Policy Paper 55

India's Sugarcane Revolution: Role of Breeding Innovations

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Preface

Innovations in sugarcane breeding have significantly transformed the landscape of India's sugar industry. In recent years, the variety Co 0238 has proven to be a significant development, leading to enhanced crop yield and sugar recovery while demonstrating adaptability to diverse agro-climatic conditions. This development has enhanced the optimization of processing efficiency in sugar mills and facilitated the growth of sugarcane-based industries, including ethanol production and electricity cogeneration. Thus, the advances in sugarcane breeding have not only converted economic value to sugarcane by promoting circular economy but also reduced environmental footprints.

This study provides a comprehensive overview of how varietal development can contribute to the farm economy and the sugar and sugarcane-based industries. The findings are expected to serve as a valuable reference for policymakers, researchers, and industry stakeholders engaged in strengthening India's sugarcane-based food, fuel, and renewable energy value chains.

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Pratap Singh Birthal

Director, ICAR-NIAP

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The authors alone, however, remain responsible for the interpretations and any remaining errors.

(Authors)

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Executive Summary

Sugarcane has become a cornerstone of India's agro-industrial economy, playing a critical role in food security, rural livelihoods, renewable energy, and industrial diversification. With the population projected to reach 1.65 billion by 2050, sugar demand is expected to rise from 29 million metric tonnes (MMT) to 48 MMT. As the sugarcane cultivation area is unlikely to exceed the current 5.5–6.0 million hectares, this increased demand must be met through improved yield and sugar recovery.

The World Energy Council anticipates that transport fuel demand will rise by 200–300% in developing countries like India over the next 25 years. Petrol consumption is projected to double to 75 MMT by 2050, placing a heavy burden on crude oil imports and challenging India's economic growth and emission targets. With a mandatory 20% ethanol blending policy already in place, ethanol production—currently dependent on molasses—is increasingly being supplemented by direct use of sugarcane juice. By 2050, sugar and ethanol demand are projected to reach 48 MMT and 20 billion litres, respectively representing a 65% increase in sugar demand and a 100% increase in ethanol demand.

This study examines the evolving sugarcane value chain with a focus on varietal innovation, particularly the variety Co 0238, and its transformative impact on yield, value addition, and system stability across sugar, gur and khandsari, fuel ethanol, and co-product sectors. Sugarcane breeding in India dates back to the establishment of the Sugarcane Breeding Institute at Coimbatore in 1912. Landmark varieties such as Co 205, Co 312, Co 419, Co 86032, and Co 0238 have since emerged. Released in 2009 for sub-tropical India, variety Co 0238—an early maturing cross of CoLk 8102 and Co 775—features tall, medium-thick canes, high fibre content, and high-quality jaggery. During the release, it was moderately resistant to red rot and smut.

Variety Co 0238 saw rapid adoption due to its superior yield (up to 20 t/ha increase), higher sugar recovery (over 25%), and broad agro-climatic adaptability. By 2022–23, it covered over 70% of sugarcane area in states such as Uttar Pradesh and Punjab. Beyond production gains, variety Co 0238 has significantly enhanced value addition. Co-products such as bagasse, pressmud, sugarcane bagasse ash (SCBA), green tops, and ethanol contribute substantially to economic returns and environmental sustainability. Bagasse is used for cogeneration, pressmud for bio-fertilizers, and SCBA in cement and silica manufacturing—forming a circular bioeconomy that reduces waste and supports energy self-sufficiency.

From 2013–14 to 2022–23, variety Co 0238 contributed over one-third of total sugar and ethanol output, 78% of gur and khandsari production, 52% of bagasse, 45% of cogenerated power, and over 43% of green tops used as fodder. White sugar production increased from 12.6 MMT in 2004–05 to 35.7 MMT in 2021–22, with its value nearly doubling from Rs. 580 billion in 2000–01 to Rs. 1,106 billion in 2021-22. Variety Co 0238's share in sugar production rose from 4.5% in 2014–15 to 36.3% in 2022–23, and in value from 4.5% to 36.2% over the same period. Gur and khandsari production reached 6.7 MMT in 2022–23, with variety Co 0238 contributing over 78%.

Under the Ethanol Blended Petrol (EBP) Programme, sugarcane contributed approximately 1.8 billion litres in 2023–24, over 40% of total ethanol from sugarcane. Bagasse output exceeded 101 MMT, powering 4,100 MWh through cogeneration, up from 211 MWh in 2000–01. Press mud and SCBA, once treated as waste, reached volumes of 11.9 and 6.11 MMT, respectively. Green tops surpassed 25 MMT, playing a key role in livestock feed systems.

The Cuddy-Della Valle Index showed reduced production instability after the adoption of variety Co 0238: sugarcane (from 5.78% to 4.53%), sugar (13.35% to 7.05%), bagasse (8.98% to 5.72%), and cogeneration (63.85% to 30.98%). These results indicate not only improved average productivity of value-added products but also reduced year-to-year variability—crucial for market stability and farmer income security.

Supportive policy measures have underpinned these gains. The Fair and Remunerative Price (FRP) ensures farmer income security, while the Minimum Selling Price (MSP) for sugar prevents price crashes due to oversupply. Other mechanisms, including buffer stock subsidies, ethanol price differentiation by feedstock (juice, B-heavy, C-heavy), and the Minimum Indicative Export Quota, help stabilize domestic supply and maintain market balance.

However, sustained production and market interventions may face constraints under WTO obligations and create skewed support within agri-commerce. A sustainable sugarcane value chain thus requires continued varietal improvement, balanced with strategic import policies that safeguard farmer income and stimulate long-term investment across the sugarcane sector.

1 Introduction

Sugarcane is at the intersection of food security, farmer income, bioenergy, and climate resilience. It is more than a cash crop; it sustains rural livelihoods, contributes to India's energy security through bioethanol, and holds promise for climate adaptation. Its multifunctionality is evidenced by a wide range of derivative products (Annexure 1). Sucrose—the primary product—is extensively used in households and industries such as bakery, confectionery, and beverages. Traditional forms like jaggery and syrup are recognized for their nutritional value, while unprocessed sugarcane juice provides essential minerals including calcium, potassium, iron, and magnesium. Derivatives from sugarcane also find applications in pharmaceuticals, including the synthesis of antibiotics and chemical compounds. Additionally, sugarcane tops, a harvesting byproduct, are rich in fibre and digestible nutrients, making them a valuable fodder source for livestock. No wonders, sugarcane is more viable and preferred crop in comparison to traditional wheat and paddy system for small farmers (Jain et al., 2025).

As a C_4 crop, sugarcane exhibits high photosynthetic efficiency, enabling effective biomass and sugar production under high-temperature and high-light conditions. Its semi-perennial nature and dense canopy contribute to soil conservation and efficient water utilization, allowing it to perform well in rainfed and drought-prone areas. These physiological traits render sugarcane particularly relevant in the context of climate change. Its rapid growth and high biomass accumulation function as a carbon sink, contributing to greenhouse gas mitigation and improved air quality (Galdos et al., 2010).

Beyond food and fodder, sugarcane is an important source of renewable energy. Ethanol produced from sugarcane offers a cleaner alternative to fossil fuels, reducing greenhouse gas emissions and improving air quality by lowering the release of particulate matter and other pollutants. India is marching towards a 20% ethanol blend with petrol. The sugarcane-to-ethanol process also yields valuable co-products such as vinasse, a nutrient-rich organic fertilizer, which further amplifies its economic and environmental benefits. Additionally, sugarcane residues are increasingly used to manufacture biodegradable packaging, disposable tableware, and construction materials, supporting the transition to a circular bioeconomy and reducing dependency on fossil fuels and plastics.

Despite these advantages, scaling sugarcane-based industries presents challenges. These include land requirements, climate variability, and susceptibility to diseases and pests. Addressing these constraints requires the development and deployment of improved sugarcane varieties through advanced breeding programs. Enhanced varieties can deliver higher yields and sugar content, improving economic returns per unit of land and securing a stable supply of raw materials for sugar and ethanol production. Improved resistance to biotic and abiotic stresses also reduces the need for chemical inputs, aligning with sustainable farming goals. Furthermore, adaptability to diverse agro-climatic conditions allows expansion into non-traditional regions, easing pressure on established cultivation zones.

This study investigates the transformative impact of wonder sugarcane varieties particularly Co 0238, on India's sugar industry. With superior yield potential and high sugar recovery, variety Co 0238 has been widely adopted by farmers and sugar mills alike. Its introduction has not only boosted farm incomes but also improved mill efficiency and overall industry competitiveness. The influence of variety Co 0238 extends across the broader sugarcane-based industrial ecosystem, driving growth in ethanol production, cogeneration, and value-added co-products. The study intends to provide insights on how varietal innovation can serve as a catalyst for agricultural and industrial development, supporting long-term economic and energy security.

2 Data and Methodology

2.1 Data

The study relies on secondary and primary data sources to comprehensively evaluate the impact of sugarcane breeding research, with a specific focus on the variety Co 0238, on India's sugar industry complex. Time series data on sugarcane area, production and yield for both tropical and sub-tropical regions were collected from the Directorate of Economics and Statistics (DES), Ministry of Agriculture and Farmers Welfare. State wise varietal adoption of Co 0238 data was compiled from reports from Cane commissioner of the respective states and annual reports from sugar mills. In addition to production data, data on sugar recovery rate, extraction percentage of value-added products and coproducts such as sugar, bagasse, pressmud and molasses were collected from the annual reports of cooperative and private sugar mills. The recovery percentage for each product were used to estimate the corresponding output produced per unit of sugarcane processed with respect to variety Co 0238.

Data on ethanol production trends, blending levels, and pricing policies, were sourced from the Ministry of Petroleum and Natural Gas (GoI, 2022b), the Department of Food and Public Distribution (DFPD), and various published documents. Additional information on feedstock-wise ethanol production, policy incentives, and trade-related aspects was obtained from industry publications and the Renewable Fuels Association (RFA), United States. The study period covers two distinct phases: pre-adoption of the wonder variety Co 0238 (2000–01 to 2012–13) and post-adoption period (2013–14 to 2022–23).

2.2 Methodology

The economic impact of sugarcane breeding research, particularly the adoption of the variety Co 0238, was evaluated through a combination of descriptive statistics and empirical analytical tools. The methodology focuses on three core aspects: measuring instability, estimating varietal contribution to value chain outputs, and quantifying economic gains from sugarcane driven value added products and its co-products.

2.2.1 Measure of instability

Production instability poses significant risks to farm income, market supply, and value chain sustainability (Hazell, 1982; Chand and Raju, 2008). To assess variability in sugarcane production and its associated value-added products, the Cuddy-Della Valle Instability Index (CDVI) was employed.

The measure of instability is a variable over time should satisfy two minimum properties. It should not include deviations in the data series that arise due to secular trend or growth. Two, it should be comparable across data sets having different means. CDVI method provides a robust measure of variability, accounting for trends in the data. A linear trend was fitted to the time series data for variables such as area, production, yield, sugar recovery, and output of co-products and byproducts. The instability index (CDVI) was then calculated using the following formula:

$$\text{CDVI} = \text{CV X} \sqrt{1 - \text{R}^2}$$

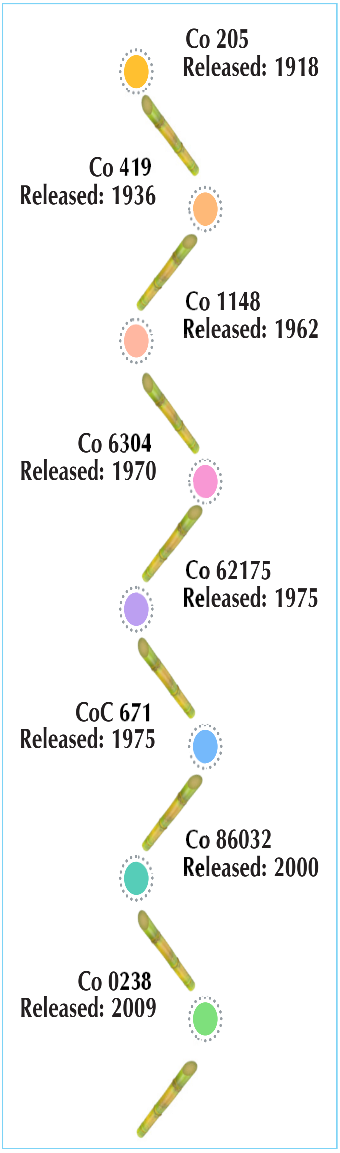
Where, CV represents the coefficient of variation, R^2 is the coefficient of determination obtained from the trend regression. To find the difference in instability, the CDVI was calculated for two different time period i) before introduction of the variety Co 0238 (2000-01 to 2012-13) and ii) after introduction of the variety Co 0238 (2013-14 to 2022-23).

3 Genetic Gains in Sugarcane: Breeding Research Journey

India has a rich and longstanding tradition of sugarcane breeding research, initiated with the establishment of the Sugarcane Breeding Station in Coimbatore, Tamil Nadu, in 1912 and rechristened as Sugarcane Breeding Institute after independence. Since its inception, significant advancements have been made in developing varieties with improved yield potential, enhanced sugar recovery, and resistance to biotic and abiotic stresses presented in Figure 1. The first major breakthrough came in 1918 with the release of sixteen hybrid varieties under the "Co" series, developed through natural hybridization. Among them, variety Co 205 well suited for the subtropical regions—emerged as a noble cane. Variety Co 205, a hybrid of *Saccharum officinarum* and *Saccharum spontaneum*, was developed with the objective of incorporating genes for stress resistance and high biomass production.

The genus Saccharum includes six species of varying polyploidy levels, two of which—*S. robustum* and *S. spontaneum*—are wild. *S. officinarum*, considered the original cultivated sugarcane, likely originated in the Indonesian Archipelago and was later introduced to South India. In contrast, *S. spontaneum* is a wild species with broad geographic distribution across Asia, North Africa, and the Middle East (Tew and Cobill, 2008). Known for its adaptability to diverse rainfall regimes and altitudes (Irvine, 1983), *S. spontaneum* contributes critical traits such as phenotypic diversity, stress resistance (Moore, 1987), and genomic variability (Zhang et

Figure 1. Evolution of wonder cane varieties in India



Source: Compiled by authors

al., 2012). While it exhibits lower sucrose content and higher fiber than noble canes, its genetic traits are essential for breeding robust hybrids.

In hybridization programs, *S. officinarum* contributes high sucrose content and robust stalk morphology, while *S. spontaneum* provides traits such as environmental resilience, fibre content, and prolific tillering. The strategic crossbreeding of these two species marked a turning point in global sugarcane breeding, influencing varietal development in countries including Cuba, the United States, Australia, South Africa, Brazil, and Argentina. Most modern sugarcane varieties trace their genetic lineage to hybrids developed in Coimbatore.

Subsequent advancements involved tri-specific crosses between *S. officinarum*, *S. spontaneum*, and *S. barberi*, resulting in varieties such as Co 213, Co 214, Co 244, Co 285, Co 290, Co 312, Co 313, and Co 419. Trihybrid varieties like Co 281, Co 290, and Co 221 were particularly suitable for subtropical regions. Among these, Co 312 became dominant from 1928 onward, sustaining sugarcane agriculture in subtropical India for over three decades. These varieties exhibited a 35% increase in sucrose content compared to their predecessors and demonstrated early maturity, waterlogging tolerance, and resistance to red rot and Sereh virus.

