel, Chromium) and toxic organic compounds (e.g. dichloroacetic acid) that could be carcinogenic if not properly managed.

***Soil microflora*:** The high pH and multi-metal content can adversely affect beneficial soil bacteria and fungi if applied without stabilisation.

Recommended application methods of spent wash

***Bio-composting*:** Mixing ash with press mud, cow dung, or other lignocellulosic waste through a 45–60 day composting cycle detoxifies the ash and produces stable organic manure.

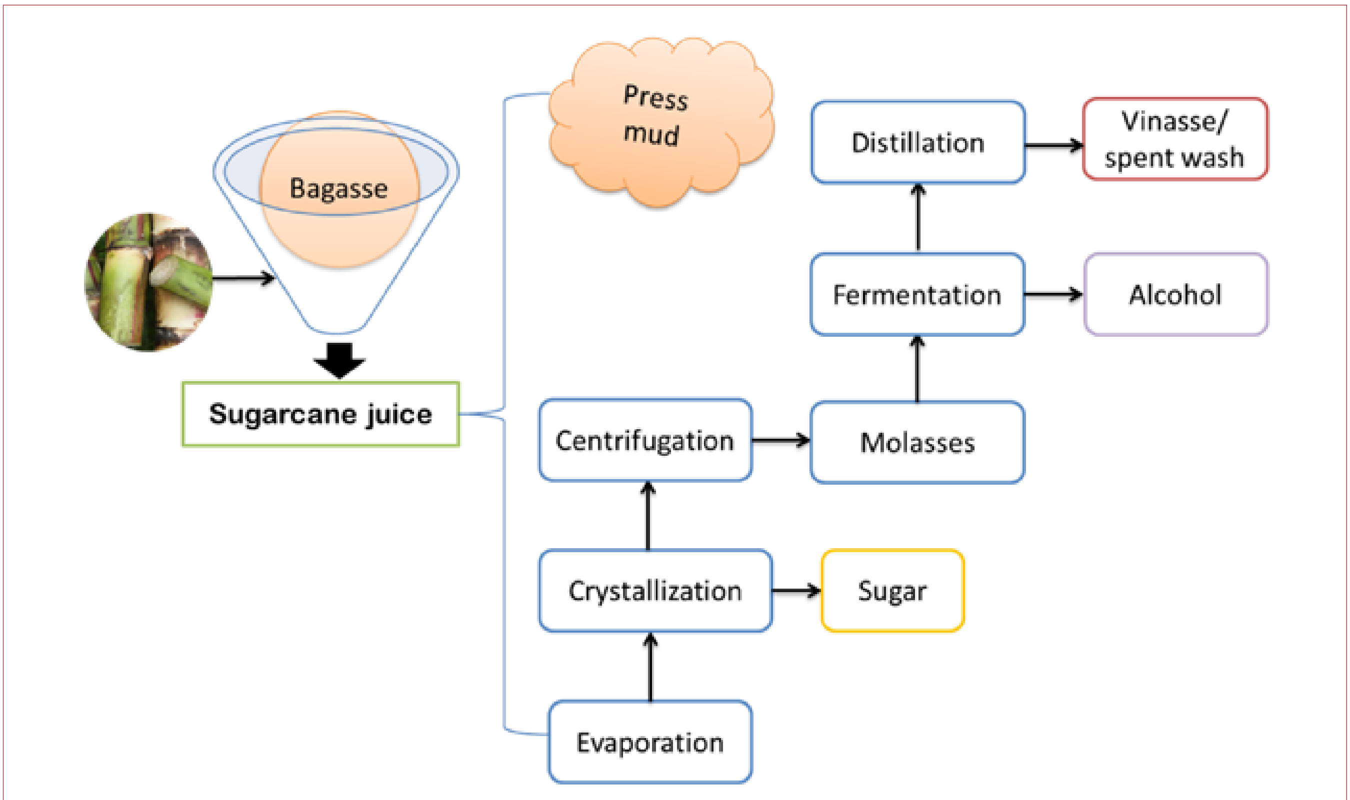
***Potash recovery*:** Advanced plants now use 'Ash to Potash' technology where ash is leached with water, filtered, and crystallised to produce potassium Sulfate (K_2SO_4), which is 98% pure and suitable for drip irrigation.

