AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 03, Issue: 04 (April, 2026)
Available online at http://www.agrimagazine.in
©Agri Magazine, ISSN: 3048-8656

Transforming Sugarcane Agro-Waste into Agricultural Wealth: Strategies for Sustainable Productivity

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The sugarcane industry generates substantial quantities of agro-residues at both field and factory levels. These residues, if efficiently recycled, can significantly enhance soil fertility, crop productivity and environmental sustainability. This chapter provides a comprehensive overview of sugarcane agro-waste, including trash, roots, bagasse, press mud, molasses, spent wash, PDM fertilizer and bagasse ash. Detailed tables describing chemical composition, nutrient contribution, agronomic effects, and environmental impacts are included to support scientific understanding and practical implementation.

Keywords: Sugarcane agro-waste, bagasse, press mud, spent wash, trash mulching, biochar, circular economy, climate-smart agriculture, soil carbon sequestration

Introduction

Sugarcane (*Saccharum officinarum* L.) is one of the most important commercial crops cultivated in tropical and subtropical regions of the world. It serves as the primary raw material for sugar production and contributes significantly to bioenergy, ethanol, jaggery, and various agro-based industries. Globally, sugarcane plays a strategic role in food security, renewable energy production, and rural employment generation.

India is the second-largest producer of sugarcane after Brazil, accounting for a substantial share of global sugar production. The Indian sugar sector is one of the largest agro-based industries, supporting nearly 50 million farmers and workers directly and indirectly. According to the Indian Sugar & Bio-energy Manufacturers Association (ISMA, 2026), India operates approximately 515 sugar mills, with Maharashtra emerging as one of the leading sugar-producing states. In the 2024–25 crushing season, India's sugar production ranged between 247–261 lakh tonnes after ethanol diversion, highlighting the scale and economic importance of this industry.

While sugarcane production contributes immensely to economic growth, it simultaneously generates large quantities of agro-residues at different stages of cultivation and processing. These residues are broadly categorized into field-level residues (such as trash, tops, roots, and stubbles) and factory-level by-products (such as bagasse, press mud, molasses, spent wash, and bagasse ash). Traditionally, many of these materials were either burned, discarded, or inadequately managed, resulting in environmental pollution, greenhouse gas emissions, and nutrient losses.

However, recent scientific advancements have shifted the perception of these materials from "waste" to "valuable bio-resources." Sugarcane agro-waste is rich in organic carbon, macro-nutrients (N, P, K), secondary nutrients (Ca, Mg, S), micronutrients (Fe, Zn, Mn, Cu), and bioactive compounds. When recycled efficiently, these residues improve soil structure, enhance microbial activity, increase soil organic carbon (SOC), and promote sustainable crop productivity.

Magnitude of Agro-Waste Generation

The magnitude of agro-waste generation in the sugar industry is substantial:

- Sugarcane trash: 8–10 tonnes per hectare
- Bagasse: 28–32% of cane weight
- Press mud: 3–5% of cane crushed
- Molasses: 4–5% of cane weight
- Spent wash: 10–15 liters per liter of alcohol produced
- Bagasse ash: 2–3% of bagasse burnt

Considering India's annual sugarcane production exceeding 350 million tonnes, the quantity of generated by-products is enormous. If not managed properly, these residues pose environmental challenges such as air pollution from burning, groundwater contamination from untreated effluents, and methane emissions from uncontrolled decomposition.

Environmental Concerns of Improper Disposal

Improper disposal of sugarcane agro-waste can lead to:

- Release of CO_2, CO, and particulate matter due to open burning
- Methane (CH_4) emission during anaerobic decomposition
- Water pollution from untreated spent wash discharge
- Soil salinity and acidification due to excess effluent application
- Nutrient runoff and loss of soil fertility

Open-field burning of sugarcane trash, in particular, has been identified as a major contributor to localized air pollution and loss of valuable organic matter. Similarly, distillery effluents (spent wash) have high Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), which can severely affect soil and water ecosystems if discharged untreated.

