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Sugarcane: A treasure of bio-energy

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Abstract
Increasing energy demands for erratically increasing population, urbanization, industrialization and environmental concerns related to fossil fuels have inclined researchers to explore alternative resources of energy. Biofuels have gained much importance due to the depleting fossil fuel resources and the over-accumulation of CO_2 and other greenhouse gases in the environment. Sugarcane (Saccharum spp. hybrids) has great potential as a major feedstock for biofuel production worldwide. It is considered among the best options for producing biofuels today due to an exceptional biomass production capacity, high carbohydrate (sugar + fiber) content, and a favourable energy input/output ratio. The conversion of sugarcane biomass into fermentable sugars for second-generation ethanol production is a promising alternative to meet future demands of biofuel production in the country. Scientific interventions have not only helped to improve the cane crop but industrial procedures have also been upgraded resulting in improved production of bioethanol. However, building a bridge between science and industry requires investments in research, development and transfer of new technologies to the industry as well as specialized personnel to deal with new technological challenges.

Keywords: Sugarcane, bio-energy, biomass, science, industry and improvement

Introduction
Due to the depletion of fossil fuel sources, the potential for oil to become more expensive, and the raising awareness of the negative impact of fossil fuels on the environment, biomass derived biofuels have been investigated and developed recently as an alternative source of renewable, sufficient, and clean energy [4]. Thus, renewable fuels have gained wider interest in the recent past, bioethanol being one of the most successful examples of a shift from fossil fuels to bio-based fuels. The use of ethanol in vehicles was first proposed by H. Ford in 1896 [14].
Complex and polyploid genome of sugarcane has an exceptional ability to produce biomass as a C4 plant with the potential of a perennial grass crop allowing harvest four to five times by using ratoons without requiring replanting [25], resulting in a lower cost of energy production from sugarcane than for most of the other potential sources of biomass [4]. To maximize the efficiency of conversion of sugarcane biomass into biofuels, it is imperative to generate improved sugarcane cultivars with not only high biomass yield and fiber content but also better biomass degradability for conversion to biofuels in addition to improving the pre-treatment and enzyme digestion technologies.
Recently, supported by Seven G20 countries (Argentina, Brazil, Canada, India, Italy, S. Africa & USA), four G20 invitee countries (Bangladesh, Singapore, Mauritius & UAE), eight non G20 countries (Iceland, Kenya, Guyana, Paraguay, Seychelles, Sri Lanka, Uganda & Finland)) and twelve international organizations (World Bank, ADB, WEF, World LPG Organization, UN Energy for All, UNIDO, Biofutures Platform, ICAO, IEA, IEF, IREA & WBA) and on the sidelines of the latest G20 Summit in New Delhi, the Global Biofuel Alliance (GBA) was announced by PM Narendra Modi on September 9, 2023, bringing together biofuel producers and consumers with the intent to strengthen global biofuels trade for greener sustainable future. To ensure energy security, affordability and accessibility for the future, the GBA will facilitate global collaboration, supporting the development and development of sustainable biofuels. GBA members constitute major producers and consumers of biofuels, such as the USA (52%), Brazil (30%) and India (10%), contributing about 92% share in production and 81% in consumption of ethanol [30].

Here, in this review focuses on the status regarding current and expected production, import, export of bio-fuels (ethanol and methane). We discuss here the improved technologies and future research strategies for more biofuel production.

1. G's of Biofuel Production

Now a days, many countries have launched programs to replace gasoline by ethanol in the midterm (Olsson 2007). This is considered to be more beneficial and feasible over all the generations of biofuel (Fig. 1) as 2G has a higher energy production potential, lower cost, sustainable CO_2 balance, no competition with the food production, and a wide range of plant biomass sources are available at costs affordable to a biorefinery [13, 8].

Fig 1: Different generations of biofuel production based on their method of production and raw material used

2. Biofuel: Production and Prices

Globally, slower rate of biofuel production due to the heavy use, unavailability of raw materials and higher production costs. Hence, prices of biofuel were touched to the sky during 2021-2022 (Fig. 2) and it will increase tremendously in near future [17]. So, it is necessary to increase the biofuel production by using different ways.

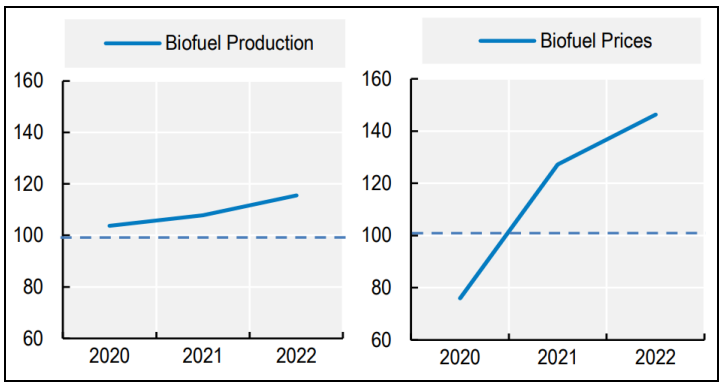


Fig 2: Market trend of Biofuel production and its prices [17]

In 2022, biofuels consumption increased, offsetting the decrease caused by the drop of global transport fuel use during the COVID-19 pandemic, which brought restrictions on people's movements, as well as disruptions in trade logistics all over the world. The ethanol market nearly came back to levels observed in 2019 [17]. Rapid consumption of fuel in near future before crisis, it is necessary to mix with other sources like ethanol for conservation of nature and sustainable use for our future generation. The use of ethanol blends has improved air quality in large urban centers, reducing emissions of carbon monoxide (CO) from 50 g/km driven to less than 5.8 g/km driven [7]. Hence, most of the countries decided to increases the blending percentage (Table 1 & Fig. 3) in the existing fuel.