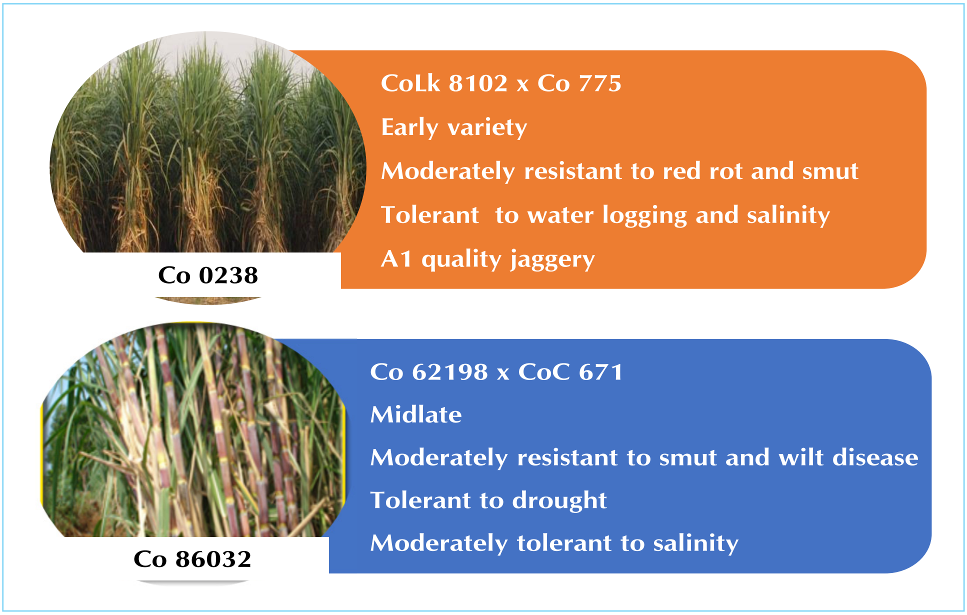
Co 419, released in 1936, became the predominant variety in tropical India, with yields reaching 136.46 t/ha and sugar recovery of 12.51%. This was followed in the 1940s by the release of Co 658 in Tamil Nadu and Co 740 in Maharashtra—the latter still in cultivation today. Co 1148 introduced in 1962 and Co 997 (introduced in 1967), were dominating cultivation in Andhra Pradesh and North India, respectively. Co 1148 remained the principal variety in subtropical India for over four decades before being gradually replaced. Co 62175 gained popularity among jaggery producers, while Co 6304 superseded Co 419 in Tamil Nadu due to its high yield.

Subsequent varietal evaluations identified high-sucrose varieties such as Co 7204, Co 7704, CoA 7601, CoC 671, Co 8336, and Co 8338. Notably, CoC 671, cultivated since 1975 in Tamil Nadu, Karnataka, and Maharashtra, exhibited sugar recovery between 8.88% and 12.74%. The variety CoJ 64 was an early maturing, high sugar, medium thick, soft and solid cane released during 1976 has made significant contribution in terms of sugar recovery (8.53% to 10.14%) and sugar yield (4.58 t/ha to 5.17 t/ha) improvement in Punjab (Mittal, 1984). CoS 8436 is a clonal selection from the cross MS 6847 × Co 1148, an early-ripening variety released in 1987, making it valuable for both early juice supply and commercial cultivation. In 1991, the variety CoPant 84211 was released, which is an early maturing known for its high sugar content and moderately resistant to red rot. After the widespread outbreak of red rot in CoC 671 and CoS 8436, a cross between Co 62198 and CoC 671 led to the development of variety Co 86032. Released in 2000 for tropical India, Co 86032 quickly gained dominance due to its high yield and ethanol potential, earning the moniker "Wonder Cane" of the millennium.

Variety Co 0238, an early-maturing variety developed from CoLk 8102 × Co 775, was introduced in 2009 for subtropical regions. Characterized by tall, medium-thick canes, high fibre content, and high-quality jaggery production, variety Co 0238 has been rapidly adopted across more than 2 million hectares, earning its status as the "Wonder Cane" of subtropical India. Varietal attributes of Co 86032 and Co 0238 are illustrated in Figure 2.

The introduction of these improved varieties has led to substantial gains in yield and sugar recovery. Historically, sugarcane breeding faced a trade-off between biomass yield and percentage sugar recovery to cane. However, variety Co 0238 has successfully broken this negative correlation, delivering a yield increase of up to 20 t/ha and a 25% improvement in sugar recovery in subtropical India. The major varieties popularized since 1918 across different agro-climatic zones of India are detailed in Annexure 2.

Figure 2. Varietal characteristics of wonder varieties



Source: Compiled by authors.

In a nutshell, India's century-long journey in sugarcane breeding has led to the development of region-specific, high-performing varieties through strategic hybridization of *S. officinarum*, *S. spontaneum*, and *S. barberi*.

Breakthrough varieties like Co 205, Co 312, Co 419, Co 86032, and Co 0238 have significantly enhanced productivity, sugar recovery, and resilience, marking milestones in both tropical and subtropical sugarcane agriculture. These genetic innovations have not only sustained the industry but also reshaped the sugarcane value chain by addressing critical challenges of yield, stress tolerance, and industrial suitability.

3.1 Advanced breeding and other techniques for sugarcane crop improvement

Molecular breeding in sugarcane uses advanced genetic tools like marker-assisted selection (MAS) and genomic selection (GS) to improve crops faster and more precisely. These techniques help breeders select for desirable traits like high sugar content, disease resistance, and stress tolerance by analyzing the plant's DNA. Technologies like CRISPR have also enabled precise gene editing to enhance traits for bioenergy and resilience.

3.1.1 Marker-assisted selection (MAS)

Marker-assisted selection (MAS) in sugarcane uses DNA markers to identify plants with desirable traits, like disease resistance or high sugar content, at an early stage, which saves time and resources compared to traditional breeding methods. Although sugarcane's complex genome has made MAS challenging, techniques like using simple sequence repeat (SSR) markers have been developed to improve the efficiency of selecting promising lines for traits such as sugar yield and resistance to diseases like downy mildew.

i) Advantages of MAS in sugarcane

It shortens the time to develop new varieties by identifying superior individuals in the early stages of breeding. It Increases selection intensity and accuracy by using a genetic marker instead of just physical traits. It helps traits that are not easily visible (e.g., disease and pest resistance) or are influenced by environmental conditions.

ii) Challenges and advancements

Genome complexity: Sugarcane's large and complex genome with its high levels of polyploidy and heterozygosity presents a major hurdle for marker development and application. Earlier, the researchers have used lower-density markers, but the development of more precise markers like SSRs and advanced techniques has made MAS more effective. Researchers are exploring integrated approaches that combine MAS with other genomic tools, such as Genomic Selection, to further accelerate the breeding cycle and improve accuracy, particularly for complex traits.

3.1.2 Genomic selection

Genomic selection (GS) in sugarcane is a breeding method that uses genome-wide DNA markers to speed up the development of new varieties and improve traits like yield and disease resistance. It works by creating a prediction equation from a large "training" population with both genetic and phenotypic data, which can then be used to predict the performance of new seedlings based on their DNA alone, significantly shortening the traditional breeding cycle from 10-12 years to 5-6 years. This is particularly useful for sugarcane, which has a complex, heterozygous, polyploid genome.

3.1.3 Gene editing

Gene editing in sugarcane is used to develop improved varieties with traits like higher sugar content, pest and drought resistance, and altered lignin for bioenergy production. Techniques like CRISPR/Cas9 are employed for precise modifications, though sugarcane's complex, polyploid genome makes this challenging. Other techniques also like Transcription Activator-Like Effector Nucleases (TALENs) and RNA interference (RNAi) have also been used. These methods are widely used and efficient method for gene editing, valued for its precision, low cost, and ease of use. Researchers are using these tools to precisely alter genes for traits that are difficult to achieve with traditional breeding methods.

3.1.4 Transgenic in sugarcane

Transgenesis in sugarcane involves introducing foreign genes to improve desirable traits like pest and disease resistance, stress tolerance, and even product development. Applications include creating varieties resistant to insects like the sugarcane borer using genes from *Bacillus thuringiensis* (Bt), enhancing tolerance to drought and salt, and engineering sugarcane to produce higher sucrose yields or industrial compounds. The complex genome of sugarcane has made genetic transformation challenging, but advancements in methods like Agrobacterium-mediated transformation and particle bombardment have led to approved commercial varieties in countries like Brazil and Indonesia.

3.2 Applications of modern methods in sugarcane

(i) It shortens the time to develop a new variety from 10-12 years to 5-6 years. It Improves breeding efficiency and genetic gain by selecting superior individuals more accurately and earlier in the process and helps in selecting for combinations of traits such as high yield, high sugar content and tolerance to biotic and abiotic stresses. It helps breeders reduce the number of plants they need to evaluate in ground nurseries and clonal trials.

(ii) Increased sugar production: Gene editing can optimize sugar metabolism by modifying genes responsible for sugar production and storage, leading to sweeter and stronger varieties.

(iii) Improved bioenergy traits: Gene editing can be used to decrease lignin content, which improves the efficiency of converting sugarcane into ethanol.

(iv) Optimized plant architecture: Researchers have used gene editing to fine-tune leaf angle by modifying genes like LIGULELESS1, which can improve light capture and overall growth.

(v) Pest resistance: sugarcane varieties have been engineered to resist pests like the sugarcane borer (*Diatraea saccharalis*) by expressing genes from *Bacillus thuringiensis* (Bt). This has resulted in the commercial release of Bt sugarcane in Brazil.

(vi) Disease resistance: Genes for resistance to various diseases, including mosaic virus, yellow leaf virus, and red rot, have been introduced to protect sugarcane from pathogens.

(vii) Abiotic stress tolerance: Genetic modification can improve a sugarcane's ability to withstand environmental stresses like drought and salinity.

(viii) Herbicide tolerance: Some transgenic sugarcane lines are engineered to be tolerant to specific herbicides, which can simplify weed management.

(ix) Industrial products: Sugarcane can be used as a "bio factory" to produce high-value compounds for industrial use through genetic engineering.

However, sugarcane has a large and complex polyploid genome, meaning it has multiple copies of each gene. This complexity makes precise editing more difficult and challenging compared to diploid crops. There is regulatory approach to gene-edited crops varies by country and is still evolving and potential concerns regarding ecological impacts and intellectual property rights that will need to be addressed.

3.3 Other modern techniques

3.3.1 Bioinformatics

Bioinformatics in sugarcane is used to analyze vast amounts of genetic data to improve crop traits like yield, stress tolerance, and sucrose content. This involves creating databases of omics data, using computational tools for gene discovery, and applying artificial intelligence (AI) to predict optimal harvest times and manage resources more efficiently. The goal is to overcome the challenges posed by sugarcane's large, complex, and polyploid genome to accelerate breeding and develop improved varieties for biofuel and other uses. in addition, bioinformatics is more precise for Genome analysis and gene discovery, Marker-assisted breeding, Functional genomics, Precision agriculture and Crop improvement for bioenergy

3.3.2 Artificial intelligence:

AI is being used in sugarcane farming to optimize resources like water and fertilizer, increase yields, and improve overall management. Technologies such as sensors and satellite imagery feed data into machine learning models to provide farmers with actionable insights, from early disease detection and soil health monitoring to predicting the optimal harvest time. Initiatives are underway in regions like Maharashtra to implement these AI-driven solutions through partnerships with organizations and tech companies.

Key applications of AI in sugarcane farming

- **Smart irrigation:** AI, integrated with IoT devices, adjusts irrigation based on real-time data like soil moisture, weather forecasts, and crop needs, leading to significant water savings.
- **Yield and resource prediction:** AI models forecast crop yields and predict optimal harvest times to maximize sugar content, a crucial factor for profitability.
- **Pest and disease management:** AI can detect pests and diseases early through image and sensor data, allowing for timely and targeted interventions to prevent crop loss.
- **Soil health and fertilization:** AI analyzes soil data to provide precise recommendations for fertilizer application and to monitor soil organic carbon levels, promoting more sustainable farming practices.
- **Supply chain and production planning:** AI helps manage the supply chain by predicting cane availability and can be used to balance production needs, such as for sugar and ethanol blending.

4 Spatio-Temporal Trends in Sugarcane Area, Production, and Yield

Sugarcane is cultivated across tropical and sub-tropical regions of India, accounting for 3.1% of the total cropped area in 2022–23 (GoI, 2022a). Research advancements at the ICAR-Sugarcane Breeding Institute (SBI) have played a pivotal role in enhancing both production and yield. Table 1 presents the area, production, and yield across tropical and sub-tropical zones.

4.1 Impact of adoption of variety Co 0238 on sugarcane area

India's sugarcane cultivation is divided between tropical and sub-tropical regions (Figure 3), with the latter comprising approximately 55% of the total area (Table 1). The sub-tropical region experienced area fluctuations between 2000–01 and 2010–11. A significant shift occurred following the release of variety Co 0238, which led to a marked and sustained expansion of sugarcane area in the sub-tropics. From 2012 onwards, the area stabilized, culminating in a record 3.19 million hectares under sugarcane cultivation in 2022–23.

Variety Co 0238's widespread popularity in northern Indian states—Uttar Pradesh, Punjab, Haryana, Bihar, and Uttarakhand—can be attributed to its superior yield potential, high sugar content, and broad agro-climatic adaptability. As of 2022–23, the variety covered approximately 81% of sugarcane area in Haryana, 80% in Uttar Pradesh, 78% in Uttarakhand, 74% in Punjab and 68% in Bihar (Table 2). However, recent outbreaks of red rot have led to a gradual reduction in its area, though it remains the predominant variety in northern India (Table 3). Reason for the sudden outbreak and extensive crop losses in thousands of hectares is attributed to monoculture of the variety in more than 80% area in the region due to 'Vertifolia effect' (Viswanathan et al., 2022). Since the economic losses are significant, the farmers and sugar mills were prohibited for cultivation of variety Co 0238 in disease endemic sugarcane zones (Chinimandi, 2024a). Therefore, the area of the variety Co 0238 has reduced to less than 50% of the cane area in disease prone zone of sub topical India since 2023-24. Specifically, the area under the variety Co 0238 is 38 thousand hectares in Punjab (Table 3) accounting 42% of the total sugarcane area, 45 thousand hectares in Haryana (51%), and 30 thousand hectares in Uttarakhand (32%).