Concept of Waste to Wealth in Sugar Industry

Modern agricultural sustainability frameworks emphasize the concept of "waste to wealth," wherein industrial by-products are recycled into productive inputs. In the context of sugarcane, agro-waste recycling contributes to:

- Circular bioeconomy
- Climate-smart agriculture
- Integrated nutrient management (INM)
- Soil carbon sequestration
- Renewable energy generation

Bagasse is widely used for cogeneration of electricity, making many sugar mills energy self-sufficient. Press mud and bagasse can be composted or vermicomposted to produce organic fertilizers. Molasses serves as a substrate for ethanol production, while spent wash can be safely utilized through controlled fertigation after dilution. Bagasse ash can function as a soil amendment and partial potash substitute.

Role in Soil Health and Carbon Sequestration

Soil organic carbon (SOC) is a key indicator of soil health and sustainability. Continuous monocropping and excessive chemical fertilizer use often lead to SOC depletion. Incorporation of sugarcane residues enhances:

- Soil aggregation
- Water-holding capacity
- Microbial biomass
- Nutrient availability
- Long-term carbon storage

Root biomass and trash mulching particularly contribute to carbon stabilization in soil systems. Biochar derived from bagasse further enhances carbon sequestration due to its recalcitrant carbon structure.

Economic and Agronomic Significance

Efficient agro-waste utilization provides multiple economic and agronomic benefits:

- Reduced dependence on chemical fertilizers

- Lower input costs for farmers
- Improved cane yield and sugar recovery
- Enhanced nutrient-use efficiency
- Sustainable intensification of production systems

In Maharashtra and other major sugarcane-growing regions, integrated use of press mud compost, trash mulching, and spent wash fertigation has shown significant improvements in cane yield and soil fertility.

Need for Integrated Agro-Waste Management

Given the scale of the sugar industry, there is an urgent need to develop integrated agro-waste management strategies that combine:

- Scientific composting
- Biochar production
- Controlled fertigation
- Nutrient budgeting
- Environmental monitoring

Such integrated approaches not only minimize environmental risks but also convert agro-residues into valuable agricultural inputs.

Classification of Sugarcane Agro-Waste

Category	Type	Source
Field-Level Residues	Sugarcane Trash	Harvest residue
	Roots & Stubbles	Post-harvest soil biomass
Factory-Level Residues	Bagasse	Juice extraction
	Press Mud	Juice clarification
	Molasses	Sugar crystallization
	Spent Wash	Distillery effluent
	Bagasse Ash	Boiler combustion
	PDM Fertilizer	Molasses-derived product

Agro-Waste Generated in Sugarcane Industry

Field-Level Residues

Sugarcane Trash: Sugarcane trash consists of dry leaves and tops left in the field after harvesting. Approximately 8–10 tonnes per hectare (t/ha) of trash is generated under normal cultivation conditions, depending on variety, yield level, and harvesting method (manual or mechanical). Traditionally, this residue was often burned in the field to facilitate ratoon management and reduce labor costs. However, burning leads to substantial nutrient loss, air pollution, and greenhouse gas emissions. Scientific research now recognizes sugarcane trash as a valuable organic resource rich in carbon and essential plant nutrients. Its proper management through mulching, composting, or in-situ incorporation contributes significantly to soil health improvement and sustainable sugarcane production systems (Memane *et al*., 2025).

Sugarcane trash contains 35–45% organic carbon, making it an important contributor to soil organic matter (SOM) buildup. Though nitrogen and phosphorus contents are relatively low, potassium concentration is comparatively higher (0.8–1.5%), which is particularly beneficial for sugarcane—a high potassium-demanding crop. The presence of secondary nutrients (Ca and Mg) and micronutrients (Fe, Zn, Mn, Cu) further enhances its agronomic value. Due to its wider C:N ratio, decomposition is relatively slow; therefore, application of nitrogen sources (such as urea) or microbial decomposer cultures is often recommended to accelerate breakdown and nutrient release.