Table 1: Ethanol production and blending (%) (Estimated & projected) in fuel with their major feedstock of different countries in the world [17]

Sr. No.	Countries	Ethanol Production (%)	Ethanol Blending (%)		Major feedstock
			2022 (Estimated)	2032 (Projected)	
1.	United States	46.4	10	15	Maize
2.	European Union	5.3	5	10	Sugar beet / wheat / Maize
3.	Brazil	25.2	20	30	Sugarcane / Maize
4.	China	7.9	5	12	Maize / Cassava
5.	India	4.3	10	25	Sugarcane / Molasses / Maize / Wheat / Rice
6.	Canada	1.6	5	10	Maize / Wheat
7.	Argentina	1	7	15	Sugarcane / Maize / Molasses
8.	Thailand	1.4	5	14	Sugarcane / Cassava / Molasses
9.	Colombia	0.4	2	12	Sugarcane
10.	Others	20.5	5	10	Sugarcane / Sugar beet / Cassava / Molasses / Maize / Wheat /Rice

3. Bio-ethanol: Global Production, Prices, Import and Export

In India, it is estimated that about 25% of ethanol was produced by sugar cane during 2022, and this share could increase to nearly 55% by 2032. However, given accelerating gasoline demand, the blending rate could reach 16% in 2025 and 20% in 2032. Ethanol production is expected to be 13 bln L in 2032 [17].

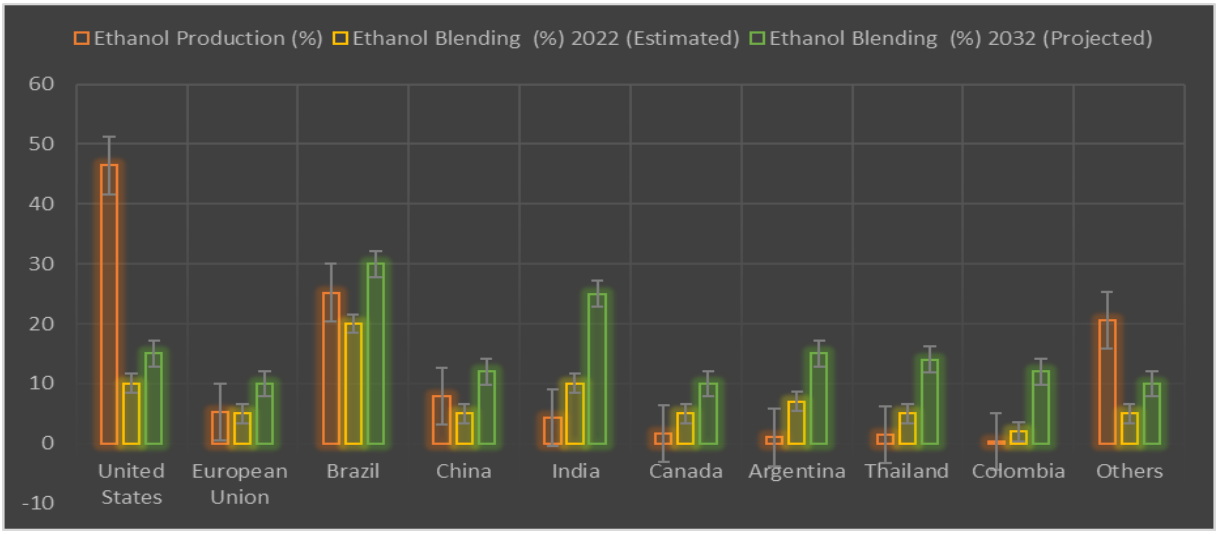


Fig 3: Ethanol production it's blending in fuel (estimated and projected) of different countries [17].

Global biofuel use is projected to expand substantially over the next decade (Fig. 4). In the United States, the largest biofuel producer, biofuel demand is expected to remain strong thanks to the Renewable Fuel Standard (RFS) regime [21]. While ethanol consumption is anticipated to remain relatively flat over the projection period, biodiesel (including renewable diesel) is expected to be the major contributor to global growth, due to the increasing targets for state and federal renewable fuel programs and biomass-based diesel tax credits, which have been extended through 2024 under the Inflation Reduction Act of 2022 [17].