Table 1. Trends in area, production and yield of sugarcane

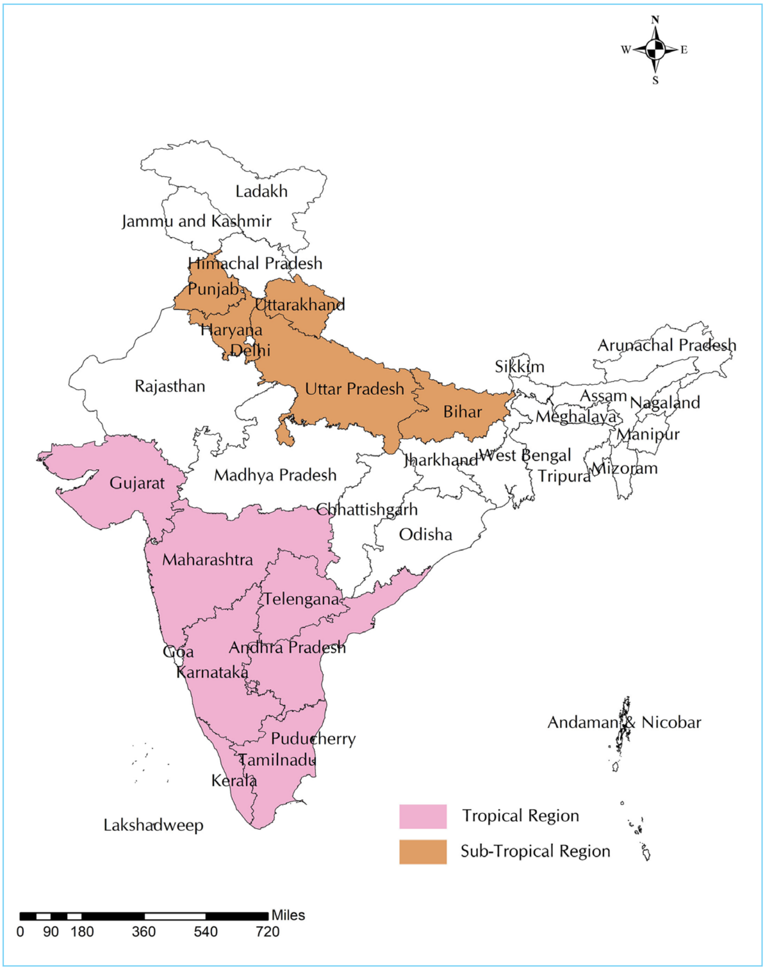
Year	Sub-Tropical			Tropical			Overall		
	A	P	Y	A	P	Y	A	P	Y
2000-01	2418	133345	55.72	1722	156086	88.86	4316	295956	68.60
2001-02	2577	149268	55.94	1700	141324	82.92	4411	297208	67.40
2002-03	2733	152741	53.92	1653	128275	77.46	4520	287383	63.60
2003-04	2545	140591	53.70	1263	87078	71.90	3938	233862	59.40
2004-05	2382	142498	56.50	1141	88456	78.64	3662	237088	64.80
2005-06	2569	148982	56.80	1483	124463	83.30	4201	281172	66.90
2006-07	2737	161605	56.90	2244	185684	84.62	5151	355520	69.00
2007-08	2662	151756	55.74	2211	188234	85.68	5055	348188	68.90
2008-09	2474	129398	52.70	1775	147670	83.38	4415	285029	64.60
2009-10	2323	137050	59.48	1698	148456	86.26	4175	292302	70.00
2010-11	2635	150019	59.92	2086	184529	87.48	4886	342382	70.10
2011-12	2663	159031	62.76	2204	193553	86.32	5038	361037	71.70
2012-13	2756	165309	63.50	2077	167556	81.58	4998	341198	68.30
Introduction of variety Co 0238									
2013-14	2781 (3.63)	167685 (3.87)	63.20	2036	175195	85.67	4993 (2.02)	352142 (1.84)	70.50
2014-15	2688 (10.12)	167468 (10.57)	65.32	2158	184228	84.88	5067 (5.37)	362330 (4.89)	71.50
2015-16	2693 (19.56)	177219 (20.05)	65.00	2003	159886	80.50	4927 (10.69)	348448 (10.20)	70.70
2016-17	2683 (33.41)	175057 (34.13)	70.17	1549	120469	76.82	4436 (20.20)	306070 (19.52)	69.00
2017-18	2768 (51.70)	214787 (52.44)	75.23	1760	153846	84.12	4732 (30.24)	376905 (29.89)	79.66
2018-19	2745 (81.51)	222448 (81.46)	79.89	2097	171541	84.01	5114 (43.75)	400157 (45.29)	78.25
2019-20	2711 (79.55)	215088 (79.76)	75.58	1655	141919	86.16	4603 (46.85)	370500 (46.31)	80.50
2020-21	2671 (85.20)	211360 (85.74)	76.66	2001	178171	87.65	4851 (46.91)	397657 (45.57)	81.98
2021-22	2628 (83.00)	211180 (83.23)	76.66	2264	207660	90.56	5098 (42.79)	425810 (41.28)	84.40
2022-23	3190 (72.39)	257540 (72.53)	77.24	2474	223939	90.67	5885 (39.24)	490533 (38.08)	83.35
2023-24	3128 (55.65)	250552 (55.64)	78.12	2388	188951	83.38	5740 (30.33)	453158 (30.77)	79.03

Source: Authors' estimates using data from GoI, various years, a.
Note: A = Area (000 ha), P = Production (000 tonnes), and Y = Yield (t/ha). The figures in parentheses indicate the percentage share from variety Co 0238.

4.2 Sugarcane production

With area remaining relatively stable, sugarcane production has increasingly been driven by yield improvements. Historically, sub-tropical regions lagged in productivity due to climatic constraints and limited adoption of improved varieties.

Figure 3. Major states under sugarcane cultivation in tropical and sub-tropical regions of India



Source: Compiled by authors.

Table 2. Share of variety Co 0238 in sugarcane area in sub-tropical regions in India

State	TE 2022-23 (000 ha)		
	Net sown area	Area under sugarcane[a]	Area under Co 0238[b]
Punjab	4116	89 (2.16)	66 (74.15)
Haryana	3602	105 (2.92)	85 (80.95)
Uttarakhand	594	96 (16.16)	75 (78.12)
Uttar Pradesh	27848	2364 (8.49)	1885 (79.73)
Bihar	5076	213 (4.20)	145 (68.07)

Source: Authors' estimates using data from GoI, various years, a.

Note: TE- Triennium Ending; [a]The figures in parentheses indicate the percentage share to the net sown area; [b]percentage share to area under sugarcane.

Table 3. State-wise area, production and yield of variety Co 0238 in sub-tropical region

State		Punjab	Haryana	Uttarakhand	Uttar Pradesh	Bihar
2013-14	A	27	0	2	73	0
	P	2001	1	90	4394	0
	Y	75.00	73.50	57.10	60.50	49.90
2014-15	A	52	23	4	177	17
	P	3900	1663	218	10977	950
	Y	74.90	73.90	60.40	62.10	55.30
2015-16	A	60	36	8	403	19
	P	4413	2624	503	26994	999
	Y	73.41	71.96	60.77	67.03	51.84
2016-17	A	60	58	14	729	36
	P	4845	4676	1007	47279	1937
	Y	81.27	80.62	69.65	64.89	54.42
2017-18	A	62	76	28	1208	58
	P	5161	6380	1931	95740	3428
	Y	83.58	84.50	69.68	79.25	59.14
2018-19	A	60	57	56	1928	137
	P	4877	4450	3870	155838	7083
	Y	81.82	78.24	69.55	80.81	51.70
2019-20	A	60	58	64	1815	159
	P	4827	4639	4849	147594	9655
	Y	80.24	80.27	75.41	81.31	60.65
2020-21	A	66	83	72	1890	165
	P	5550	7137	5982	154040	8510
	Y	83.82	86.18	82.90	81.50	51.73
2021-22	A	65	96	76	1807	138
	P	5511	7759	6084	147263	9156
	Y	85.34	81.23	80.00	81.50	66.25
2022-23	A	67	77	76	1957	132
	P	5697	6372	6107	161040	7571
	Y	84.69	82.23	80.00	82.31	57.46
2023-24	A	38	45	30	1517	111
	P	3197	3722	2479	123385	6635
	Y	83.25	83.58	82.64	81.35	59.78

Source: Authors' estimates using data from GoI, various years, a.

Note: A = Area (000 ha), P = Production (000 tonnes), and Y = Yield (t/ha).

Production in the sub-tropics fluctuated between 133.35 million metric tonnes (MMT) in 2000–01 and 161.61 MMT in 2006–07, declining to 129.40 MMT in 2008–09. However, the introduction of variety Co

0238 catalysed a dramatic rise, pushing production to 257.54 MMT in 2022–23—nearly double the pre-adoption level. Tropical production exhibited greater variability, ranging from 87.08 MMT (2003–04) to 223.94 MMT (2022–23).

Before 2012, sub-tropical production was lower despite having greater area under cultivation. Post-adoption of variety Co 0238, sub-tropical states consistently outperformed tropical ones by 5–40%, reversing historical trends and underscoring variety Co 0238's transformative impact.

4.3 Sugarcane yield

Yield improvements are central to sustainable production. While tropical regions frequently adopted improved varieties, such adoption was delayed in sub-tropical zones until the introduction of variety Co 0238 around 2008–09. This led to yield increment of up to 20 t/ha in the sub-tropics, rising from 55.72 t/ha in 2000–01 to 79.89 t/ha in 2018–19, with a slight decline to 77.24 t/ha in 2022–23.

Tropical yields showed greater fluctuations, from 71.90 t/ha (2003–04) to a peak of 90.67 t/ha (2022–23). Despite marginally higher yields than sub-tropical areas, tropical regions have not seen sustained improvement. Nationally, variety Co 0238 has driven average sugarcane yield from 59.4 t/ha to 83.35 t/ha (Table 1).

4.4 Sugar recovery rate

Sugar recovery trends differ significantly across regions (Figure 4). In the sub-tropics, recovery ranged from 9.69% in 2000–01 to a low of 8.97% in 2008-09. The release of variety Co 0238 in 2013–14 reversed this trend, pushing recovery to 11.15% by 2019–20. Recent declines to 9.57% in 2022–23 are attributed to juice diversion for ethanol production in Uttar Pradesh, despite peak recovery exceeding 11%.

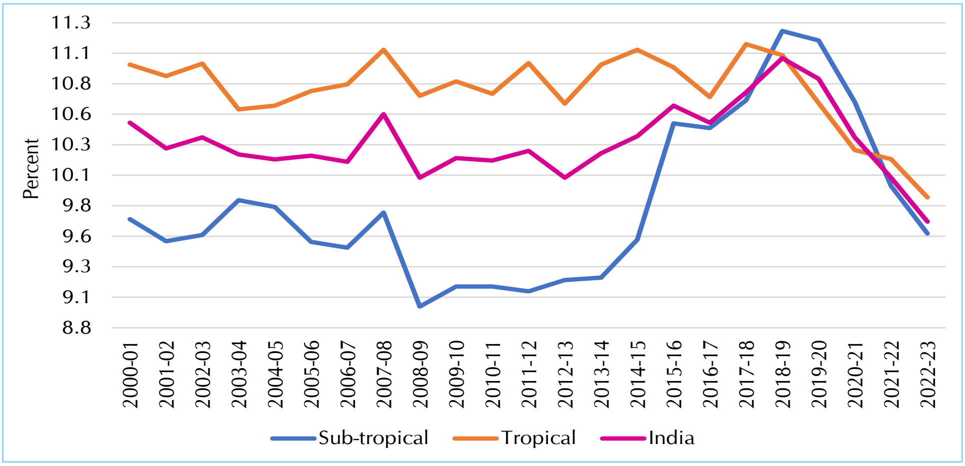
Tropical regions maintained higher recovery rates, fluctuating between 10.6% and 11.1% until 2010–11. Since 2013–14, a gradual decline has been observed from 10.96% to 9.87% indicating the need for continued research to enhance processing efficiency and varietal performance.

4.5 Sugar production

Sugar production in sub-tropical regions followed a rising trend, increasing from 4.97 MMT in 2008–09 to a peak of 15.11 MMT in 2019–20 (Figure 5). This was followed by a decline to 12.42 MMT in 2021–22 and a modest recovery to 13.01 MMT in 2022–23. Tropical sugar production displayed greater volatility, rising from 6.14 MMT (2004–05) to a peak of 22.65 MMT

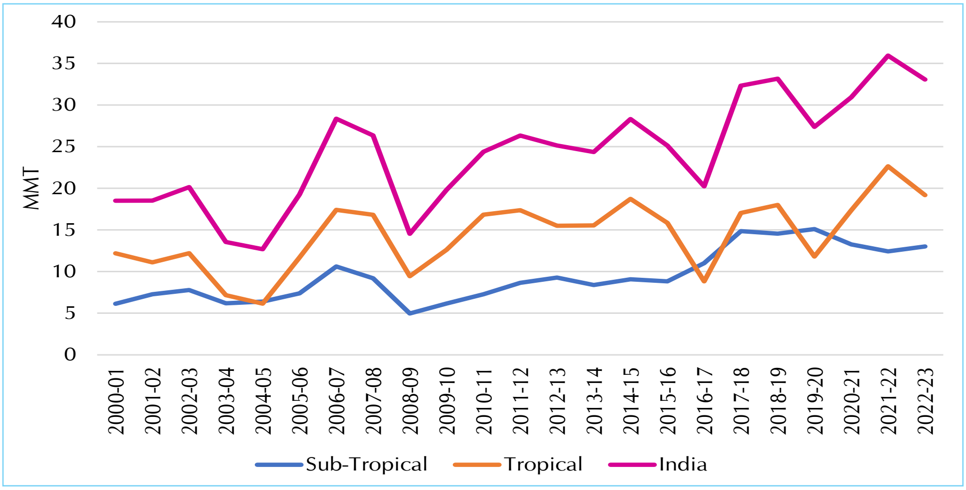
(2021–22), before falling to 19.18 MMT in 2022–23. Tropical sugar production displayed greater volatility, rising from 6.14 million tonnes (2004–05) to a peak of 22.65 million tonnes (2021–22), before falling to 19.18 million tonnes in 2022–23. In recent years, tropical regions have overtaken sub-tropical ones in sugar output, driven by less diversion of cane to ethanol. This shift underscores the evolving dynamics of regional production in response to policy and market incentives.

Figure 4. Sugar recovery pattern in tropical and sub-tropical regions of India between 2000-01 and 2022-23 (%)



Source: Computed by authors based on NFCSF, 2025.

Figure 5. Sugar production in tropical and sub-tropical regions of India between 2000-01 and 2022-23 (MMT)



Source: Computed by authors based on NFCSF, 2025.
MMT-million metric tonnes.

4.6 Changes in instability in production of sugarcane and sugar

A regional analysis of production instability before and after the adoption of variety Co 0238 reveals notable shifts. In the sub-tropics, sugarcane area and yield instability rose slightly, while production instability declined. In tropical regions, all three indicators—area, production, and yield—showed reduced volatility. At the national level, sugarcane area and production instability declined, although yield instability marginally increased.

Sugar production exhibited significant stability gains, with overall instability decreasing from 13.35% to 7.05% from the period 2000-13 to the period 2013-23 (Table 4). In contrast, sugar recovery showed divergent trends—declining slightly in the sub-tropics, but increasing in tropical and national averages—primarily due to ethanol-related juice diversion. Despite the rise in yield variability, particularly in the sub-tropics, variety Co 0238 contributed substantially to reducing overall production instability, establishing itself as a cornerstone in enhancing productivity and resilience in India's sugar sector.