Sugarcane Trash

Chemical Composition of Sugarcane Trash

Component	Content (%)
Organic Carbon	35–45
Nitrogen (N)	0.4–0.7
Phosphorus (P_2O_5)	0.10–0.20
Potassium (K_2O)	0.8–1.5
Calcium	0.3–0.6
Magnesium	0.15–0.30
Micronutrients	Fe, Zn, Mn, Cu

Agronomic Benefits of Sugarcane Trash

1. **Improves Soil Organic Matter (SOM):** Addition of trash increases organic carbon content, enhancing overall soil fertility and long-term productivity.
2. **Enhances Soil Physical Properties:** Improves soil aggregation, porosity, aeration, and water-holding capacity.
3. **Conserves Soil Moisture:** Surface mulching reduces evaporation losses and maintains soil moisture, particularly beneficial in semi-arid regions like Maharashtra.
4. **Suppresses Weed Growth:** Acts as a physical barrier, reducing weed emergence and minimizing herbicide use.
5. **Stimulates Microbial Activity:** Decomposition promotes beneficial soil microorganisms, enhancing nutrient cycling and biological health.
6. **Improves Nutrient Availability:** Gradual decomposition releases essential nutrients, especially potassium and micronutrients.
7. **Prevents Nutrient Loss from Burning:** Avoids loss of nitrogen, sulfur, and organic carbon that occurs during open-field burning.
8. **Reduces Air Pollution:** Minimizes emissions of CO_2, CO, particulate matter, and other harmful gases.

9. **Enhances Carbon Sequestration:** Contributes to long-term soil carbon storage and supports climate-smart agriculture.
10. **Supports Integrated Nutrient Management (INM):** Acts as an important component of sustainable sugarcane residue and soil fertility management systems.

Roots and Stubbles: Roots and stubbles are the below-ground and basal portions of the sugarcane plant that remain in the soil after harvesting. Although they are often overlooked compared to above-ground residues, they represent a substantial source of organic biomass. During crop growth, sugarcane develops an extensive root system that continuously deposits organic compounds into the rhizosphere through root exudation, sloughing, and turnover. After harvest, these roots and stubbles gradually decompose, adding considerable amounts of organic carbon and nutrients back into the soil. Because this biomass is already incorporated within the soil profile, it plays a more stable and long-lasting role in soil organic matter (SOM) buildup compared to surface residues (Sathya *et al*., 2025). The nutrient composition of roots and stubbles indicates their significant contribution to soil fertility and carbon cycling. With organic carbon content ranging from 30–40%, they act as an important source of soil organic carbon (SOC). Nitrogen content (0.5–0.9%) is relatively higher than that of trash, which supports microbial decomposition and nutrient mineralization. In addition, the presence of phosphorus (0.15–0.25%), potassium (0.6–1.2%), calcium (0.4–0.7%), and magnesium (0.20–0.35%) enhances soil nutrient reserves. As decomposition occurs within the soil matrix, nutrients are released gradually, improving nutrient-use efficiency and reducing losses through volatilization or runoff.

Sugarcane Root

Nutrient Composition of Roots & Stubbles

Component	Content (%)
Organic Carbon	30–40
Nitrogen	0.5–0.9
Phosphorus (P_2O_5)	0.15–0.25
Potassium (K_2O)	0.6–1.2
Calcium	0.4–0.7
Magnesium	0.20–0.35