***Neutralisation*:** Ash should ideally be neutralised to a pH near 7.0 before direct soil application.

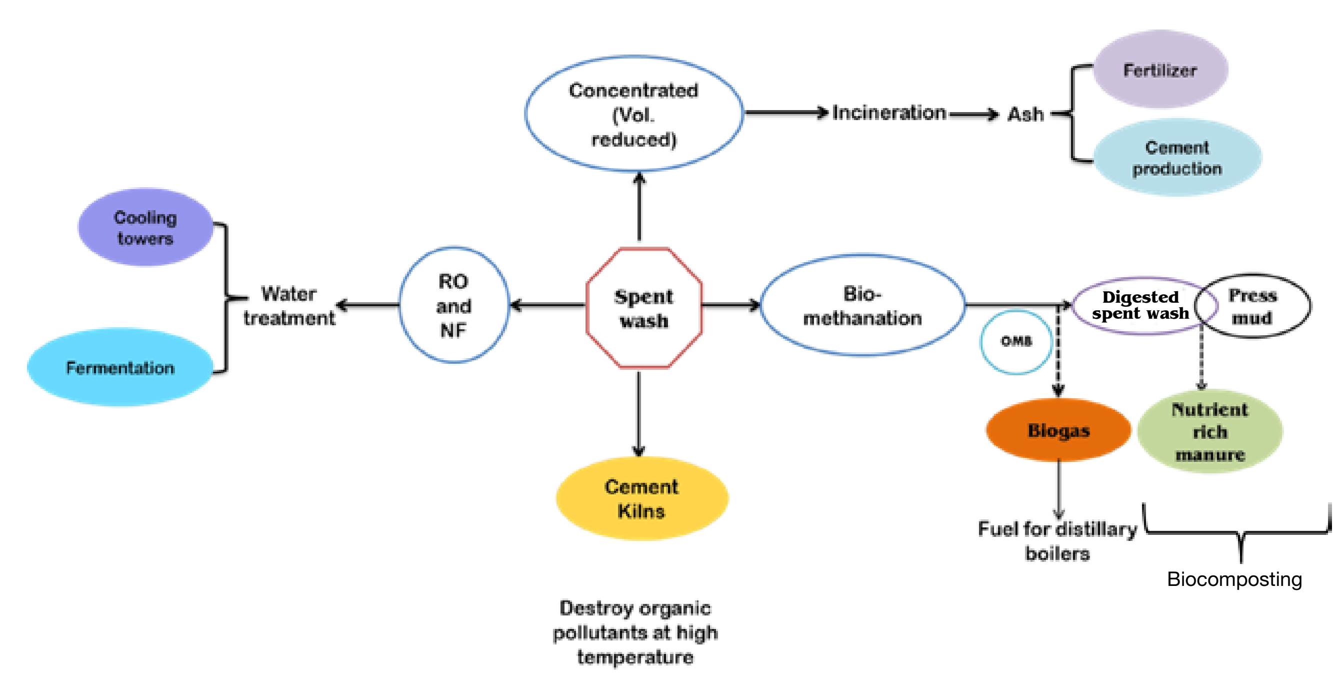
Applications of sugar waste products toward environmental sustainability

Energy generation and biofuels (Bagasse and molasses):

- **Bagasse cogeneration:** The fibrous residue (bagasse) is burned in high-pressure boilers to generate steam and electricity for the sugar mill, with excess power often exported to the grid.
- **Ethanol production:** Molasses, a by-product of crystallisation, is fermented to produce ethanol,



Products and by-products generated in sugar industry



Standard treatment and disposal methods of spent wash

which can be blended with petrol to create cleaner-burning fuel, reducing fossil fuel dependence.

- **Bio-CNG and biogas:** Through anaerobic digestion of press mud and distillery effluents (spent wash), sugar mills can produce Bio-CNG, a renewable, high-methane fuel.

Sustainable agriculture and soil health (Press mud and vinasse):

- **Bio-composting:** Press mud is rich in organic matter and nutrients. It is often mixed with distillery effluent (vinasse) to create nutrient-rich bio-compost, improving soil structure, water-holding capacity, and fertility.
- **Fertigation:** Treated vinasse can be used as a liquid fertiliser (fertigation) in sugarcane fields, providing potassium, nitrogen, and phosphorus, which reduces the need for synthetic chemical fertilizers.
- **Trash management:** Incorporating sugarcane leaves and trash (trashing) into the soil helps control weeds, reduces soil temperature, prevents erosion, and adds organic matter.
- **Organic manure:** Bagasse and press mud can be used as source of organic manure after processing. Biochar is one such where modern research is being conducted. This act as a good soil conditioner improving soil physical, chemical and biological properties along with being a better carbon sequester, thereby lowering carbon footprint, increasing water retention capacity, nutrient uptake and other physic-chemical properties as well.
- **Mushroom cultivation:** High cellulose, hemicellulose and lignin content of bagasse favours mushroom cultivation than traditionally used paddy straw due to its nutrient content. It thereby supplements parallel agro-industry.
- **Potash alternative:** Spent wash serves as an indigenous substitute for imported Muriate of Potash (MOP). The Government of India supports this through the Potassium Derived from Molasses (PDM) policy, which provides a subsidy (approx. ₹345/tonne for 2024–25) to promote its use.
- **Yield improvement:** Studies on crops like rice have shown that applying 10 t/ha of incineration ash alongside recommended fertilisers can significantly increase grain and straw yields.
- **Soil amendment:** Due to its alkaline nature (pH ~9.5), it can help neutralise acidic soils and improve soil structure, especially in 'Black Cotton' or expansive soils, by increasing dry density and bearing capacity.