Table 4. Instability in sugarcane area, production, yield, and sugar across regions

Particulars	Period	Sub-tropical (%)	Tropical (%)	India (%)
Sugarcane area	Before*	4.22	14.84	6.76
	After**	4.24	10.05	5.15
Sugarcane production	Before	4.84	17.44	5.78
	After	4.01	11.84	4.53
Sugarcane yield	Before	1.41	4.49	1.67
	After	1.46	3.85	2.26
Sugar production	Before	13.37	20.14	13.35
	After	8.84	15.34	7.05
Sugar recovery	Before	3.84	0.55	1.38
	After	3.76	0.88	3.64

Source: Computed by authors.

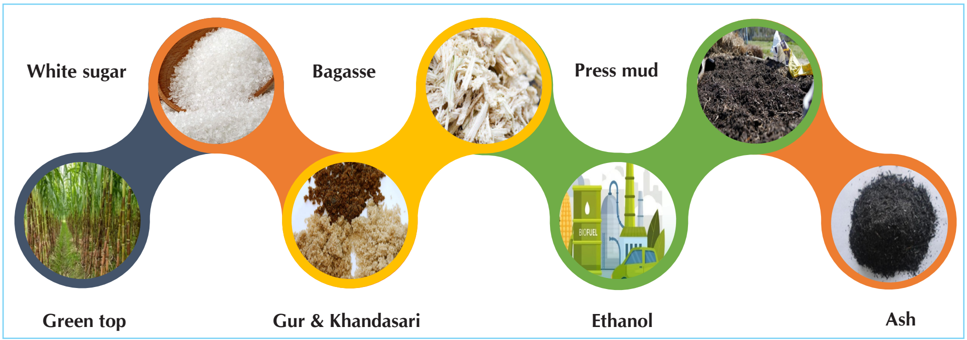
Note: *- Before refers to the period 2000-01 to 2012-13 and **- After refers to the period 2013-14 to 2022-23.

In a nutshell, the introduction of variety Co 0238 has been a game-changer for India's sugarcane sector, particularly in the sub-tropical belt. It led to substantial gains in area coverage, yield, sugar recovery, and overall production, reversing long-standing regional disparities. Sub-tropical states, once lagging, have outperformed tropical regions in yield and production following its adoption. While recent red rot outbreaks and ethanol-related juice diversion have moderated some gains, variety Co 0238 has significantly enhanced productivity, stabilized output, and redefined India's sugarcane breeding success story. Its impact underscores the critical role of varietal innovation in driving sustainable agricultural growth.

5 From Cane to Commerce: Value-Added Products of Sugarcane Sector

Sugarcane contributes far beyond its 3% share in agricultural GDP (GoI, Various years, a), playing a pivotal role in multiple sectors through its diverse value-added products. Its utility spans food, fodder, fuel, and industrial applications, making it one of the most versatile crops in Indian agriculture. The primary co-products from sugarcane processing—molasses, ethanol, and bagasse—serve distinct functions across energy, food, and manufacturing industries (Figure 6).

Figure 6. Value chain of sugarcane-based production system



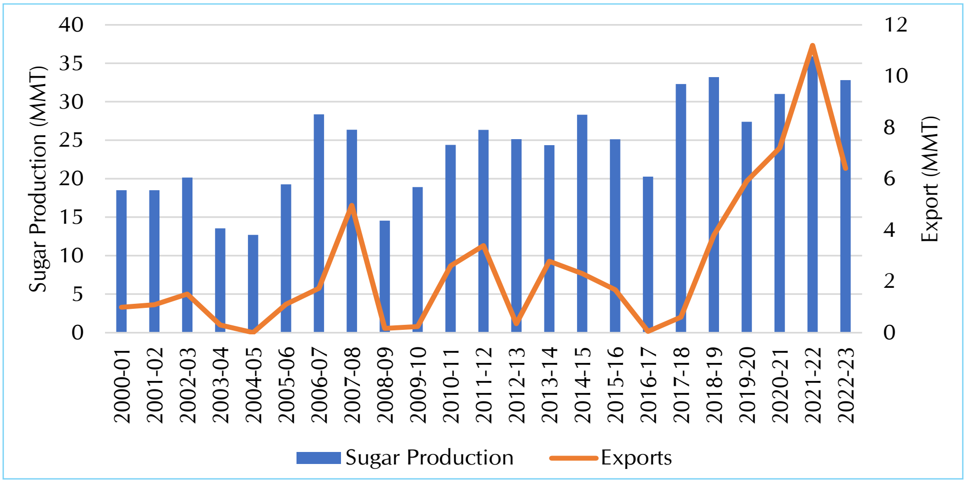
Source: Compiled by authors.

5.1 White sugar

Table 5 presents data on sugar production and its market value, highlighting notable fluctuations over the past two decades. Production varied from a low of 12.69 million metric tonnes (MMT) in 2004–05 to a peak of 35.76 MMT in 2021–22. These variations were driven by changes in acreage, yield, and recovery rates. Over the same period, the value of sugar output nearly doubled, rising from Rs. 580 billion in 2000–01 to Rs. 1,007 billion in 2022–23, influenced by both increased output and market price dynamics.

A critical inflection point in this trajectory was the introduction of variety Co 0238, which significantly transformed sugar production. Its contribution to total sugar output rose from 4.5% in 2014–15 to 36.3% in 2022–23, while its share in the value of production increased correspondingly from 4.5% to 36.2%. This varietal breakthrough boosted domestic sugar availability and helped stabilize India's position in the global sugar market. Prior to variety Co 0238's widespread adoption, India oscillated between being a net importer and exporter, with significant imports in 2003–04, 2004–05, 2008–09, and 2009–10. Enhanced productivity driven by variety Co 0238 has reduced import dependence and enabled sustained sugar exports (Figure 7), reinforcing India's status as a global net exporter.

Figure 7. Sugar production and export in India



Source: Computed by authors based on NFCSF, 2025.

*MMT-million metric tonnes.

5.2 Gur and khandsari

Gur (jaggery), a traditional unrefined sweetener, retains essential nutrients from sugarcane juice, offering a nutritional advantage over refined white sugar. Composed of over 70% sucrose, less than 10% glucose and fructose, and about 5% minerals, high-quality jaggery is rich in calcium, iron, potassium, and magnesium. These components confer multiple health benefits, including blood purification, prevention of rheumatism, and protection against bile disorders and lung infections. Scientific research has further supported jaggery's therapeutic potential in promoting organ health.

In addition to its culinary use, gur serves as a raw material in distilleries, Ayurvedic medicine, cattle feed, and the leather and tobacco industries. Gur and khandsari are primarily produced in sugarcane-growing regions through small-scale, cottage-based units. While urbanization and shifting consumption patterns had led to a decline in demand, recent health-conscious trends have revitalized interest in these traditional products.

Table 5. Production of sugar and gur & khandsari and contribution of variety Co 0238

Year	White sugar				Gur & Khandsari			
	Total quantity (000 tonnes)	Quantity from variety Co 0238 (000 tonnes)	Total value (Rs. billion)	Value from variety Co 0238 (Rs. billion)	Total quantity (000 tonnes)	Quantity from variety Co 0238	Total value (Rs. billion)	Value from variety Co 0238 (Rs. billion)
2000-01	18511	-	580	-	8538	-	225	-
2001-02	18528	-	550	-	8215	-	208	-
2002-03	20145	-	602	-	5949	-	141	-
2003-04	13546	-	392	-	7353	-	234	-
2004-05	12690	-	372	-	8410	-	279	-
2005-06	19267	-	577	-	5905	-	189	-
2006-07	28367	-	857	-	4302	-	129	-
2007-08	26357	-	739	-	5776	-	156	-
2008-09	14539	-	429	-	6650	-	210	-
2009-10	18912	-	555	-	7196	-	219	-
2010-11	24394	-	759	-	6183	-	183	-
2011-12	26343	-	808	-	6112	-	168	-
2012-13	25141	-	788	-	5026	-	131	-
Introduction of variety Co 0238								
2013-14	24396	534 (2.19)	761	17	6339	121 (1.91)	169	3
2014-15	28310	1275 (4.50)	869	39	5435	297 (5.46)	167	9
2015-16	25125	2805 (11.17)	764	85	7147	962 (13.46)	236	32
2016-17	20285	3851 (18.98)	624	118	7682	1810 (23.56)	255	49
2017-18	32479	8667 (26.68)	897	239	5399	2260 (41.86)	148	62
2018-19	33162	10599 (31.96)	1040	333	5466	3620 (66.23)	141	93
2019-20	27411	12037 (43.91)	839	368	4400	2990 (67.95)	143	97
2020-21	31192	12708 (40.74)	973	396	5600	4100 (73.21)	157	115
2021-22	35760	11487 (32.12)	1106	355	6500	5200 (80.00)	181	145
2022-23	32815	11912 (36.30)	1007	365	6700	5250 (78.36)	161	126

Source: Computed by authors based on NFCSF, 2025.

Note: Values are in constant prices, (base year-2011-12); Figures in the parenthesis indicate percentage share to total in respective year.

Production data from 2000–01 to 2012–13 (Table 5) show a decline in gur and khandsari output from 8.54 MMT to 5.03 MMT, with a low of 4.30 MMT in 2006–07. The corresponding value dropped from Rs. 225 billion to Rs. 131 billion, reflecting weakened market demand.

The introduction of variety Co 0238 in 2013–14 reversed this trend. Production from variety Co 0238 increased from just 121 thousand tonnes in 2013–14 to 5.25 MMT in 2022–23. By 2019–20, the variety contributed 2.99 MMT out of 4.40 MMT total production, highlighting its dominant role. From 2018-19 onwards, variety Co 0238 consistently accounted for nearly 50% of total gur and khandsari output, ensuring the sustainability and revival of this traditional industry.

Instability indices for sugar and gur/khandsari production (Table 6) underscore this impact. Post-introduction of variety Co 0238, sugar production instability declined from 13.37% to 8.84%, while gur and khandsari instability fell from 15.58% to 11.89%. These reductions in year-to-year variability indicate increased production reliability and supply chain resilience, reaffirming variety Co 0238's critical role in stabilizing and strengthening value-added outputs in India's sugarcane sector.

Table 6. Instability index of sugar and gur & khandsari

	Before introduction of variety Co 0238 (%) (2000-01 to 2012-13)	After introduction of variety Co 0238 (%) (2013-14 to 2022-23)
Sugar	13.37	8.84
Gur and Khandsari	15.58	11.89

Source: Computed by authors.

In a nutshell, the introduction of variety Co 0238 has not only boosted white sugar production but also revived and stabilized traditional sweetener industries like gur and khandsari. Its widespread adoption has reduced India's sugar import dependency, enabled steady exports, and brought new life to rural livelihoods tied to small-scale processing. variety Co 0238 stands as a cornerstone varietal innovation, anchoring growth, diversification, and resilience in India's sugarcane economy.

6 Value Added Co-Products from Sugarcane

The economic and environmental value of sugarcane extends well beyond its primary outputs of sugar and ethanol. A range of co-products generated from its processing—bagasse, pressmud, spent wash, sugarcane bagasse ash (SCBA), and green tops—play a crucial role in enhancing resource efficiency, supporting industrial diversification, and promoting circular economy principles. The introduction of the variety Co 0238 has significantly influenced the production, value generation, and stability of these co-products across the sugarcane value chain.

6.1 Bagasse

Bagasse, the fibrous residue left after juice extraction, is a highly versatile biomass co-product. Unlike other biomass sources, it does not compete for land or energy, making it an environmentally benign input for industrial applications. In sugar mills, bagasse is primarily used for cogeneration or sold to external industries, while gur and khandsari units rely on it as fuel for processing. The shift towards bio-refining and value addition from bagasse—including production of bio-based chemicals—aligns with sustainable development and circular economy goals.

Between 2000–01 and 2012–13, bagasse production from the organized sector exhibited fluctuations, with major declines in 2004–05 and 2008–09 and a peak in 2006–07. However, its economic value steadily increased, reflecting rising demand and industrial utilization. Post-2013–14, following the adoption of variety Co 0238, bagasse production initially dipped but rebounded consistently thereafter. Its value rose from Rs. 116 billion in 2013–14 to Rs. 196 billion in 2022–23 (Table 7). Variety Co 0238 played a pivotal role, peaking in 2018–19 with a 60.27% share in quantity and 70.32% in value, underscoring its economic significance for bagasse generation.

6.2 Cogeneration/power

Cogeneration, the simultaneous production of electricity and heat from bagasse, has emerged as a key strategy for energy self-sufficiency in sugar mills. While power generation grew modestly from 2000–01 to 2012–13, the introduction of variety Co 0238 in 2013–14 marked a significant transformation. Its superior biomass yields increased fuel availability for cogeneration.

Table 7. Production of bagasse and power and contribution of variety Co 0238

Year	Bagasse				Cogen power			
	Total quantity (000 tonnes)	Quantity from variety Co 0238 (000 Tonnes)	Total value (Rs. billion)	Value from variety Co 0238 (Rs. billion)	Total power produced (MWh)	Power produced from variety Co 0238 (MWh)	Total revenue (Rs. billion)	Revenue from variety Co 0238 (Rs. billion)
2000-01	44165	-	38	-	211	-	1.9	-
2001-02	45087	-	64	-	216	-	1.9	-
2002-03	48591	-	76	-	228	-	1.9	-
2003-04	33128	-	37	-	200	-	1.0	-
2004-05	31193	-	40	-	170	-	1.0	-
2005-06	47168	-	80	-	151	-	1.1	-
2006-07	64238	-	128	-	220	-	1.9	-
2007-08	59977	-	114	-	275	-	2.6	-
2008-09	36246	-	56	-	294	-	2.2	-
2009-10	46387	-	106	-	274	-	1.7	-
2010-11	59952	-	128	-	279	-	1.4	-
2011-12	64244	-	161	-	362	-	2.2	-
2012-13	62650	-	108	-	420	-	2.5	-
Introduction of variety Co 0238								
2013-14	71453	1946 (2.72)	116	3	472	10 (2.14)	5.2	0.1
2014-15	81952	5313 (6.48)	135	9	850	41 (4.82)	11	0.5
2015-16	70949	10413 (14.68)	107	16	920	94 (10.19)	10	1.1
2016-17	58030	17578 (30.29)	93	28	720	141 (19.55)	7	1.4
2017-18	90359	33443 (37.01)	108	40	1149	343 (29.83)	15	4.9
2018-19	90354	54457 (60.27)	130	78	2200	784 (35.64)	19	7.7
2019-20	75851	52101 (68.69)	130	89	2500	1243 (49.71)	28	16
2020-21	90286	53893 (59.69)	160	96	3500	1577 (45.04)	46	24
2021-22	106919	50949 (47.65)	211	100	4100	1237 (30.16)	53	21
2022-23	101836	53552 (52.59)	196	103	NA	NA	NA	NA

Source: Computed by authors based on NFCSF, 2025.
Note: Values are in constant prices, (base year-2011-12); Figures in the parenthesis indicate percentage share to total in respective year.

Variety Co 0238's contribution to cogeneration surged from just 10 MWh in 2013–14 to 1,577 MWh in 2020–21. Consequently, total cogeneration output grew from 472 MWh in 2013–14 to 4,100 MWh in 2021–22. Revenue followed a similar trend, peaking at Rs. 53 billion in 2021–22, with variety Co 0238 alone contributing Rs. 21 billion in 2021-22. These developments underscore the variety's role in expanding energy output and economic returns in the sub-tropical sugar sector.