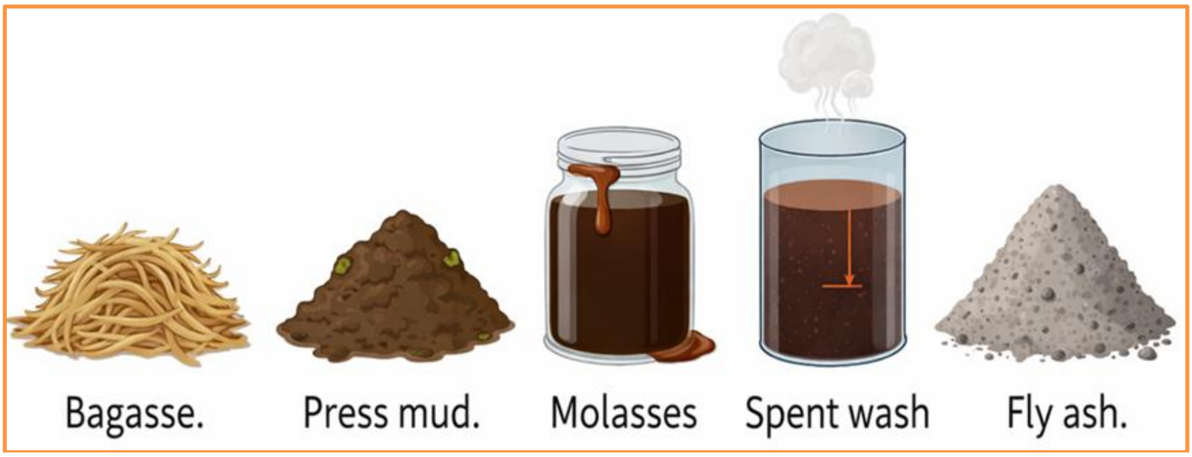
Role of Roots and Stubbles in Soil Carbon Sequestration

1. **Stable Carbon Source:** Root-derived carbon is more resistant to rapid decomposition compared to surface residues, contributing to long-term carbon stabilization.
2. **Increase in Soil Organic Carbon (SOC):** Continuous root biomass addition enhances overall soil organic carbon stocks.
3. **Deep Soil Carbon Deposition:** Carbon from roots is incorporated deeper into the soil profile, reducing susceptibility to oxidation and erosion losses.
4. **Improved Soil Aggregation:** Decomposing roots bind soil particles together, forming stable aggregates.
5. **Enhanced Aggregate Stability:** Stable aggregates protect organic carbon from rapid microbial breakdown.
6. **Improvement in Soil Structure:** Better aggregation improves porosity, aeration, and root penetration.

7. **Stimulation of Microbial Activity:** Root decomposition enhances microbial biomass and enzymatic activity in the rhizosphere.
8. **Enhanced Nutrient Cycling:** Increased microbial processes improve mineralization and nutrient availability.
9. **Reduced Carbon Loss:** Subsurface carbon is less exposed to environmental factors, minimizing carbon loss.
10. **Supports Climate-Smart Agriculture:** Retention of roots and stubbles strengthens soil resilience, promotes sustainability, and contributes to long-term carbon sequestration strategies.

Factory-Level Agro-Waste

Bagasse: Bagasse is the fibrous residue remaining after extraction of juice from sugarcane stalks in sugar factories. It constitutes nearly 28–32% of the cane weight and represents one of the largest by-products of the sugar industry. Traditionally, bagasse is used as boiler fuel for cogeneration of steam and electricity, making many sugar mills energy self-sufficient. However, beyond its energy value, bagasse is increasingly recognized for its agricultural potential due to its high organic carbon content (45–50%) and fibrous lignocellulosic structure. Although nitrogen content is relatively low (0.2–0.3%) and the C:N ratio is wide (100–120), proper composting or biological treatment can convert it into a valuable soil amendment.



Factory-Level Agro-Waste

Chemical Properties of Bagasse

Parameter	Value
Organic Carbon	45–50%
Nitrogen	0.2–0.3%
C: N Ratio	100–120
Moisture Content	45–55%
Silica	Present

Agricultural Uses of Bagasse

Bagasse can be utilized in multiple ways in agriculture after suitable processing. Conversion into biochar enhances soil organic carbon (SOC) and nutrient retention due to its stable carbon structure. Composting and vermicomposting improve nutrient availability and reduce the C:N ratio. Mulching with processed bagasse conserves moisture and suppresses weeds, while soil incorporation improves structure and aeration. Vermicomposting using Eisenia fetida significantly enhances nutrient enrichment and accelerates decomposition, producing high-quality organic manure (Hu *et al.*, 2023).

