Sugar Tech (May-June 2022) 24(3):630–650
https://doi.org/10.1007/s12355-022-01123-5

S.I. : INNOVATION FOR SUSTAINABILITY OF THE SUGAR AGRO-INDUSTRY

Indian Sugar Industry: Towards Self-reliance for Sustainability

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Received: 22 December 2021 / Accepted: 27 December 2021 / Published online: 15 April 2022

Abstract The South-Asian region including India is a major hub of sugar producing countries with ample presence in the global sugar scenario. India has a rich history of sugarcane and sugar production since time immemorial, and the industry has gradually evolved to find a place among the top sugar producing countries of the world. The innovative technological interventions for sugarcane improvement, production and management have helped the industry to progress towards a diversified and bio-based productive, sustainable and profitable one, thereby gradually becoming self-reliant. This self-reliant industry with the right mix of linkages and collaborations, has been successful in tackling the various unforeseen challenges including those that cropped up during COVID-19 pandemic. The industry also fulfils its Corporate Social Responsibilities leading to the overall betterment of its stakeholders. This has enabled the Indian sugar industry to align itself with the 2030 Agenda for Sustainable Development Goals.

Keyword Indian sugar industry · Innovative technologies · Self-reliance · Sustainability · Diversification · SDG

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Introduction

India is a major sugar producing country in the South-Asian region and has recorded bumper sugar production in the recent past. It has a strong sugar sector backed by a well-developed R&D set-up. This has helped the industry overcome most of the challenges, be it in the area of production, processing or other related sectors. Even from very early period, as mentioned in medieval literature, India has been cultivating sugarcane and processing the cane. Slowly innovative technologies were developed to suit the time-based and location-specific demands that facilitated India to become a major player at the global level. The sugar industry is inherently inclusive with the crop occupying around 5.0 million hectares, i.e. 2.57% of the gross cropped area and supporting over 7 million farmers and their families, along with workers and entrepreneurs of over 550 sugar mills. In India, sugar is an essential item of mass consumption, and the domestic demand is around 27 million tons per annum. Sugar and jaggery are the cheapest source of energy, supplying around 10% of the daily calorie intake. Sugarcane has been projected as the crop for the future contributing to the production of not only sugar but also as a renewable source of green energy in the form of bio-fuels, bio-electricity and many bio-based products. The industry produces 370–400 million tons (MT) cane, 27–30 MT white sugar and 6–8 MT *jaggery* and *khandsari* every year. Besides, about 3.2 billion litres of alcohol and 4700 MW of power and many chemicals are also produced. The industry has the capability to export around 3500 MW of power to the national grid. Sugar industry has gradually transformed into sugar complexes by producing sugar, bioelectricity, bioethanol, biomanure, bio-CNG and chemicals. The Indian sugar industry has been capable of meeting the sweetener and

energy demand of the nation and to a great extent, has become self-reliant, showing the path to the other countries in building a productive, profitable and sustainable industry (Solomon 2014).

Indian Sugar Industry: The Pre-independence Era

Sugarcane was grown in India from the Vedic period even though there are no reports of a well-organized sugar industry at that time. *Atharva Veda* (1500–800 BC) has numerous references about sugarcane in India, while the famous historians like Herodotus mentioned about the crop in their works. Ibn Battuta and Francois Bernier were other famous voyagers who wrote about the sugarcane cultivation in Kerala and Bengal. Tamil literature also has several references about sugarcane. The technique of boiling sugarcane juice to extract sugar was first discovered in India during the first millennium BC. Mention of establishment of first sugar factories in India can be found as early as 1610 at Masulipatnam and Coromandel coast and subsequently at Surat in 1912. There are unconfirmed reports of the initiation of the first sugar plant in Orissa in 1824 by the French. In 1904, the first modern sugar processing unit was established at Saran in Bihar, with the setting up of the first vacuum-pan process plant (Mishra 2018). The performance of the industry during the period demanded much improvement. With the setting up of Tariff board in 1931–1932, the colonial government imposed 185% *ad valorem* import duty on the sugar imported from Java and this was followed by a substantial increase in the number of sugar factories in the country. The number of factories rose from 29 to 137 between 1931 and 32 and 1936–37. There was an increase of more than 300% in their numbers, with around 140 factories in 1946–47. A corresponding increase in the sugar production was also realized, from 1.61 lakh tons to 9.5 lakh tons during this period. The sugar production recorded a CAGR of 11.62% during the period. The average capacity of the mills increased at a compound rate of 1.61% with a corresponding increase of 0.75% for the sugar recovery. There was a substantial increase in the other factors like sugarcane acreage (CAGR 0.67%), cane production (1.01%) and cane yield (1.09%) (Reviewed in Mishra 2018).