6.3 Press mud and distillery spent wash

Press mud, a byproduct of juice clarification, contains substantial organic matter and nutrients (Chen et al., 1993). Traditionally underutilized or incinerated, it now finds increasing use as an organic fertilizer (Nasir, 2006), especially when composted or enriched with Distillery Spent Wash. India's heavy dependence on imported potassium (2.5–3 million metric tonnes (MMT) annually) makes the valorization of pressmud crucial for domestic fertilizer security.

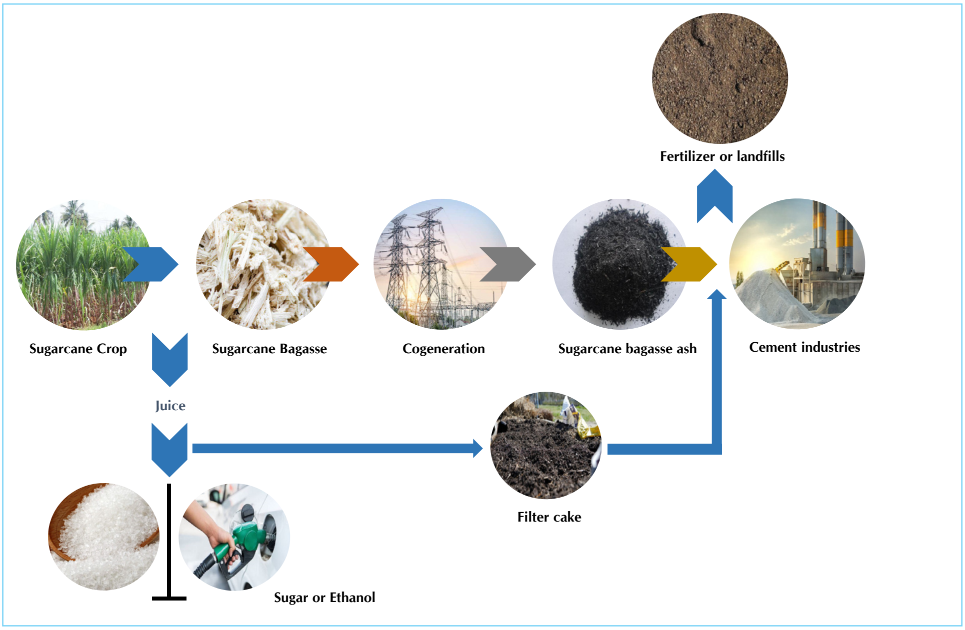
From 2000–01 to 2012–13, pressmud production increased from 5.3 to 7.5 MMT, with value rising from Rs. 901 million to Rs. 1,623 million (Table 8). Post-2013–14, variety Co 0238 drove a substantial increase, contributing nearly 41% of total output by 2019–20. Total pressmud production peaked at 12.47 MMT in 2021–22, with value from variety Co 0238 rising from Rs. 34 million in 2013–14 to Rs. 747 million in 2022–23. This demonstrates the variety's crucial role in enhancing nutrient recycling and reducing fertilizer import dependence.

6.4 Sugarcane bagasse ash (SCBA)

SCBA, the residual ash from bagasse combustion (Figure 8), is a growing concern due to its volume and environmental impact. However, its high amorphous silica content offers potential as a supplementary cementitious material and a source for industrial silica extraction. SCBA composition varies with cogeneration technology, combustion temperature, and feedstock properties. It contains minerals such as amorphous silica, quartz, alumina, and maghemite, making it suitable for use in cement, concrete, and ceramic industries.

The mineral composition of sugarcane bagasse ash (SCBA) varies with geographical origin, pulverization methods, and combustion conditions—particularly temperature and duration, which critically influence its chemical and mineralogical profile (Zeidabadi et al., 2018). SCBA typically contains a blend of crystalline and amorphous phases, comprising minerals such

Figure 8. Production process of sugarcane bagasse ash



Source: Authors.

as quartz, anhydrite, maghemite, cristobalite, graphite, aluminium oxide, calcium compounds, and predominantly, amorphous silica. Formed at combustion temperatures around 700°C, amorphous silica imparts high pozzolanic reactivity, making SCBA a valuable supplementary cementitious material.

Research across diverse conditions confirms SCBA's potential in enhancing the strength and durability of cement-based composites. Its high silica content also offers promise as an alternative source for silica extraction. In India, with annual cane crushing of 300–320 MMT, around 90–100 MMT of wet bagasse are generated, potentially yielding 9–10 MMT of SCBA under optimal cogeneration at Indian sugar mills which includes ash from coal[1]. The projected production and economic value of SCBA are detailed in Table 8.

[1] Research indicates that a bagasse-to-coal ratio of (80:20) is often cited as the best blend, as it significantly lowers the ignition temperature of the mixture compared to Bagasse, leading to more intense and efficient combustion reduced emissions of pollutants like SO2 and NOx.

Table 8. Production of pressmud and SCBA and contribution of variety Co 0238

Year	Pressmud				SCBA			
	Total quantity (000 tonnes)	Quantity from variety Co 0238 (000 tonnes)	Total value (Rs. million)	Value from variety Co 0238 (Rs. million)	Quantity (000 tonnes)	Quantity from variety Co 0238 (000 tonnes)	Total value (Rs. million)	Value from variety Co 0238 (Rs. million)
2000-01	5300	-	901	-	2650	-	1201	-
2001-02	5410	-	1185	-	2705	-	1185	-
2002-03	5831	-	1485	-	2915	-	1237	-
2003-04	3975	-	1138	-	1988	-	813	-
2004-05	3743	-	1092	-	1872	-	728	-
2005-06	5660	-	1843	-	2830	-	1053	-
2006-07	8379	-	2208	-	3854	-	1355	-
2007-08	7497	-	1872	-	3599	-	1497	-
2008-09	4349	-	1158	-	2175	-	827	-
2009-10	5566	-	1419	-	2783	-	1014	-
2010-11	7194	-	1529	-	3597	-	1195	-
2011-12	7709	-	1420	-	3855	-	1183	-
2012-13	7518	-	1623	-	3759	-	1281	-
Introduction of variety Co 0238								
2013-14	8336	160 (1.92)	1780	34	4287	117 (2.72)	1373	37
2014-15	9561	383 (4.00)	1465	59	4917	319 (6.48)	1507	98
2015-16	8277	842 (10.17)	1490	151	4257	625 (14.68)	1277	187
2016-17	6770	1155 (17.06)	1319	225	3482	1055 (30.29)	1018	308
2017-18	10542	2600 (24.66)	2072	511	5422	2007 (37.01)	1522	563
2018-19	10541	3180 (30.16)	1936	579	5421	3267 (60.27)	1458	879
2019-20	8849	3611 (40.81)	1753	715	4551	3126 (68.69)	1602	1101
2020-21	10533	3743 (35.53)	2243	797	5417	3234 (59.69)	1846	1102
2021-22	12474	3239 (25.97)	2687	698	6415	3057 (47.65)	2010	958
2022-23	11881	3484 (29.33)	2546	747	6110	3213 (52.59)	1746	918

Source: Computed by authors based on NFCSF, 2025.
Note: Values are in constant prices, (base year-2011-12); Figures in the parenthesis indicate percentage share to total in respective year.

The data indicates a notable shift in sugarcane bagasse ash (SCBA) production trends, particularly following the introduction of the variety Co 0238 in 2013–14. Prior to this, SCBA production remained relatively stable, fluctuating modestly between 2,650 thousand tonnes in 2000–01 and 3,759 thousand tonnes in 2012–13, with dips in 2004–05 and 2008–09. Correspondingly, the value of ash increased modestly from Rs. 1,201 million to Rs. 1,281 million over the same period.

The adoption of variety Co 0238 marked a turning point, triggering a sharp and sustained rise in both volume and value of SCBA. In 2013–14, total ash production rose to 4,287 thousand tonnes, with 117 thousand tonnes contributed by variety Co 0238. This variety's share expanded rapidly, reaching 3,267 thousand tonnes by 2018–19, while total production climbed to 5,421 thousand tonnes. The peak was recorded in 2021–22, with SCBA production hitting 6,415 thousand tonnes, valued at Rs. 2,010 million.

This steep growth highlights SCBA's increasing economic and strategic importance within the sugarcane value chain. It not only generates additional revenue for sugar mills, but also serves as a valuable input for cement, construction, and allied industries. Furthermore, its effective utilization presents an eco-friendly solution for managing industrial waste and reducing environmental hazards associated with sugar production in India.

6.5 Green tops/trash

Sugarcane tops, comprising 15–25% of above-ground biomass, include green leaves and immature cane (Naseeven, 1988; Ortiz-Rubio et al., 2007). Traditionally left in fields due to their impact on sugar crystallization, they are increasingly used as fodder—either fresh, dried, or ensiled (Larrahondo, 1995; McKenzie and Griffiths, 2007). Depending on total sugarcane production, India's annual production of green tops ranges from 25 to 40 MMT, with about 50% used in livestock feeding systems. The conventional estimate and imputed value of green top (Rs. 0.5/kg) was used to estimate the potential value of green top by the variety Co 0238 (Sant and Pal, 2020).

Between the fiscal years 2000-01 and 2012-13, the monetary value of green tops fluctuated between Rs. 6.8 billion and Rs. 7.0 billion underscoring their growing importance in animal feed usage and market demand. Commencing in 2013-14, a new trend emerged with the introduction of the variety Co 0238. The value of green tops from this variety began at Rs. 8.6 billion in 2013-14 and experienced rapid growth, reaching Rs. 12.8 billion by 2016-17 and peaking at Rs. 15.1 billion in both 2017-18 and

Table 9. Total value of green top produced from sugarcane fields during 2000-01 and 2022-23

Year	Green top			
	Total quantity (000 tonnes)	Quantity from variety Co 0238 (000 tonnes)	Total value (Rs. billion)	Value from variety Co 0238 (Rs. billion)
2000-01	20002	-	6.8	-
2001-02	22390	-	7.4	-
2002-03	22911	-	7.3	-
2003-04	21089	-	7.5	-
2004-05	21375	-	7.3	-
2005-06	22347	-	7.3	-
2006-07	24241	-	7.5	-
2007-08	22763	-	6.6	-
2008-09	19410	-	5.8	-
2009-10	20558	-	6.1	-
2010-11	22503	-	6.4	-
2011-12	23855	-	5.7	-
2012-13	24796	-	7.0	-
Introduction of variety Co 0238				
2013-14	25153	973 (3.87)	8.6	0.3
2014-15	25120	2656 (10.57)	10.3	1.1
2015-16	26583	5330 (20.05)	13.3	2.7
2016-17	26259	8961 (34.13)	12.8	4.4
2017-18	32218	16896 (52.44)	15.1	7.9
2018-19	33367	27182 (81.46)	15.0	12.2
2019-20	32263	25735 (79.77)	14.2	11.3
2020-21	31704	27183 (85.74)	13.5	11.6
2021-22	31677	26366 (83.23)	12.4	10.3
2022-23	38631	28018 (72.53)	13.8	10.0

Source: Computed by authors based on NFCSF, 2025.
Note: Values are in constant prices, (base year-2011-12); Figures in the parenthesis indicate percentage share to total in respective year.

2018-19. This upward trend corresponds with the widespread adoption of variety Co 0238, which became the predominant sugarcane variety during this period.

6.6 Instability of value added co-products

The Cuddy-Della Valle instability index was used to assess production variability before (2002–03 to 2012–13) and after (2013–14 to 2023–24) the introduction of variety Co 0238. Results (Table 10) indicate a significant reduction in year-to-year fluctuations for most co-products:

Table 10. Instability index of sugarcane value added co-products

	Before introduction of the variety Co 0238 (%) (2000-01 to 2012-13)	After introduction of the variety Co 0238 (%) (2013-14 to 2022-23)
Bagasse	8.98	5.72
Cogen	63.85	30.98
Press mud	10.92	6.20
Sugarcane bagasse ash	8.42	5.10
Green top	4.33	4.36

Source: Computed by authors.

These results confirm that variety Co 0238 not only increased the volume and value of sugarcane co-products but also enhanced the stability of their production. This stability is vital for planning, investment, and sustainability in the sugarcane processing ecosystem.

In a nutshell, the introduction of variety Co 0238 has revolutionized the value-added co-product landscape of Indian sugarcane. It significantly boosted the quantity, economic value, and stability of key byproducts like bagasse, cogeneration power, pressmud, SCBA, and green tops. This varietal breakthrough has not only enhanced resource efficiency and circular economy outcomes but also reinforced industrial diversification and environmental sustainability within the sugarcane value chain.

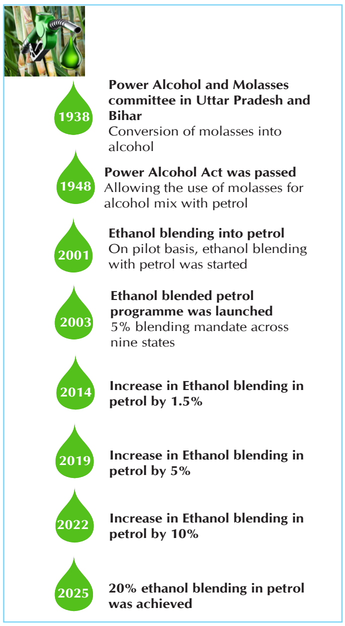
7 Sustainable Energy from Sugar: The Ethanol Push

7.1 Prologue

Ethanol[2] production from sugarcane is closely linked to sugar manufacturing. Sugarcane, which contains approximately 14% Total Fermentable Sugars, is crushed to extract juice for sugar production. The residual molasses, a byproduct of sugar crystallization, serves as a primary feedstock for ethanol production (Raju et al., 2012; Shinoj et al., 2011). Molasses progresses through three stages (A, B, and C), with the final stage containing the highest concentration of non-crystallizable sugars. From one tonne of sugarcane, approximately 110 kg of sugar and 10–11 litres of ethanol can be produced from the resulting molasses. Alternatively, direct fermentation of sugarcane juice can yield 65–72 litres of ethanol per tonne of cane (Annexure 3).

In India, the blending of ethanol with petrol was first recognized under the Power Alcohol Act, 1948, which promoted the use of molasses-based ethanol (power alcohol) in gasoline (Figure 9). The feasibility of ethanol blending was revisited in 2001 through pilot projects in Miraj and Manmad (Maharashtra) and Bareilly (Uttar Pradesh) (Saini et al., 2010). The EBP Programme was officially launched in January 2003 with a 5% blending mandate across nine states (Ray et al., 2011). However, due to production shortages in 2004–05, the mandate was made optional. The program resumed in 2006 with further geographic extension.

Figure 9. History of ethanol blending in India



Source: Compiled by authors

The National Biofuel Policy of 2009 established an indicative target of 20% blending of biofuels (biodiesel and bioethanol) by 2017. In 2010, the

[2] Ethanol (CH_3CH_2OH) is a versatile organic compound with broad industrial applications. Commonly referred to as ethyl alcohol, grain alcohol, or EtOH, it is a clear, colourless liquid whose chemical composition remains constant irrespective of its source. In the automotive sector, ethanol's higher-octane number relative to gasoline enhances fuel performance and mitigates engine knocking. The energy content of ethanol-gasoline blends varies with ethanol concentration, influencing fuel economy and engine calibration requirements.