Bagasse Utilization in Agriculture

Application	Benefit
Biochar Production	Improves SOC & nutrient retention
Composting	Organic fertilizer

Vermicomposting	Nutrient-rich compost
Mulching	Moisture conservation
Soil Amendment	Improves structure

Press Mud: Press mud, also known as filter cake, is obtained during the clarification and filtration of sugarcane juice. It is rich in organic matter and contains considerable amounts of macro- and secondary nutrients. Unlike bagasse, press mud has a comparatively narrow C:N ratio and higher nutrient concentration, making it a superior organic fertilizer. Its pH range (6.5–8.0) allows it to function as a buffering material in slightly acidic soils. Due to its nutrient density and organic content, press mud plays an important role in integrated nutrient management systems.

Chemical Composition of Press Mud

Component	Range
Organic Matter	20–30%
Nitrogen	1.0–1.5%
Phosphorus	1.0–2.5%
Potassium	0.5–1.0%
Calcium	3–5%
pH	6.5–8.0

Application of press mud improves soil organic carbon, enhances available NPK levels, buffers soil pH, and stimulates microbial biomass. Numerous field studies have reported increased sugarcane yield following its application.

Effects of Press Mud on Soil

Soil Parameter	Effect
Soil Organic Carbon	Increased
Available NPK	Improved
Soil pH	Buffered
Microbial Biomass	Enhanced
Crop Yield	Increased

Molasses: Molasses is a viscous by-product obtained after sugar crystallization. It contains high levels of fermentable sugars (45–55%) and significant potassium content (3–5%), along with calcium and organic acids. Due to its rich carbohydrate content, molasses serves as an excellent substrate for microbial growth and fermentation processes. In agriculture, diluted molasses application enhances soil microbial activity and nutrient cycling processes, thereby improving soil fertility (Dhumri *et al*., 2022).

Composition of Molasses

Component	Range
Total Sugars	45–55%
Potassium	3–5%
Calcium	0.5–1.0%
Organic Acids	Present
pH	4.5–5.5

Agricultural Benefits of Molasses

- Stimulates microbial growth
- Improves nutrient cycling
- Supplies potassium
- Enhances soil biological activity

Spent Wash (Vinasse): Spent wash is a liquid effluent generated from distilleries during ethanol production from molasses. It is characterized by high organic load, elevated Biological Oxygen Demand (BOD), and Chemical Oxygen Demand (COD). Though it poses environmental risks if discharged untreated, controlled and diluted application in agricultural fields can be beneficial due to its high potassium and organic carbon content.

Chemical Properties of Spent Wash

Parameter	Range
pH	4.0–5.0
BOD (mg/L)	40,000–60,000
COD (mg/L)	80,000–120,000
Potassium	High
Organic Carbon	High

When applied judiciously, spent wash improves soil fertility, enhances microbial activity, and significantly contributes to potassium nutrition. However, over-application may lead to salinity buildup and soil acidification, necessitating proper dilution and monitoring.

Benefits and Risks of Spent Wash Application

Aspect	Impact
Soil Fertility	Improved
Potassium Supply	Significant
Microbial Activity	Increased
Over-application	Soil salinity risk
Undiluted Use	Soil acidification

PDM Fertilizer (Potash Derived from Molasses): PDM (Potash Derived from Molasses) fertilizer is an eco-friendly product developed from molasses-based distillery waste. It contains approximately 14.5% potash (K_2O) and serves as a partial substitute for imported potassic fertilizers. Being organic-based, it improves potassium nutrition while contributing to sustainable nutrient management.

Chemical Composition of PDM

Parameter	Value
Potash (K_2O)	~14.5%
Organic Base	Present
Eco-friendly	Yes

Bagasse Ash

Bagasse ash is generated after combustion of bagasse in sugar mill boilers. It contains appreciable amounts of potassium, calcium, magnesium, and silica. Due to its alkaline pH (8.5–10.5), it can be used as a soil amendment in acidic soils. The presence of silica enhances plant structural strength and resistance to lodging.

Composition of Bagasse Ash

Component	Content
Potassium	3–7%
Calcium	2–5%
Magnesium	1–3%
Silica	High
pH	8.5–10.5

Agricultural Benefits of Bagasse Ash

Benefit	Effect
Neutralizes acidic soils	pH correction
Supplies K	Improves yield
Adds silica	Better plant strength
Improves porosity	Better aeration

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