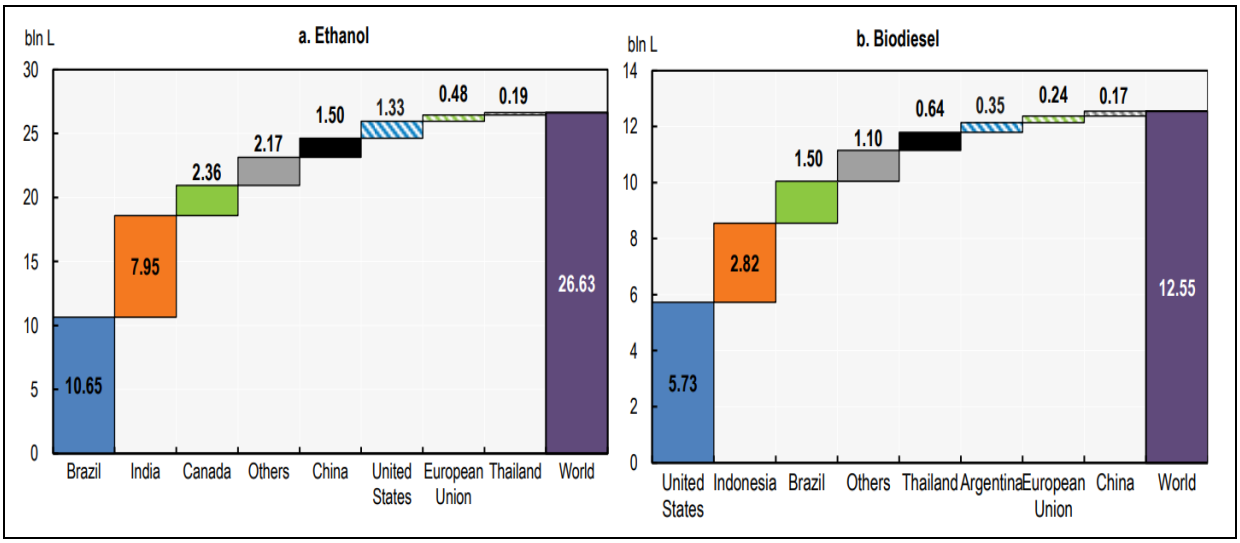


Fig 4: Projected global biofuel consumption (2023-2032) [17]

Global ethanol and biodiesel production is projected to increase to 150.9 bln L and 66.9 bln L, respectively, by 2032 and will continue to be dominated by traditional feedstocks despite the increasing sensitivity to the sustainability of biofuel production observed in many countries [17]. The growth rate in sugar production globally is expected to be lower than in the past decade, reflecting a slower growth in sugarcane production and greater diversion to ethanol (Fig. 5).

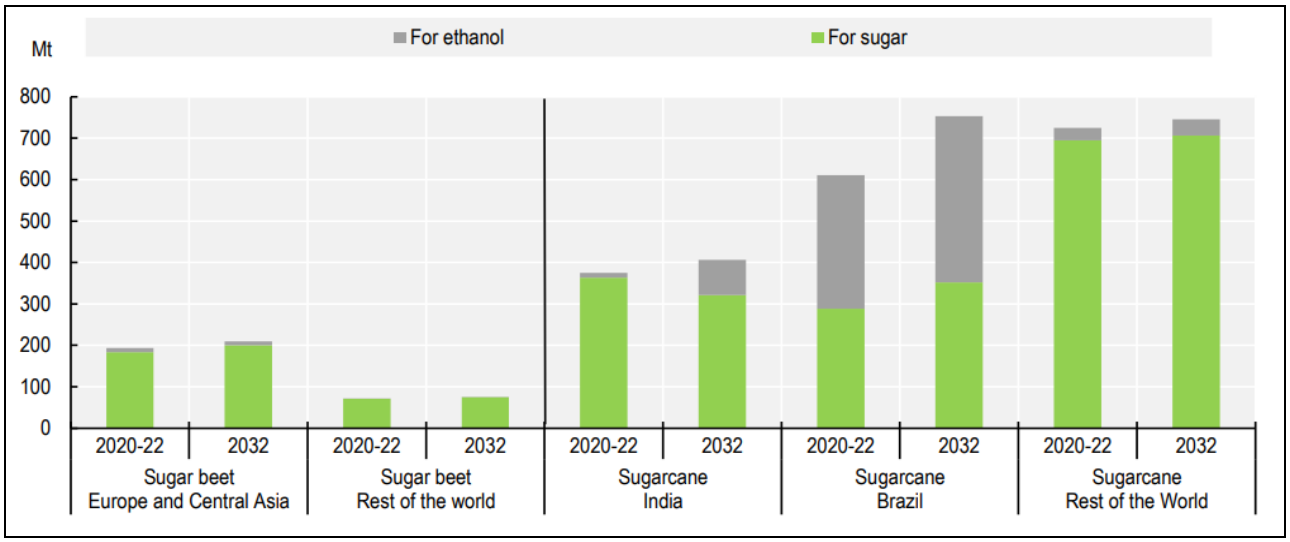
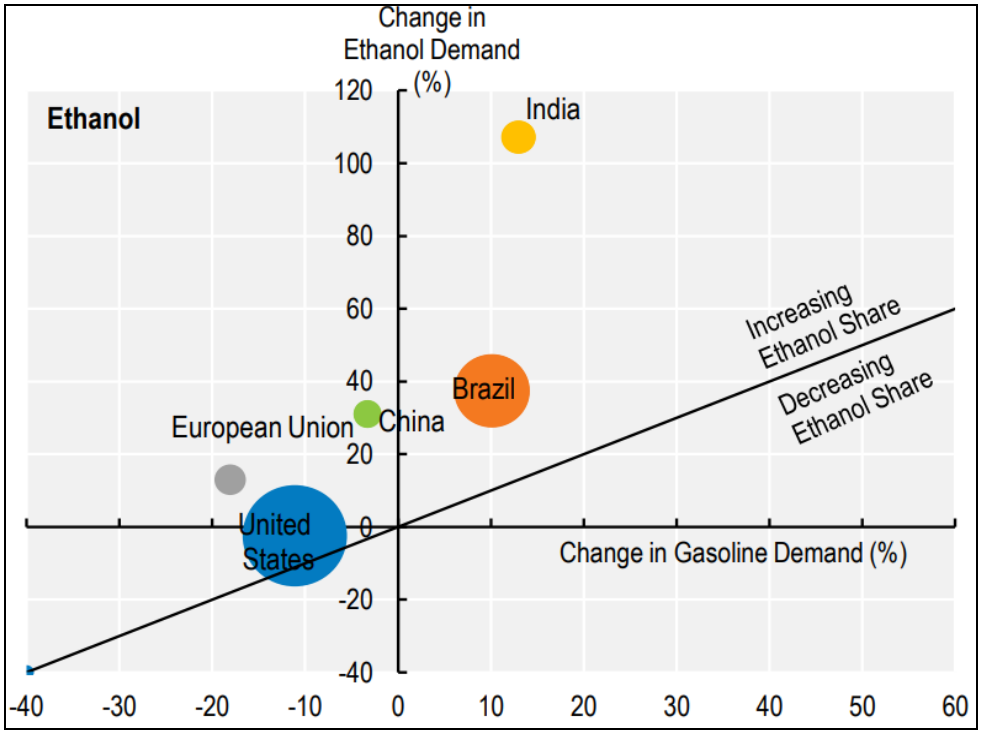