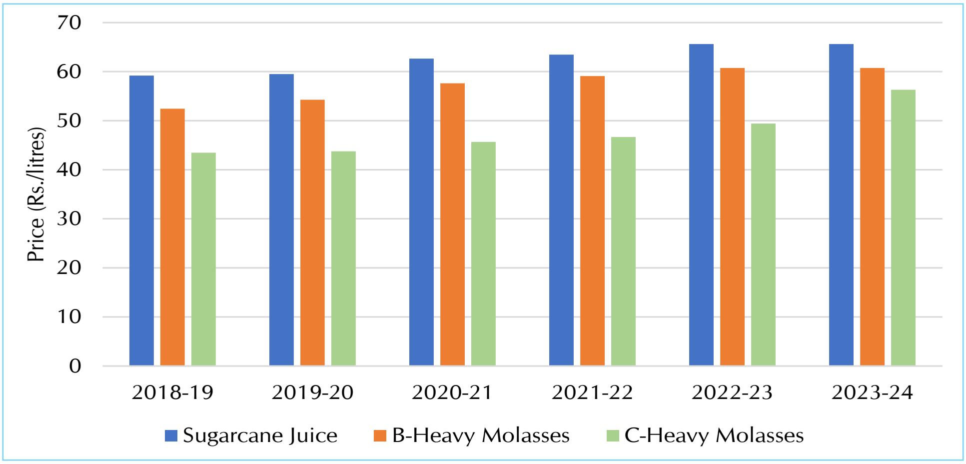
government introduced a provisional procurement price of Rs. 27 per litre for ethanol for ethanol blending program.

In 2012, the Cabinet Committee on Economic Affairs (CCEA) aimed to ensure sustainable benefits for sugarcane farmers by mandating 5% blending nationwide, with procurement prices negotiated between Oil Marketing Companies (OMCs) and ethanol suppliers (Aradhey and Lagos, 2013). In 2014, a pricing mechanism accounting for the distance between distilleries and OMC depots was implemented, and the government began notifying administered prices for ethanol. The 12.36% excise duty on ethanol was temporarily removed in April 2015 but reinstated in August 2016.

7.2 India's fuel ethanol drive: A path to energy security

The revised National Biofuel Policy of 2018 established the National Biofuel Coordination Committee to expand the feedstock base to include B-heavy molasses, sugarcane juice, and damaged grains. To boost ethanol production capacity, the Interest Subvention Scheme was introduced in July 2018, offering an interest subsidy of 6% per annum or 50% of the interest rate charged by banks (whichever is lower) for five years. The policy also introduced differential ethanol pricing based on feedstock type (Sarwal et al., 2021). The Ministry of Petroleum and Natural Gas under the EBP Programme achieved 10% ethanol blending by 2021–22 and 20% by 2025 (GoI, 2022b). To support this, ethanol prices from sugarcane juice rose from Rs. 59.19/ litre in 2018–19 to Rs. 65.61/litre in 2023–24; for B-heavy molasses from Rs. 52.43/litre to Rs. 60.73/litre; and for C-heavy molasses from Rs. 43.46/litre to Rs. 56.28/litre over the same period (Figure 10).

Figure 10. Differential price for fuel ethanol offered by OMCs* (Rs./litre)



Source: Ministry of Petroleum & Natural Gas, New Delhi.

Note: Values are in current prices, *Oil marketing companies (OMCs).

Commercial production and distribution of ethanol-blended gasoline began in January 2003 (Sugar Report, 2003). In its first phase, 5% ethanol blending was mandated in nine states and four union territories. In 2005, an agreement between the sugar industry and petroleum companies facilitated ethanol procurement. With a rise in sugarcane output in 2006–07, the government launched the second phase of the EBP in September 2006, expanding the 5% blending mandate to 20 states and eight union territories, subject to commercial viability. Nevertheless, despite policy backing and surplus sugarcane, the 5% target remained elusive due to operational challenges.

Official estimates indicate ethanol requirements at various blending levels (5%, 10%, 15%, and 20%) (Table 11). However, ethanol supply has consistently lagged behind tendered quantities (Table 12), primarily due to constraints such as limited distillation capacity and feedstock availability.

Table 11. Bioethanol demand for ethanol blending programme

Year	Petrol demand (million litres)	Ethanol blending requirements (million litres)			
		5%	10%	15%	20%
2019-20	37,140	1,857	3,714	5,571	7,418
2024-25	49,482	2,227	4,453	6,680	8,907
2029-30	60,203	2,709	5,418	8,127	10,836

Source: Murali et al., 2016.

In 2018–19, India achieved a 5% blending rate, driven by new policy directives and fair pricing mechanisms. Between Ethanol Supply Years (ESYs) 2015 and 2025, government estimates suggest CO_2 emission reduction of approximately 73.6 million metric tonnes (MMT), the equivalent of planting 300 million trees. During this period, OMCs disbursed Rs. 1,960 billion to distillers, including Rs. 1180 billion to farmers. India has since accelerated ethanol production, aiming to reach the E20 target by 2025, ahead of the initial 2030 goal. Despite challenges in scaling feedstock supplies, expansion to non-sugarcane sources such as rice, wheat, and coarse grains is expected to bolster production. Sugar mills are increasingly investing in capacity to produce ethanol directly from sugarcane juice, supported by soft loans. In 2023, approximately 68.8% of fuel ethanol originated from sugarcane, though this share may fluctuate based on feedstock availability. With rising gasoline demand, the ethanol blending rate could reach 18–20% in 2025 and 25–30% by 2030, with total ethanol production projected to reach 13 billion litres by 2030.

Table 12. Details of fuel ethanol supplied and blending

Ethanol Supply Year	Quantity tendered by OMCs* (million litres)	Quantity allocated (million litres)	Quantity supplied (million litres)	Blending % PSU# OMCs
2012-13	1030	320	154	0.67
2013-14	1150	704	380	1.53
2014-15	1280	865	674	2.33
2015–16	2660	1305	1114	3.51
2016–17	2800	807	665	2.07
2017–18	3130	1610	1505	4.22
2018–19	3320	2390	1886	5.00
2019-20	NA	NA	1730	5.00
2020-21	3250	2850	2955	8.10
2021-22	NA	NA	4080	10.0
2022-23	5997	5667	5064	12.01
2023-24	NA	NA	7074	14.60

Source: Sarwal et al., 2021 and GoI, 2022b
Note: *Oil Marketing Companies (OMCs); #Public Sector Undertaking.

Table 13 highlights the transition in fuel ethanol production from various feedstocks between 2013–14 and 2022–23. Previously, statutory constraints prevented ethanol production from sugarcane juice, but the new biofuel policy enabled its use. Though negligible in 2018–19, sugarcane juice accounted for 14.6% of total ethanol production by 2023–24. B-heavy molasses emerged as a major contributor post-2020, as its dual output of ethanol and sugar offered economic advantages. C-heavy molasses, once the sole source of ethanol for the EBP, has declined due to comparatively lower procurement prices. Ethanol production from sugarcane surged during 2019–20 and 2022–23, reaching 1,571 and 3,485 million litres, respectively. The corresponding production value peaked at Rs. 276 billion in 2022–23, underscoring the growing economic significance of ethanol within sugar complexes.

Figure 11 illustrates the increasing role of sugarcane variety Co 0238 in ethanol production. Its contribution rose from 562 million litres in 2017–18 to 1,895 million litres in 2022–23, with associated economic value increasing from Rs. 21 billion to Rs. 83 billion. This trend highlights the strategic importance of variety Co 0238 in meeting the E20 blending target.

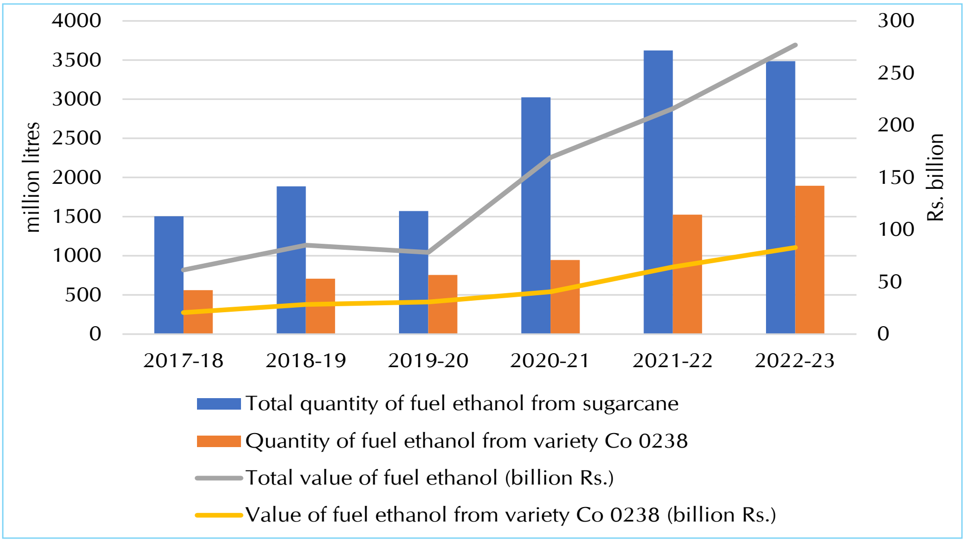
Uttar Pradesh is the leading ethanol-producing state (Gupta, 2022), with around 100 operational distilleries in 2023–24 and plans to expand to 140 within three years. The expansion is supported by investment commitments made during the 2022–23 Global Investors Summit. The state also promotes grain-based distilleries, leveraging surplus paddy and wheat stocks. In 2022–23, Uttar Pradesh produced 1,340 million litres of ethanol, the highest among Indian states. However, production capacity remains uneven across regions.

Table 13. Total value of fuel ethanol produced from different sources between 2013-14 and 2022-23

Year	Ethanol from juice (million litres)	Ethanol from B Heavy molasses (million litres)	Ethanol from C heavy molasses (million litres)	Total qty of ethanol supplied (million litres)	Share of fuel ethanol by sugarcane (%)	Total value (Rs. billion)
2013-14	0	0	400			15
2014-15	0	0	700			29
2015-16	0	0	1100			46
2016-17	0	0	700			27
2017-18	0	0	1505			61
2018-19	7.5	343	1535	1886	100	85
2019-20	148	681	741	1571	91	78
2020-21	459	1950	614	3023	86	169
2021-22	793	2702	127	3622	83	215
2022-23	850	2533	102	3485	75.4	214

Source: Computed by authors based on data from Chinimandi, 2022.
Note: Values are in current prices.

Figure 11. Share of the variety Co 0238 in total fuel ethanol supply in India between 2017-18 and 2022-23



Source: Computed by authors.
Note: Values are in constant prices, (base year-2011-12).

States with surplus ethanol production under the E20 mandate include Maharashtra, Uttar Pradesh, Punjab, and Karnataka. Additional surplus states are Bihar, Haryana, Madhya Pradesh, and Jharkhand. In contrast, Tamil Nadu, Kerala, Rajasthan, and Delhi face significant deficits, while Telangana, Odisha, Gujarat, Assam, and West Bengal exhibit moderate deficits (Figure 12).

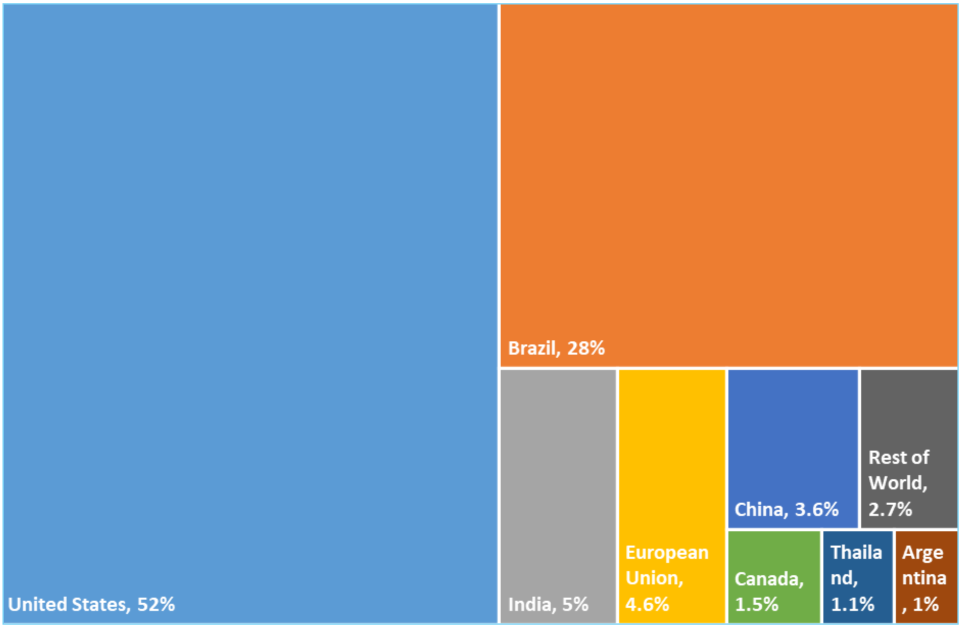
Figure 12. State-wise ethanol availability and deficit in India (2024)

Source: GoI, 2024.

7.3 Global scenario

The most widely used ethanol production method today involves yeast fermentation of starch and sugars derived from feedstocks such as corn, sugarcane, and sugar beet. In the United States, corn is the predominant feedstock for fuel ethanol due to its abundance and cost-effectiveness (Araújo, 2016). The starch in corn kernels is hydrolyzed into sugars and subsequently fermented into ethanol. Globally, sugarcane and sugar beet serve as the principal feedstocks outside the U.S. Brazil, the second-largest ethanol producer after the U.S., relies primarily on sugarcane and its derivatives (Chan and Reiner, 2011).

Figure 13. Share of global fuel ethanol production



Source: Computed by authors based on Table 14.

Figure 13 illustrates the global ethanol production shares in 2023. The U.S. and Brazil together accounted for approximately 80% of global fuel ethanol output (RFA, 2024), followed by the European Union, India, China, and Canada. Table 14 presents fuel ethanol production trends since 2018. Global production experienced a general upward trend but declined sharply in 2020 due to the COVID-19 pandemic. This downturn coincided with an 8.5% decrease in global transport fuel use and an 8.7% decline in biofuel consumption compared to 2019, driven by mobility restrictions and disrupted logistics.

Biofuel demand has been recovering since 2021, aligned with overall fuel consumption recovery. Medium-term growth in global biofuel consumption is expected, primarily driven by higher blending targets in developing countries. In contrast, biofuel expansion in developed nations will remain constrained by declining fossil fuel demand and reduced policy incentives. International biofuel prices are projected to rise, influenced by feedstock and crude oil prices, distribution costs, and policy instruments such as subsidies, mandates, and production incentives.