Industrial and material recycling (Bagasse and ash):

- **Eco-friendly packaging:** Bagasse is used to manufacture biodegradable plates, cups, and food packaging, providing a sustainable alternative to single-use plastics.
- **Paper and pulp:** Due to its high cellulose content, bagasse serves as a sustainable raw material for the paper and pulp industry, reducing deforestation. This also requires fewer chemicals during the process, facilitating in ecofriendly paper production.
- **Construction materials:** Bagasse fly ash, produced after incineration, is used as a substitute for cement in bricks, concrete, and paver blocks. Fire-resistant good insulating materials can be produced promoting sustainable resources by reducing the dependence on wood.
- **Bio-adsorbents:** Bagasse ash is used as a low-cost adsorbent for treating industrial wastewater, specifically for removing heavy metals and dyes.

Table 1. Comparison of disposal options of spent wash

Method	Key benefit	Major challenge
Biomethanation	Generates renewable energy (biogas).	Effluent still contains high residual organic load.
Bio-composting	Low cost; creates high-value organic manure.	Requires large land area; limited by monsoon seasons.
Incineration	Achieves ZLD; produces potash-rich ash.	High capital and operating costs; prone to boiler scaling.
ZLD (Combined)	Total elimination of liquid discharge; high water recovery.	Highly energy-intensive and capital-heavy.

ZLD: Zero liquid discharge.

Water conservation:

- **Recycling and reuse:** Sugar mills are increasingly using Condensate Polishing Units (CPU) to treat and reuse process water, such as condensate from evaporators, for cooling and other operations.
- **Zero Liquid Discharge (ZLD):** Implementing ZLD technologies treats wastewater to a high standard, allowing it to be reused for irrigation, thus conserving freshwater resources.
- **Carbon neutrality:** Utilising bagasse for cogeneration allows mills to generate renewable energy, replacing fossil fuels and achieving a carbon-neutral energy cycle. Burning bagasse for energy generation is considered carbon neutral as it releases same amount of CO_2 as the sugarcane crop absorbs while growing. Thus, ensuring a net-zero carbon emission.
- **Waste valorisation:** Converting molasses into bioethanol provides a cleaner alternative to gasoline, directly addressing global climate goals.
- **Soil restoration:** Returning nutrient-rich press mud to the soil as organic fertiliser closes the nutrient loop, reducing the ecological damage caused by synthetic chemicals.

Challenges and future outlook

Despite the progress, challenges such as logistics of waste handling, the need for advanced technological investments, and the potential for pollution is a concern if by-products are not managed properly. Bulkiness of the by-products such as bagasse and press mud require sufficient storage space and has to be handled carefully as they pose risk to fire and have odor issues. High capital cost limits the implementation of these technologies in a country where there are small industries. Such technologies become unaffordable to them without external support. Composition of waste varies with region, input used and extraction process. Standardisation of technology in waste management needs to be addressed by research community.

Agro-based industries depend on crops for their raw material. Fluctuation in the supply of raw materials affects the running capacity of these industries. Efficient utilisation of waste generated from them can help these industries generate income even during non-seasonal period. Bagasse cogeneration can be a promising tool to produce carbon neutral electricity where there is decreasing availability of coal and shooting up of fossil fuel price. Increase in the greenhouse gas production can also be reduced by reducing the dependency on the fossil fuels. This provides energy to run the industry and also supply the rest to the grid, thereby providing additional income generation.

SUMMARY

The Indian sugar industry is actively transitioning from a traditional, high-pollution sector to a sustainable, circular economy model by effectively valorising its primary by-products like bagasse, molasses, spent wash and press mud. By adopting these practices, the industry reduces environmental hazards, minimises waste, lowers carbon emissions, and supports renewable energy production, playing a key role in India's sustainable development goals. During processing, every tonne of sugarcane generates substantial residues. By-products are major sources of renewable energy, reducing reliance on fossil fuels and lowering carbon footprints. Instead of disposal, nutrient-rich by-products are returned to the fields as organic amendments. Bagasse's high cellulose content makes it a versatile alternative to non-biodegradable materials. Modern mills aim for a 'Zero Liquid Discharge' (ZLD) status, ensuring economic viability apart from a sustainable approach. Thus, it is a game-changer in agriculture both on and off-the field generating additional income, employment, reducing dependency in imports of fertilisers, maintaining a better soil health and much more if government can frame better policies in collaboration with industries and farmers.

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