Fig 5: World production of sugar crops classified according to their end product

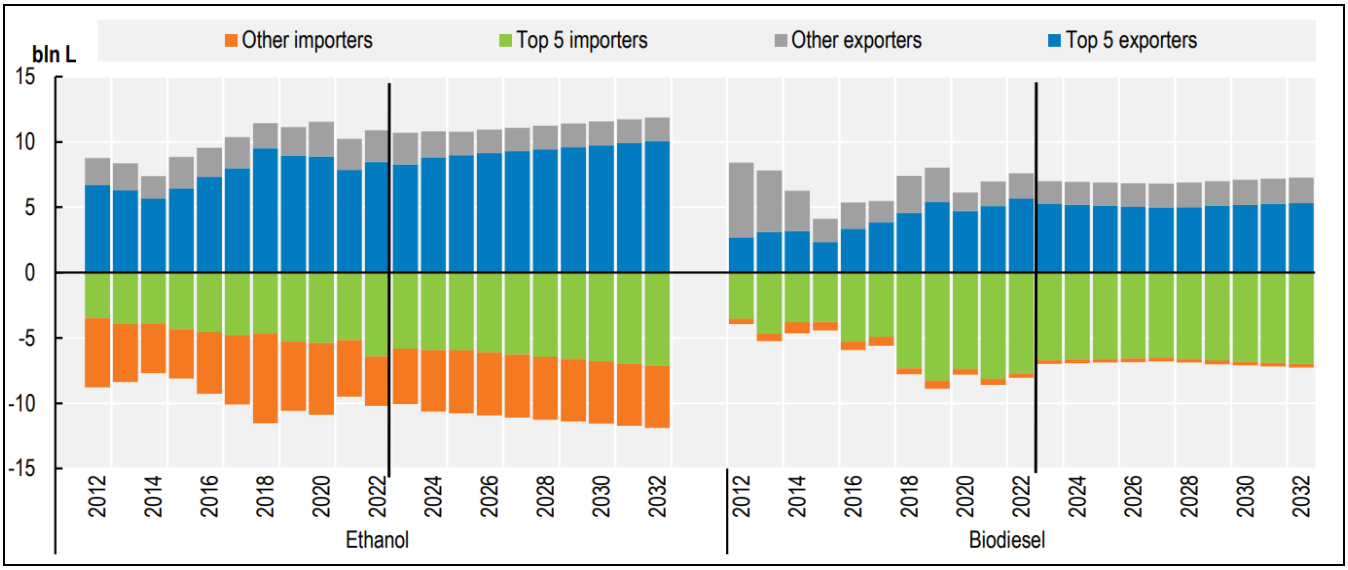
Demand for biofuels is expected to increase due to developments in transportation fleets in most of the countries where total fuel consumption is still projected to increase and domestic policies that favour higher blends [17]. Figure 6 shows that the share of biofuels in total transport fuels increases almost for all major producers.



Note: Shares calculated on demand quantities expressed in volume. The size of each bubble relates to the consumption volume of the respective biofuel in 2022. (17)

Fig 6: Biofuel demand trends in major regions

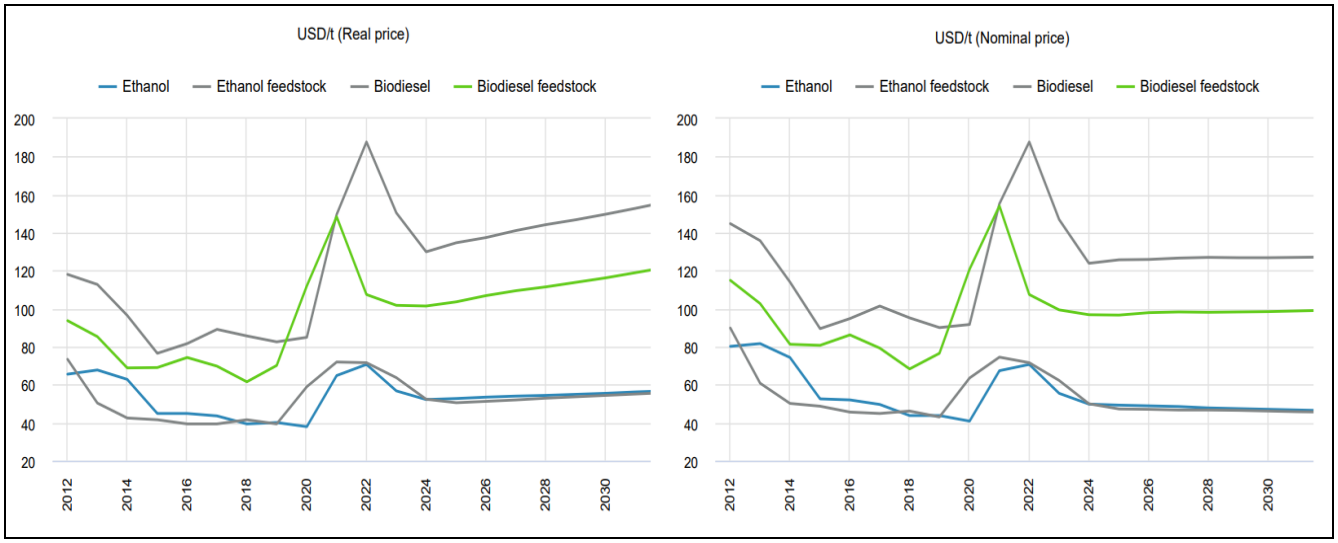
Projected global market trend of import and export of ethanol and biodiesel is shown in figure 7. The world ethanol trade is projected to increase from 10 bln L in the base period (2023) to 12 bln L in 2032, while the total share of production will remain constant at 8%. The United States and Brazil are expected to remain the main exporters of maize- and sugarcane-based ethanol. Approximately, 23.4 billion liters (6.19 billion U.S. liquid gallons) of ethanol was produced in Brazil in the year 2014 [21]. Whereas, biodiesel trade accounts for 13% of production and is projected to decrease from 7.6 bln L to 7.3 bln L by 2032 with its share in production falling to 11% [17].