Post-independence Era

The post-independence era also witnessed remarkable developments with respect to the sugar sector. The R&D sector scaled new heights with new research organizations being established. Special programmes were initiated to overcome the upcoming challenges like disease and pest incidence in this crop. Development of improved sugarcane varieties with desirable traits, application of novel agro-techniques for crop production and management, mechanization of sugarcane agriculture, modernization and improvement of performance of the sugar mills, etc., contributed to an overall improvement in the cane production and productivity. By the end of last century, the sugarcane area in the country increased to 4.4 million ha, with the cane yield touching 68 t/ha. The sugar production in 2000 was 18.2 million tons. Further developments in terms of varieties and technologies including ICT-based technologies in the sugar sector led to a quantum jump in sugar production, with a record production of 33 million tons in 2018–19 (Anon. 2021). Promising varieties like Co 0238 that have resulted in an improvement of 102% sugar recovery during the period from 2012 to 2019–2020 (Ram and Hemaprabha 2020) are an example of how the technological advancement in the sugar sector has revolutionised the industry. The area under the crop increased over 300% (1.71 million ha in 1950–51 to 4.841 in 2019–20. The yield of sugarcane during this period has gone up from 40.5 tons/ha (1950–51) to 71.1 t/ha in 2019–20. The sugar recovery has gone up by around 10% from that during the ‘50 s and ‘60 s. Presently, many innovative, sustainable and promising technological interventions like better planting techniques, integrated resource management strategies, bio-intensive plant protection methods, information technology-driven user-friendly computer/mobile phone-based applications for precision agriculture, mechanization, etc., are being put to use in the sugarcane cultivation scenario. A high level of modernization has taken place in the processing arena, enabling the sugar processing units to perform better, at the same time delving into product diversification. Transition towards a “Green Smart Sugar-Agro Complex” with an emphasis to produce green energy and other bio-based products apart from sugar, is the hallmark of the present-day sugar factories. All these had been possible due to the constant efforts of the sugar sector to evolve and excel and to become self-reliant to the maximum extent possible. The constraints faced by the industry during the COVID-19 pandemic (Solomon et al. 2020) have also been an important reason for the Indian sugar industry to move towards self-reliance.

The sugar industry has also been involved in the betterment of life in the sugar mill command areas. Most of the sugar factories are generally situated in rural settings, with limited basic facilities being available in the sugar mill operational areas. This was perceived by the sugar industry as a golden opportunity to take up developmental activities in these areas, ensuring the socio-economic development of the industry beneficiaries in their respective mill operational areas. As a part of their professional

commitment, the mills promote a better living for its beneficiaries through their many developmental programmes. The mills also conform to the National Green Tribunal (NGT) standards, thereby facilitating a healthy clean environment in the area. The rural industrialization brought about by diversification and other activities has also enhanced employment opportunities. This also has brought in an element of self-reliance in the society. Thus, sugar and related industries have been important components of the social fabric in the pre-and post-independence era, contributing towards the country's economy. The sector has been instrumental in social development, mobilization of resources and employment generation and has been from time immemorial, a significant player in fulfilling the Corporate Social Responsibility (Solomon et al. 2019) and integration of the Sustainable Development Goals of Agenda 2030. This is true not only in India, but also in many of the sugarcane growing countries all over the world, especially those in South Asia, that are major players in the global sugar markets.

R&D Network in Sugar Sector

India has a very strong R&D network comprising the national sugarcane research institutions (ICAR-Indian Institute of Sugarcane Research at Lucknow, Uttar Pradesh, in the sub-tropical region and ICAR-Sugarcane Breeding Institute at Coimbatore, Tamil Nadu in the tropical region), research centres funded by state government, research institutes by private organizations and sugar mills, State Agricultural Universities and their research centres, etc. Apart from these, the All India Co-ordinated Research Project (AICRP) on Sugarcane co-ordinates the sugarcane research activities through its network of centres in the different states all over the country. Through its network of 22 regular and 15 voluntary centres, AICRP on Sugarcane aims at pooling the research resources of the country involving SAUs, Central and State Sugarcane Research Stations as well as Non-Government Organizations in a national grid for addressing the problems of regional and national importance. This entire R&D network forms the major source of a well-trained and highly efficient human resource, thereby facilitating the innovative and cutting edge research in the areas of sugarcane improvement, production and management, including the diversification (Sinha 2016). These research institutions are well equipped to cater not only to the national demands for capacity building, but also for the international stakeholders. In addition, there are institutions like National Sugar Institute (NSI), Kanpur, and Vasantdada Sugar Institute (VSI), Pune, that impart quality technical education and also act as a rostrum to develop human potential to its greatest degree in the field of sugar processing, alcohol technology and diversification.