Table 14. Recent trends in fuel ethanol production among major producers (in million gallons)

Region	2018	2019	2020	2021	2022	2023
United States	16,097	15,778	13,941	15,016	15,361	15,580
Brazil	8,058	8,860	8,100	7,320	7,400	8,470
India	449	500	530	950	1,220	1,510
European Union	1,350	1,360	1,310	1,380	1,420	1,390
China	811	1,020	940	900	960	1,070
Canada	459	497	429	434	447	454
Thailand	390	430	390	350	380	340
Argentina	290	290	210	270	310	310
Rest of World	707	685	630	690	722	806
Total	28,611	29,240	26,480	27,310	28,220	29,930

Source: RFA, 2024. 1 Gallon = 3.785 litres.

7.3.1 United States

In the United States, biofuels are regulated under the Renewable Fuel Standard administered by the Environmental Protection Agency. While transportation fuel demand is projected to decline, ethanol blending—primarily at the E10 level—is expected to continue, with modest growth in E15 blends. However, infrastructure and technological constraints limit expansion to higher-level blends. The fuel ethanol blending rate is projected to increase to 11% by 2032, with maize remaining the dominant feedstock, accounting for 99% of bio-ethanol production. Although cellulosic ethanol capacity is projected to grow, it will remain a minor contributor. The U.S. is expected to maintain its position as the leading fuel ethanol producer, but its global share is projected to decline from 52% to 40% by 2032 (Ramsey et al., 2023).

7.3.2 European Union

EU biofuel policy has been shaped by the Renewable Energy Directive (RED) of 2009, mandating that 10% of transport energy originate from renewable sources by 2020 (Gregg et al., 2017). RED II, implemented in 2021 under Directive 2018/2001, revised the target to 14% by 2030, with a cap on food and feed crop-based biofuels not exceeding 7%. While overall fuel consumption (diesel and gasoline) is projected to decline in the EU, biofuel consumption—particularly ethanol—is expected to increase. Fuel ethanol's share in gasoline use is projected to rise from 5.03% in 2022 to 8.7% by 2030.

7.3.3 Brazil

Brazil possesses a large fleet of flex-fuel vehicles capable of operating on either gasohol (gasoline mixed with anhydrous ethanol) or pure hydrous fuel ethanol. The mandated fuel ethanol blend rate for gasohol is currently 27%, although actual blending may vary depending on market prices. In 2022, tax exemptions and falling gasoline prices led to increased gasoline consumption, favouring fuel anhydrous ethanol. The RenovaBio programme, launched in 2018 to reduce emissions intensity in the transport sector, is expected to sustain ethanol consumption. While sugarcane remains the dominant feedstock, maize-based ethanol—growing from under 0.3 billion litres to over 4.4 billion litres in five years—is projected to reach 7 billion litres by 2032. Unlike in the U.S. and EU, gasoline consumption in Brazil is expected to increase, supporting continued bio ethanol demand. Fuel ethanol consumption is projected to grow at an annual rate of 2.5%.

7.3.4 China

China's fuel ethanol policy has been inconsistent in recent years, limiting consumption growth. The blending rate, which was around 1.2%, is expected to increase modestly to 1.7% by 2032, with ethanol consumption growing at 1.1% annually. Most fuel ethanol will continue to be produced domestically due to limited imports.

7.3.5 Thailand

Thailand's Alternative Energy Development Plan has set production targets for fuel ethanol derived from sugarcane, molasses, and cassava. However, constrained domestic feedstock availability and stagnant fossil fuel demand are expected to limit growth. Average fuel ethanol blending is projected to remain around 11%, with production stabilizing at 1.5 billion litres annually over the next decade.

7.4 Challenges and prospects of the ethanol value chain

India's ethanol value chain has witnessed substantial expansion over the past two decades, driven by policy initiatives, technological advancements, and evolving energy security imperatives. Fuel ethanol consumption increased from approximately 45 million gallons (MG) in 2000 to 499 MG in 2019 (IEA, 2021; Chandra, 2021), reflecting more than an 11-fold growth. By Ethanol Supply Year (ESY) 2024–25, the blending rate reached 19.2% (November-October, 2025), a marked improvement from below 5% prior to 2020.

India has set ambitious targets of 10% ethanol blending by 2022 and almost achieved 20% by 2025 under the EBP Programme. While policy frameworks and pricing mechanisms have supported this trajectory, several structural and operational challenges continue to impede full realization of the blending targets.

7.4.1 Key challenges

i. Infrastructure deficits

A major bottleneck is the lack of blending and storage infrastructure across key consumption centres. The uneven distribution of distilleries and fuel ethanol logistics hampers the consistent supply of bio-ethanol to OMCs, particularly in fuel ethanol-deficit states.

ii. Inter-state procurement barriers

Regulatory discrepancies between states, along with logistical inefficiencies, constrain the free movement of fuel ethanol. Although amendments to the industries (Development and Regulation) Act aim to address these issues, full harmonization is yet to be achieved.

iii. Limited production capacity and feedstock volatility

While sugarcane remains the primary feedstock, production capacity is tightly linked to fluctuations in agricultural output and seasonal availability. In particular, fuel ethanol production depends heavily on the supply of B-heavy molasses and sugarcane juice, both of which are influenced by climatic conditions, sugar recovery, and mill performance.

iv. Capital investment requirements

The transition of sugar mills toward a fuel ethanol-integrated model—especially for juice-based ethanol—requires substantial upfront investment in distillation capacity, wastewater treatment, and ancillary infrastructure. This has historically acted as a deterrent, particularly for small and mid-sized mills.

v. Policy and price uncertainty

Frequent changes in procurement prices, tax incentives, and export-import regulations generate market uncertainty. Oil price volatility also affects the relative competitiveness of fuel ethanol, thereby influencing procurement strategies and investment decisions.

vi. Food-fuel trade-offs

Expansion of fuel ethanol production into grain-based feedstocks (e.g., surplus rice and maize) raises concerns about food security and land-use dynamics. Policymakers must balance energy goals with nutritional and environmental priorities, especially in times of food inflation or crop failure.

7.4.2 Strategic prospects

Despite the aforementioned constraints, the long-term outlook for the ethanol sector remains robust, particularly for sugarcane-based ethanol, which is expected to remain the backbone of India's blending programme.

i. Role of variety Co 0238 in feedstock assurance

The widespread adoption of the variety Co 0238 sugarcane variety has significantly contributed to feedstock reliability by improving per-hectare yields, sugar recovery, and juice purity. This variety underpins the viability of both molasses and juice-based ethanol routes and is central to the performance of integrated sugar- fuel ethanol-energy complexes. However, spread of red rot disease in variety Co 0238 has restricted its cultivation in sub tropics warranties of similar wonder varieties is need of the hour for sustainability.

ii. Technological advancements and diversification

The adoption of high-efficiency distillation technologies, digital supply chain management, and hybrid feedstock blending models can further increase production efficiency and reduce lifecycle emissions.

iii. Policy continuity and incentive alignment

Ensuring long-term policies—including administered pricing, differential feedstock incentives, and financing support—will be essential for attracting private investment. The National Biofuel Coordination Committee (NBCC) must continue to monitor and recalibrate support mechanisms based on feedstock trends and market conditions.

iv. Integration with climate and energy goals

Ethanol blending contributes to India's commitments under the Paris Agreement by reducing greenhouse gas emissions in the transport sector. Between ESY 2015 and 2025, CO_2 emission reductions are estimated at 74 MMT, reinforcing fuel ethanol's role in India's decarbonization strategy.

v. Market expansion for high-blend fuels

The introduction of E85 and E100 vehicles in fuel ethanol-surplus regions, alongside awareness campaigns and standards set by the Bureau of Indian Standards (BIS), can facilitate market diversification and demand absorption.

In nutshell, the outlook for the fuel ethanol value chain is a critical pillar of India's integrated bioeconomy strategy. Sugarcane-based fuel ethanol—particularly from wonder varieties will continue to be the primary enabler for achieving E30 targets beyond 2030. However, sustained progress will depend on addressing infrastructure deficits, investment barriers, and policy coordination. With targeted interventions, India can transform fuel ethanol from a sugar surplus management tool into a cornerstone of its clean energy transition.

8 Sugarcane and Sugar Sector Policies: Unlocking the Full Value Chain Potential

India's sugarcane economy is supported by an intricate policy framework that governs cane pricing, sugar trade, ethanol blending, and the utilization of byproducts. These policies not only stabilize farmer incomes and mill revenues but also contribute significantly to national energy goals and rural employment. The enhanced adoption of high-yielding varieties such as variety Co 0238 has amplified the impact of these policies by improving sugar recovery, juice yield, and biomass availability, which in turn support diversified processing into sugar, ethanol, electricity, and fodder.

8.1 Sugarcane policy

8.1.1 Fair and Remunerative Price (FRP)

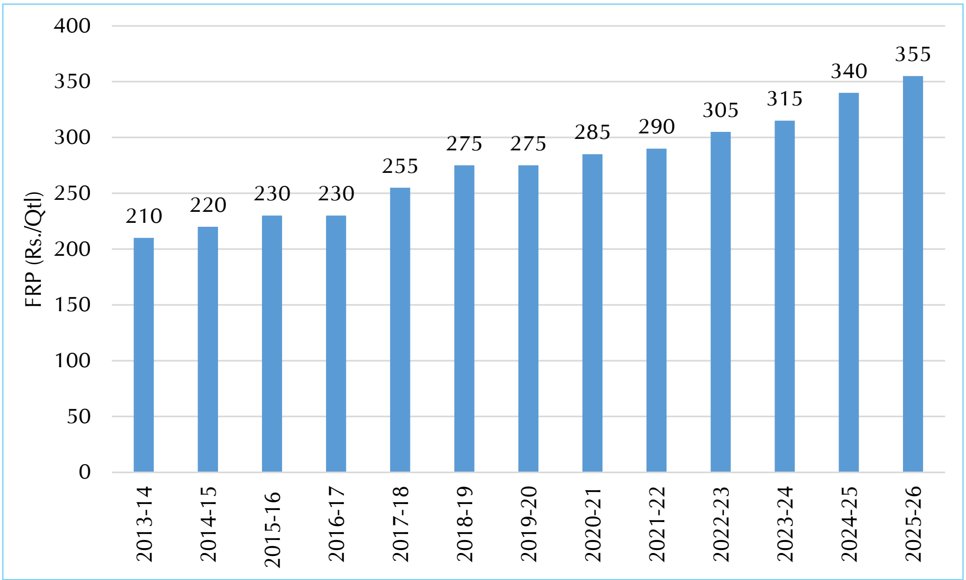
FRP is the centrally determined minimum price that sugar mills obligatory to pay for supplying sugarcane by the registered cane farmers. It is announced annually by the Government of India based on recommendations from the Commission for Agricultural Costs and Prices (CACP) and is linked to a basic recovery rate.

For the 2025-26 sugar season, the FRP has been fixed at Rs. 355 per quintal at a basic recovery of 10.25%, with a premium of Rs. 3.46 per quintal for every 0.1% increase in recovery above the base. This continues the upward trend in cane prices, reflecting rising input costs and improved recovery due to widespread cultivation of variety Co 0238, which has been instrumental in achieving recovery rates of over 11% in many regions, especially in Uttar Pradesh. The FRP announced by the Government for the last 10 sugar season are given in Figure 14.

8.1.2 State Advised Price (SAP)

In addition to FRP, states such as Uttar Pradesh, Punjab, Haryana, Uttarakhand, Bihar, and Tamil Nadu announce State Advised Prices (SAPs), which are typically higher than FRP. For the 2024–25 season, Uttar Pradesh has maintained the SAP at Rs. 370 per quintal for early maturing varieties, Rs. 360 for mid-late varieties, and Rs. 355 for late varieties—unchanged from the previous year. However, farmers cultivating high-recovery varieties like variety Co 0238 continue to realize higher effective returns due to early maturing category and increased sugar recovery.

Figure 14. Sugarcane fair and remunerative prices



Source: NFCSF, 2025.

8.1.3 Cane reservation area

The Sugarcane Control Order (1966) provides for the reservation of cane catchment areas to specific mills, ensuring assured procurement for mills and stable market access for farmers. Farmers within the notified area are registered with the designated mill and are required to supply cane only to that unit. This mechanism, coupled with high-yielding varieties, ensures consistent throughput for mill operations.

8.1.4 Minimum distance criteria

To avoid unhealthy competition for cane and ensure equitable cane availability, a minimum radial distance of 15 km between sugar mills is mandated under the Sugarcane Control Order. While this provision remains in force, recent discussions at the policy level have explored relaxing the criteria in certain zones to allow for modernization and new ethanol-distillery projects under the EBP Programme.

8.1.5 National Food Security Mission – Commercial Crops (NFSM-CC) – sugarcane

Under the NFSM–Commercial Crops initiative, sugarcane productivity enhancement programmes continue in 13 states. As of 2023–24, approximately 0.25 million hectares were covered under high-yielding varietal replacement and frontline demonstrations. Co 0238 remains the most widely promoted variety under this scheme due to its proven yield, ratoon performance, and wide adaptability.

8.2 Sugar policy

8.2.1 Minimum Selling Price

To protect mills from market fluctuations and ensure timely payment to farmers, the Government has retained the Minimum Selling Price (MSP) of sugar at Rs. 31/kg since February 2019. Although there is growing industry demand to revise this to Rs. 42/kg (PTI, 2025) due to rising cane costs and operational expenses, no upward revision has been announced as of October 2025.

8.2.2 Buffer stocks

The Government of India continues to operate a buffer stock mechanism to manage inventory and prevent sugar price crashes in surplus years. As of 2023–24, a buffer stock of 4 million metric tonnes (MMT) was maintained. Subsidies are reimbursed quarterly, with part of the amount directly used to clear cane arrears. This intervention has supported liquidity for sugar complexes and contributing significantly to the ethanol supply chain.

8.2.3 Trade

In light of rising domestic demand for ethanol, the Government of India has prohibited sugar exports for the 2023–24 and 2024–25 seasons, except under government-to-government agreements. A modest quantum of one MMT of sugar export was allocated for the 2024-25 season. This aligns with the strategy to prioritize diversion of 3.5 MMT of excess sugar toward ethanol production under the E20 programme.

8.3 Biofuel policy

India's ethanol blending journey began with the Power Alcohol Act (1948) and progressed significantly with the launch of the Ethanol Blended Petrol (EBP) Programme in 2003. The National Policy on Biofuels (2018) marked a major milestone, setting the roadmap for 20% blending (E20) by 2025 and allowing broader feedstock use including B-heavy molasses, sugarcane juice, and damaged grains.

As of ESY 2024–25 (November-October, 2025), India has achieved an average national ethanol blending rate of 19.2% (PIB, 2025) up from 10.2% in 2021–22.

8.3.1 Key highlights of the biofuel policy (as updated till 2025)

- **Funding Support:** Rs. 50 billion allocated to support 2G ethanol bio refineries; 10 projects have been commissioned with an estimated annual capacity of 1,000 KLPD (Kilo Litres Per Day) as of early 2025.