Note: Top five ethanol exporters in 2032: United States, Brazil, Pakistan, European Union, Paraguay. Top five ethanol importers in 2032: Canada, Japan, European Union, United Kingdom, India. Top five biodiesel exporters in 2032: China, Argentina, United States, European Union, Malaysia. Top five biodiesel importers in 2032: European Union, United States, United Kingdom, Canada, China. [17]

Fig 7: Biofuel trade dominated by a few global players

Nominal ethanol and biodiesel prices reached historical high levels in 2021 and in 2022 and it will increase further. Following the prices for feedstock commodities as well as the oil price, nominal and real biofuel prices are assumed to decrease in 2023 and 2024, but thereafter nominal prices are projected to slowly increase through to 2032 (Fig. 8). In real terms, both ethanol and biodiesel prices are expected to increase over the coming decade.



Note: As proxy for the biodiesel feedstock price, the world vegetable oil price is used and for ethanol a weighted average between raw sugar and maize is applied [17]

Fig 8: The evolution of biofuel prices and biofuel feedstock prices

Currently, about 60% of ethanol is produced from maize, 23% from sugarcane, 7% from molasses, 3% from wheat, and the remainder from other grains, cassava or sugar beets. As feedstock prices increases the prices of biofuel will increases. Hence, it is need to generate huge biomass for biofuel production by lowering the prices of feedstock and this will be achieved by sugarcane cultivation globally.

Sugarcane has an exceptional ability to produce biomass as a C_4 plant with the potential of a perennial grass crop allowing harvest four to five times by using ratoons without requiring replanting [25], resulting in a lower cost of energy production from sugarcane than for most of the other potential sources of biomass [4]. Genetically diverse sugarcane germplasm (Table 2) may play a key role in improving sugarcane for biofuels through breeding and biotechnological approaches. Genetic variation may be found in biomass yield, fibre content, and sugar composition in the Saccharum germplasm [1].

Table 2: List of sugarcane genotypes for more biomass production

Sr. No.	Name of Hybrids/genotypes/varieties/clones	Biomass production/ha	Brix (%)	References
1.	KGS 99-100	163.99	16.80	16
2.	KGS 2004-48	157.46	18.63	
3.	KGS 2004-186	141.27	18.38	
4.	KGS 2004-13	140.27	17.06	
5.	GU 07-3849	138.52	15.41	
6.	GU 04-432	125.47	16.53	
7.	KGS 2004-60	121.20	18.55	
8.	99-438	120.18	17.60	9
9.	99-488	104.19	18.70	
10.	SBIEC 11001	101.27	09.75	
11.	SBIEC 11002	85.10	15.92	
12.	SBIEC 11003	80.04	15.04	
13.	SBIEC 11004	75.94	07.80	
14.	Vertix 2	123.20	13.65	27
15.	Vertix 3	122.56	10.34	

As the efficiency of different feedstocks for bioethanol production (Table 3), bioethanol yield from only sugarcane bagasse is estimated at about 3,000 l/ha in a total yield of 9,950 l/ha from sugar and bagasse while in comparison Sugar beet yield of 7,900 l/ha followed by Maize 3,800 l/ha, wheat 1700 l/ha and Cassava 137 l/ha [12, 24].

Table 3: Comparative efficiency of different feedstocks for biofuel production

Sr. No.	Feedstock	Conditions	Biofuel production (l/ha)
1.	Sugarcane	Fermentation	9,950
2.	Sugar beet	Hydrolysis/fermentation	7,900
3.	Maize	Hydrolysis/fermentation	3,800
4.	Wheat	Hydrolysis/fermentation	1700
5.	Cassava	Hydrolysis/fermentation	137

4. Technologies for Ethanol Production

In this paper includes three main pathways according to the technology used. These pathways have in common that they include the same type of subsystems (agriculture and milling), but they differ in the technologies used to produce sugar and ethanol, as shown in Figure 9.

- Pathway 1 produces ethanol from molasses. The sugarcane is milled. Then, the cane juice is processed with technology T_1, and finally, the resulting molasses are converted into ethanol in a distillery type T_3.
- Pathway 2 produces ethanol from honey obtained in a manufacturing process that uses technology T_2. Honey is converted into ethanol in a distillery using technology T_4.
- Pathway 3 produces ethanol directly from sugarcane juice coming from sugarcane milling. Ethanol is obtained through technology T_5. This pathway does not produce sugar.

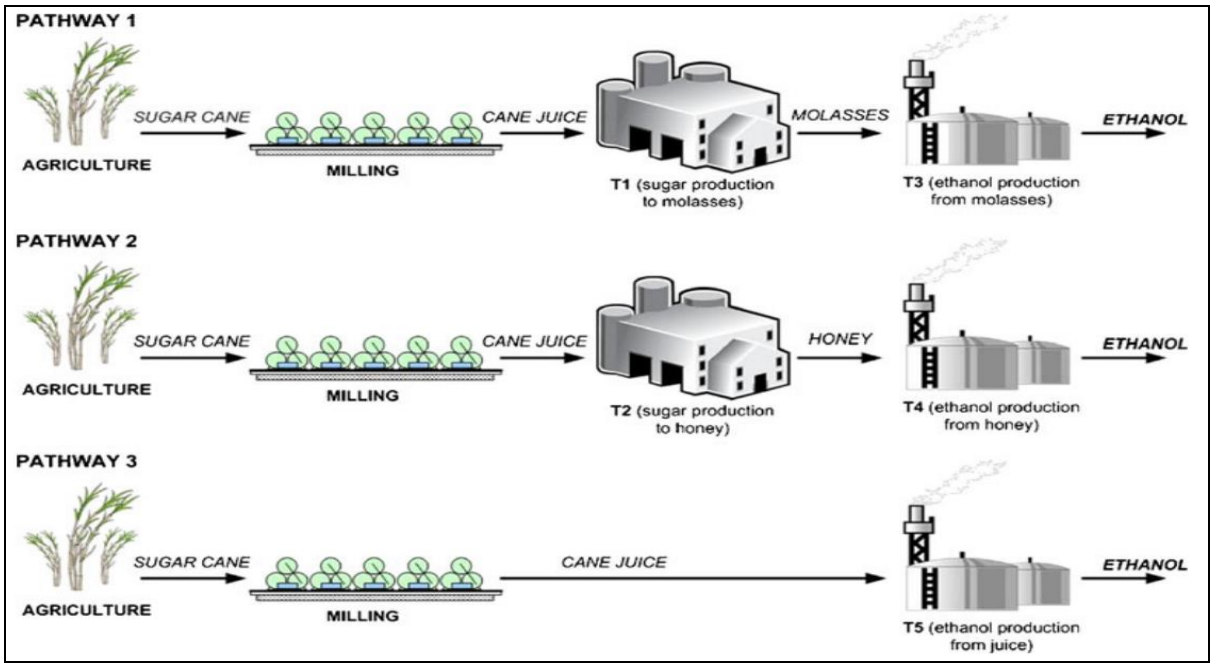


Fig 9: Three different schematic pathways considered for ethanol production (14)

In Brazil, P3—autonomous distillery—is very common [6, 22], whereas in Argentina, this pathway is practically inexistent. In Mexico, García *et al*. [29] considered the three options in the study, while in Thailand, Nguyen and Gheewala [28] claim that ethanol from molasses (P1) is the most common pathway. Among all the pathways, figure 10 shows the productive system for ethanol production from sugarcane in Argentina [14] and India also.

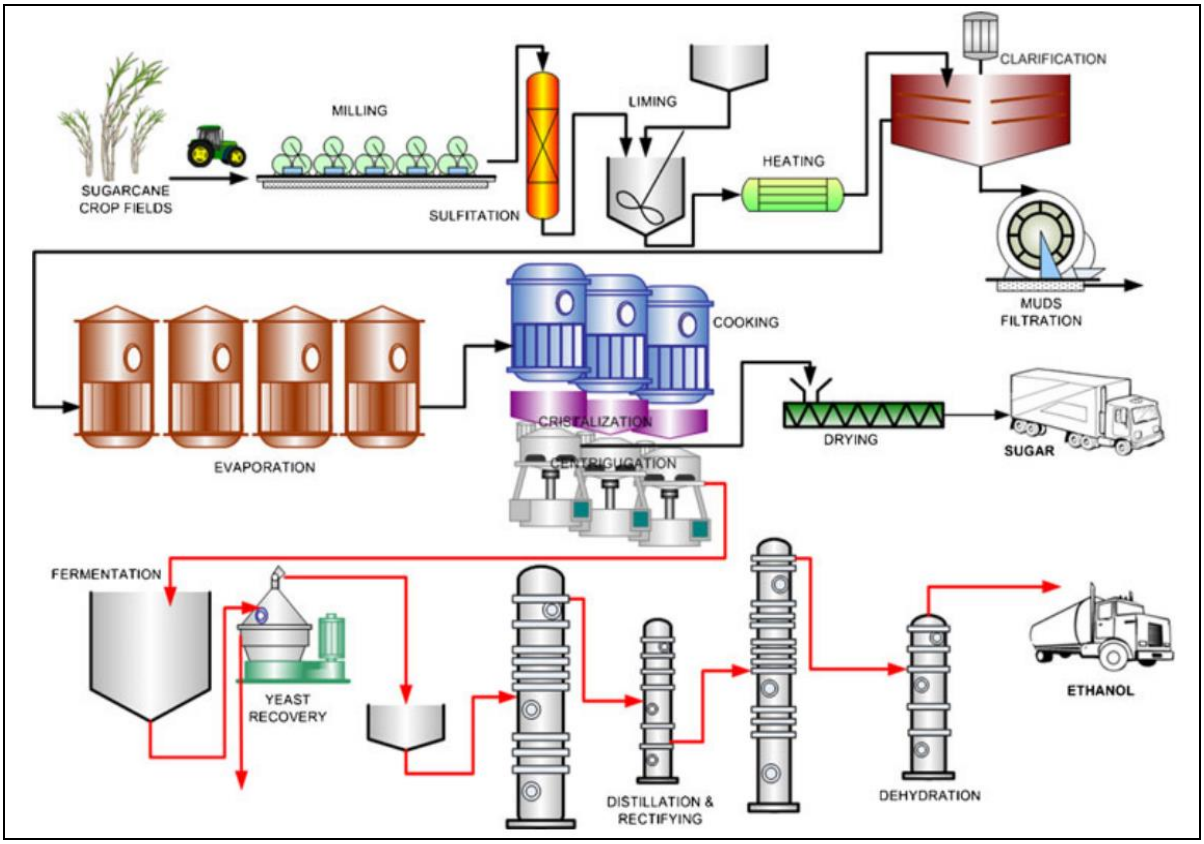


Fig 10: Productive system for ethanol production from sugarcane [14]