- **Foreign Exchange Savings**: Estimated forex savings from ethanol blending stood at Rs. 1440 billion between ESY 2014-15 and 2025 (ET, 2025), largely due to reduced petrol imports.
- **OMC Investments**: Oil Marketing Companies have invested Rs. 120 billion in ethanol storage, blending infrastructure, and 2G plants across major states.
- **NBCC Oversight**: The National Biofuel Coordination Committee (NBCC), chaired by the union minister for Petroleum and Natural Gas, continues to monitor blending progress, policy implementation, and feedstock supply dynamics.
- **Movement and Pricing**: Following amendments to the IDRA, inter- and intra-state movement of ethanol is centrally regulated. Ethanol prices for 2024–25 (announced in November 2024) is:
    - ❖ **Sugarcane juice**: Rs. 69.48/litre
    - ❖ **B-heavy molasses**: Rs. 63.45/litre
    - ❖ **C-heavy molasses**: Rs. 56.20/litre
- **Soft Loans**: Over Rs. 125 billion in low-interest loans have been sanctioned to mills and standalone distilleries for capacity augmentation under the interest subvention scheme.

8.4 Strategic outlook

The success of India's ethanol and sugar value chain policies has been significantly amplified by varietal advancements, especially the large-scale adoption of variety Co 0238. Its superior yield, high juice recovery, and ratoon performance have ensured stable feedstock supply for both sugar and ethanol production, supporting the viability of integrated sugar complexes. As India nears its E20 blending target by 2025, sustaining feedstock productivity, refining policy coherence, and enabling infrastructure development will be critical to balancing food-energy trade-offs and rural income generation.

9 Strategic Conclusions and Policy Roadmap for Efficient Sugarcane Value Chain

This study has critically examined the evolving dynamics of India's sugarcane value chain, with particular attention to the role of varietal innovation, processing diversification, and supportive policy frameworks. Sugarcane has emerged as a strategic multi-utility crop, producing sugar, ethanol, bagasse-based electricity, pressmud for bio-fertilizers, and sugarcane tops for fodder. Its outputs directly contribute to India's priorities in food security, renewable energy, climate resilience, and rural employment.

At the core of this transformation has been the large-scale adoption of the variety Co 0238 hailed as a game-changer in India's cane economy. Introduced in 2009 and widely adopted post-2012-13, variety Co 0238 now occupies over 57.13% of cane acreage in Uttar Pradesh, and significant area in Bihar, Uttarakhand, and Haryana. Its early maturity, high juice purity, and consistent recovery of 11.2–11.5% in North India enabled substantial gains in sugar yield and ethanol productivity, forming the backbone of the ethanol blending programme.

However, recent observations from the sugar season 2023–24 show that variety Co 0238 has come under increasing pressure from red rot (*Colletotrichum falcatum*)—a devastating fungal disease. Yield losses of 15–25% have been reported in Eastern and Central Uttar Pradesh, with ratoon crops showing higher vulnerability. These outbreaks highlight the urgent need to replace the variety Co 0238 with newer, red rot–resistant varieties that retain its superior traits. This situation calls for accelerated breeding, using marker-assisted selection, genomic selection, and multiplication models to fast-track resistant varietal development and dissemination.

9.1 Performance highlight (as of 2024-25)

- Sugar production in sugar season 2023–24 is estimated at 31.9 million metric tonnes (MMT), down from 32.8 MMT in 2022–23 and 35.9 MMT in 2021–22—partly due to sugar diversion to ethanol and early signs of biotic stress in variety Co 0238 areas.

- Sugar diversion for ethanol reached a record 3.4 MMT in 2024-25, down from 4.3 MMT in 2022–23. The Government's target remains 4.5 MMT by 2025-26 to support the E20 target.
- Ethanol production in 2024–25 is reported at 10,003 million litres, with 3,160 million litres (31.5%) from sugarcane (major contribution from variety Co 0238-based juice and molasses), and 6,870 million litres from grains.
- Bagasse-based cogeneration: Indian sugar mills generated 8,040 MW, with 6,600 MW exported to the national grid. Uttar Pradesh and Maharashtra are the top contributors, supported by the wonder varieties.
- Press mud output in 2023–24 crossed 12.2 MMT, while sugarcane tops provided over 27 MMT of fodder, contributing to livestock productivity.

9.2 Emerging challenges

The emergence of red rot in variety Co 0238 has disrupted yield gains in several regions. Studies by ICAR–Sugarcane Breeding Institute (2024) indicate a need to replace at least 30–40% of Co 0238 area in high-risk districts over the next two years. The variety Co 0238 is being replaced by the selected red rot resistant varieties such as Co 0118, Co 15023, CoLk 14201, CoS 13235, CoLk 16202, CoS 17231, and CoS 18231 (Chinimandi, 2024b).

Varietal monoculture has made India's ethanol roadmap vulnerable to supply-side shocks. For instance, a 10% yield loss across variety Co 0238 zones would reduce ethanol output by over 500 million litres, affecting blending targets. Thus, India must now shift to a multi-variety, climate- and disease-resilient portfolio approach. While this study analyses role of sugarcane breeding in terms of economic, value chain and energy security gains, the excessive use of inputs has environmental implications. There are unpublished reports mentioning excessive use of fertilizers and pesticide for variety Co 0238, but it was done by a few farmers only. In general, the recommended doses of fertilizers and chemicals are used by the farmers. Hence, further research should focus on the environmental impact, concerning biodiversity, soil health, and the excessive use of agro-chemicals.

9.3 Policy implications

- *Accelerate varietal replacement using speed breeding:* Introduce red rot–resistant, high-sucrose varieties using genomic tools. ICAR institutes and state agri-universities must be supported to develop next-generation varieties within 7–8 years, down from the current 12–14 years. Varieties like Co 11015, Co 18009 and Co 15023 (Karnal) show promise. Varieties like CoSe 17451, CoLk 16470 (mid-late), and CoLk 15466 are specifically recommended.

- *Align ethanol infrastructure to new varietal zones:* Distilleries and blending depots must track emerging high-yielding zones and adapt procurement accordingly. Regions transitioning from variety Co 0238 to newer varieties will require handholding on harvesting protocols and juice handling.
- *Restructure incentives for co-product utilization:* Revise tariffs for bagasse-based cogeneration to reflect biomass input quality and guarantee of supply. Encourage bio-fertilizer certification for pressmud compost, especially in organic farming zones.
- *Promote feedstock flexibility and risk insurance:* While expanding grain-based ethanol, build contingency mechanisms (crop insurance, buffer stock ethanol) for cane-based EBP supply security. Variety Co 0238's decline makes this urgent.
- *Modernize traditional processing units:* Enable variety Co 0238's successors to integrate into gur and *khandsari* units through low-cost, modular technology interventions. Energy-efficient furnaces and food-grade standards will support artisanal processing.
- *Institutionalize a national cane resilience roadmap:* Establish an inter-ministerial task force to develop a "Cane 2040" roadmap, linking varietal planning, biofuel targets, and climate resilience. Sugarcane should be treated not only as a commercial crop but as a strategic renewable resource.
- *ICAR-Sugarcane Breeding Institute (ICAR-SBI):* It is majorly responsible improved varietal development needs to be equipped with modern infrastructure for meeting out the future needs of sugarcane research and development.

In nutshell, India's sugarcane economy has transitioned impressively over the past decade, driven by variety Co 0238's genetic gains, ethanol policy innovation, and infrastructure expansion. However, the red rot threat has exposed the systemic risks of varietal concentration. Going forward, India must embrace a model of agronomic diversification, bio-industrial integration, and fast-track innovation to secure its, sugar, ethanol and energy goals.

With clear policy direction, accelerated breeding strategies, and coordinated public-private partnerships, India can ensure that sugarcane continues to serve as a pillar of energy independence, climate action, and rural transformation well into the next decade.

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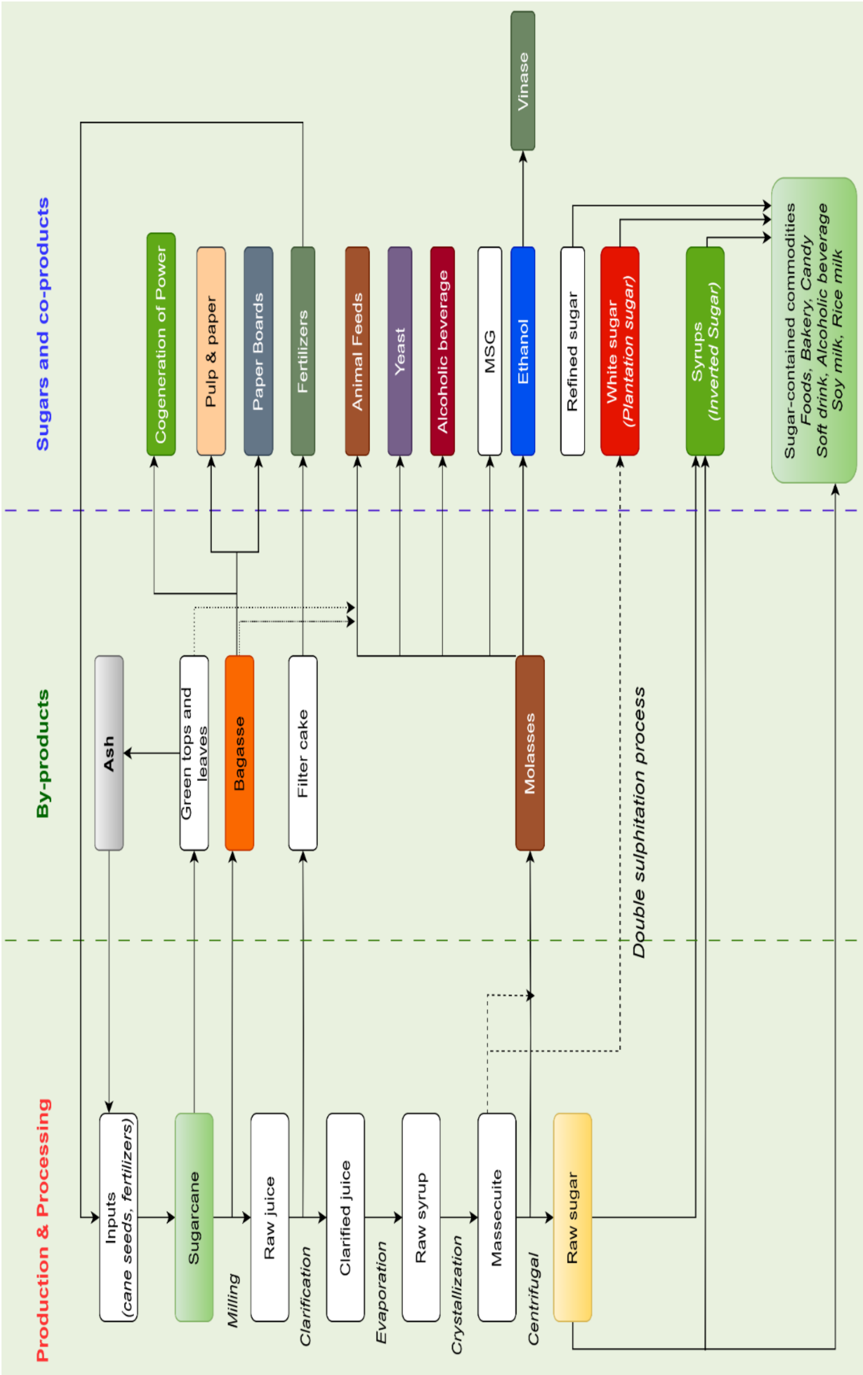
Annexure 1. Sugarcane value chain



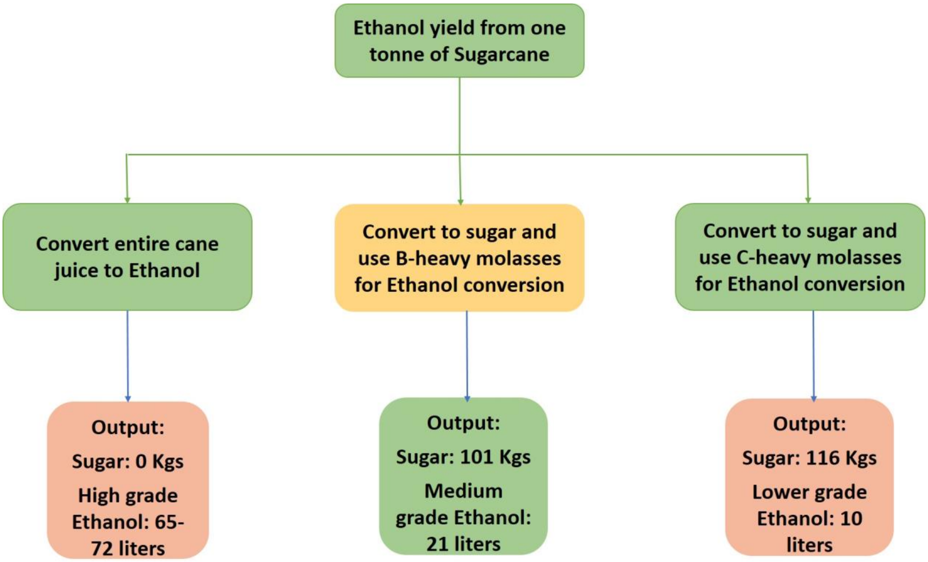
Source: Compiled by authors

Annexure 2. List of varieties popular since 1918

Year	Cane varieties
	Sub-Tropical Zone varieties
1920-1929	Co 205, Co 210, Co 213, Co 214, Co 224, Co 281, Co 290
1930-1939	Co 205, Co 213, Co 223, Co 244, Co 281, Co 285, Co 290, Co 312, Co 313
1940-1949	Co 213, Co 312, Co 313, Co 331, Co 356, Co 453
1950-1959	Co 312, Co 313, Co 453, Co 951
1960-1969	Co 312, Co 975, Co 1107, Co 1148
1970-1979	Co 312, Co 1148, Co 1158
1980-1989	Co 1148, Co 1158, Co 7717, Co 7314
1990-1999	Co 1148, Co 89003
2000-2009	Co 89003, Co 98014, Co 0238, Co 0118, CoSe 01434, Co 94008, CoLk 94184
2010-till date	Co 0238, Co 0239, CoH 160, Co 05011, Co 15023
	Tropical Zone varieties
1920-1929	C0 213
1930-1939	Co 213, Co 243, Co 281, Co 290, Co 313
1940-1949	Co 213, Co 419
1950-1959	Co 419, Co 449, Co 527
1960-1969	Co 419, Co 527, Co 658, Co 740, Co 853, Co 975, Co 997
1970-1979	Co 419, Co 527, Co 658, Co 740, Co 975, Co 997, Co 853, Co 62175, Co 6304, Co 6806, Co 6415
1980-1989	Co 419, Co 740, Co 975, Co 62175, Co 6304, Co 6907, Co 7219
1990-1999	Co 740, Co 62175, Co 6304, Co 7219, Co 7704, Co 7527, Co 7508, Co 7504, Co 8011, Co 8014, Co 8021, Co 8208, Co 8362, Co 8371, Co 8338, Co 85004, Co 85019, Co 86249, Co 97009
2000-2009	Co 86032, Co 94012, Co 99004, Co 99006, Co 2001-13, Co 2001-15, CoM 265, Co 92005
2010-till date	Co 86032, Co 11015, 2003 V 46, CoV94101, CoV92102, Co 0212, Co 09004

Source: Compiled by authors

Annexure 3. Fuel ethanol output from different feedstock of sugarcane



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