5. Electricity Generation

India's electricity sector is dominated by fossil fuels, in particular coal, which produced about three quarters of the country's electricity [26, 20]. Energy security and environmental conservation issues are likely to remain two of the major long-term challenges facing human existence globally [23]. To minimize the load on fossil fuel Indian government declared its efforts to increase investment in renewable energy (Fig. 11). The governments draft National Electricity Plan of 2022 states that the country does not need any more fossil fuel power plants in the utility sector until 2027, aside from those currently under constrictions [19, 12, 13]. It is expected that non-fossil fuel generation contribution is likely to reach around 44.7% of the total gross electricity generation by 2029-30 [21].

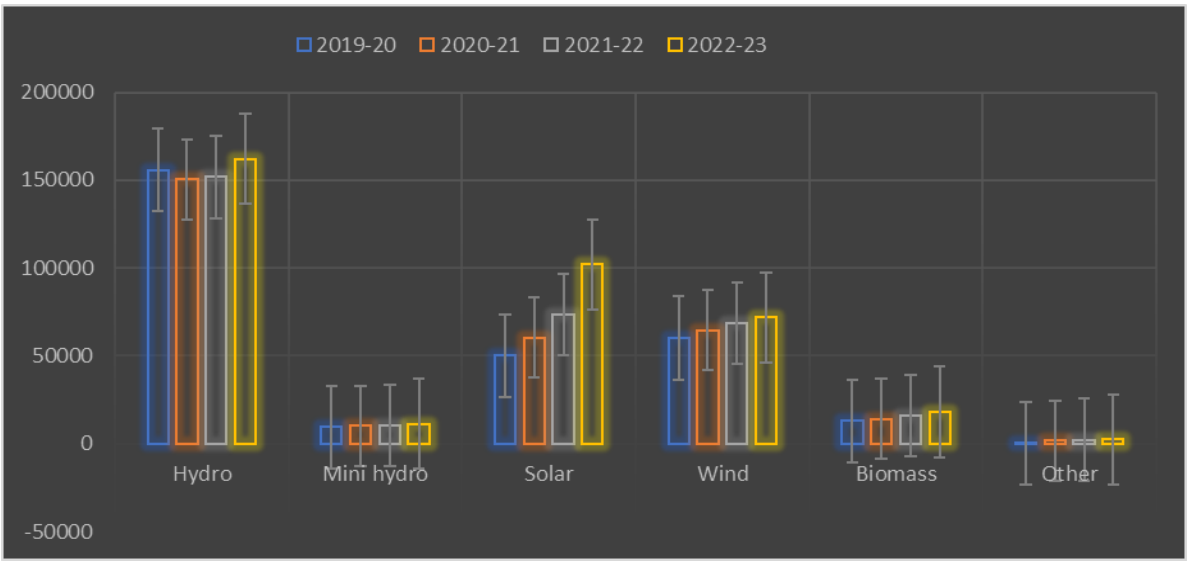


Fig 11: Electricity production by different sources in India

Indeed, a midway strategy has been proposed, in which sugarcane and forests could be used together to preserve and regenerate forests and produce bioenergy at the same time [5]. Meanwhile, lignocellulose biomass such as sugarcane bagasse (SCB), corn stover, cereal straw, and forest woody residue (e.g., birch, spruce, eucalyptus) are substances with a high energy content that can assuage the impending energy crisis [22, 2, 3]. The SCB is a potential feedstock (30%−34%) for numerous applications due to its chemical composition, as shown in Figure 12. It is typically rich in cellulose (44%) and hemicellulose (28%), lignin (21%), ashes (5%) and extractive (2%) [11].

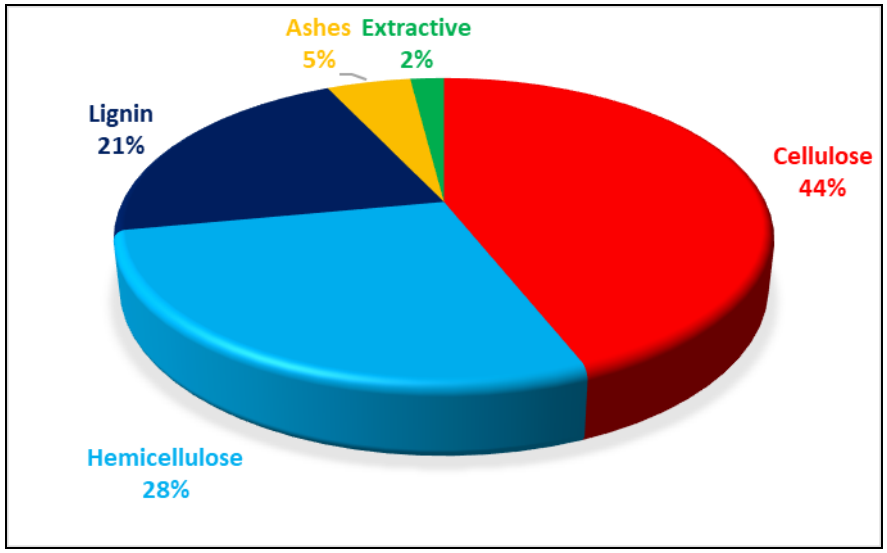


Fig 12: Typical chemical composition of SCB

As of 2009, sugarcane bagasse contributes to about 15% of the total electricity consumed in Brazil, and it is predicted that energy generated from sugarcane stalks could supply more than 30% of the country energy needs by 2020 and will be equal to or more than the electricity produced from hydropower [15]. Most bagasse is currently burned to produce bioelectricity, being responsible for approximately 9% of the electricity produced in Brazil [10]. In Argentina, 15 sugar mills produce electricity from bagasse for their own use, but there are four sugar mills which cogenerate electricity and sell the excess to the electrical grid [14].

According to the IIT researchers and scientists, the energy generated from production of sugar and electricity surpassed the energy required for both the jobs (Sugar production and Cogeneration), leaving producers with surplus electricity for sale. According to the Indian Sugar Mills Association (ISMA), Currently, sugar mills in India generate around 8,000MW power from bagasse, 6,500 MW of which is supplied to the grid as surplus [19].

Bio-methane

The raw spent wash generated after fermentation and distillation is acidic in nature, having dark brown colour with unpleasant odour, high COD, and BOD (1,00,000 and 45,000 mg L^{-1}). Bio-methanation is one of the options to treat such organically rich raw spent wash. With the adoption of primary treatment, 1100 million cubic feet of methane gas per annum is generated in India which is used for steam generation and to run the boilers. Ling *et al.* [13] recorded the maximum bio-methane production rate from SCB is achieved after 18 days, using inoculum in the form of sludge from an anaerobic digestion factory. Rabelo *et al.* [20] also studied the production of bio-methane from the pre-treated and enzymatically hydrolysed SCB which was carried out in a bioreactor at 35 °C in the presence of a buf solution, macro-elements, inoculum and oligo-elements. Upon nitrogen degasification, 165–168 LN of methane/kg of biogas was obtained after 36 days.

Future Research Strategy

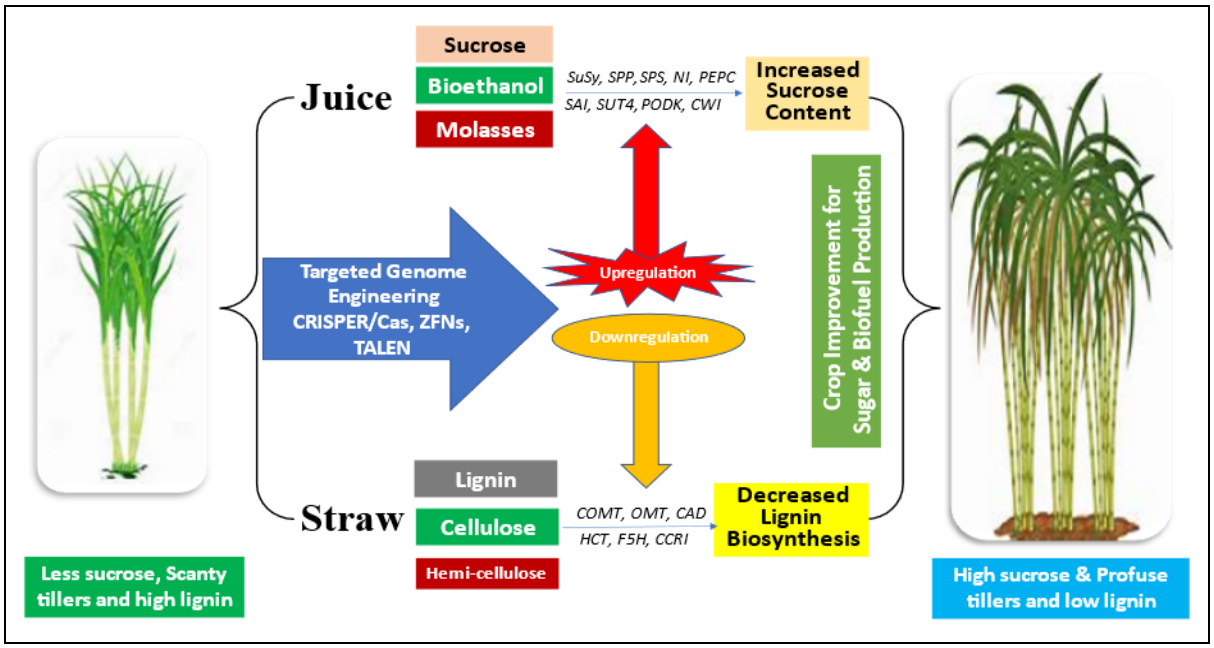


Fig 13: Schematic sketch of future research strategy to uplift Sugar and Biofuel production from Sugarcane

By upregulation, enhance the function of genes i.e., *SuSy*, *SPP*, *SPS*, *SUTA1*, *NI*, *PEPC*, *SAI*, *CWI*, *PODK* etc. to improve the sucrose in juice for higher sugar and ethanol production while downregulation or dysfunction of genes i.e., *COMT*, *OMT*, *CAD*, *HCT*, *F5H*, *CCRI* etc. to decrease the lignin content and produce highly efficient biomass mainly for ethanol and biorefinery chemicals by using recently developed scientific targeted genome engineering techniques i.e., CRISPER/Cas, ZFNs, TALEN etc. Improved cane should have high sucrose, profuse highly productive canes with less amount of lignin content, which will be used for production of high sugar and biofuel in future (Fig. 13).

Conclusion

Fuel energy and electricity are an inevitable necessity of life and is anticipated to gain key standing in the world's economy. Biofuels are potential candidates that provide an eco-friendly and sustainable energy source to meet the energy demand of the whole world. Sugarcane has been shown to be a good candidate for use as a lignocellulosic biomass feedstock for second-generation biofuel production. Research efforts are direly needed, not only to increase biomass production but also the betterment of industrial processes involved in the production of biofuel including biodiesel. Advancements in omics and other innovative disciplines have opened new horizons paving the way to develop future energy crops resulting in the replacement of fossil energy with renewable energy.

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