Technological Interventions for Self-reliance in Indian Sugar Industry

Development of Improved Sugarcane Varieties

Sugarcane varietal development is a very significant component of the sugarcane R&D in India. The nation has several research organizations, viz. ICAR-Sugarcane Breeding Institute (ICAR-SBI), Coimbatore, considered as the cradle of sugarcane breeding, ICAR-Indian Institute of Sugarcane Research (ICAR-IISR), Lucknow, which caters to the sub-tropical part of the nation, Vasantdada Sugar Institute (VSI), Pune, state funded research institutions like Uttar Pradesh Council of Sugarcane Research (UPCSR), Shahjahanpur in Uttar Pradesh, the various sugarcane research stations under the State Agricultural Universities (SAUs), etc., that take care of the location-specific as well as the nation-wide demands.

In India, through a well-organized network of All India Co-ordinated Research Project (AICRP) on Sugarcane, around 116 improved sugarcane varieties have been identified and approximately 60 varieties have been notified for commercial cultivation from 2000 till now. All these have been developed by the researchers in India, and many of these varieties are under cultivation in large areas, for example, Co 86032 (70%) in Peninsular Zone, Co 0238 (55%) in North West and North Central Zones, CoLk 94184 (28.25%) in North Central Zone, CoM 0265 (18%) in Karnataka, CoOr 03151 (18%) in Odisha & Co 06030 (18%) in East Coast Zone (Shukla et al. 2018). The recently notified varieties like CoLk 11203, CoLk 12207, CoLk 12209, CoLk 14201, Co 11015, etc., have begun to show their worth in the respective sugarcane growing zones. This speaks volumes about the well-developed self-reliant varietal development scenario in the country that caters to all the sugarcane growing zones of the country in terms of improved high yielding, high sugar, stress resistant sugarcane varieties.

The germplasm collection at ICAR-SBI, Coimbatore, has around 4000 accessions. Besides, the National Hybridization Garden (NHG) houses around 500 improved sugarcane clones suited for different parts of India. The Distant Hybridization Facility of ICAR-SBI situated at Agali is also a valuable parental source that contains more than 1200 accessions including *Saccharum officinarum* clones. These have been well characterized and are being utilized by the sugarcane breeders all over India as parental clones in varietal development. The pre-breeding programmes have contributed improved parental clones to

NHG. For example, more than 60 genetic stocks for high sugar and red rot resistance have been contributed by ICAR-IISR, Lucknow, besides the many other improved varieties and superior clones from the other research organizations and SAUs. Many proven crosses involving these improved sugarcane clones/varieties that are developed in India are being carried out by the researchers every year, giving rise to more promising varieties for cultivation in farmers' field. This is apart from the exotic clones and the World Germplasm Collection housed at the Regional Centre of ICAR-Sugarcane Breeding Institute, Kannur, which has approximately 3300 accessions (ICAR-SBI Annual Report 2020). Thus, the country is fully self-sufficient with respect to the improved sugarcane varieties and parental genetic stocks that can be used for genetic base broadening.

The canes bred at SBI, Coimbatore, have spread to several parts of the world. The Coimbatore-developed canes (Co canes) have been reported to be successful in around 28 sugarcane growing countries of the world, either as parental clones for developing location-specific varieties or as commercially cultivated varieties (Amalraj and Balasundaram 2006). Thus, the country as a whole has many improved sugarcane varieties with desirable traits, and we are not dependent on other sugarcane growing countries for suitable sugarcane varieties that can satisfy our demand.

Quality Seed Production

Quality seed production is being taken up within the country by the research organizations and also in the farmers' field. The industry is self-reliant with respect to availability of quality seed of improved varieties, with the participation of the stakeholders. The research institutes under ICAR in collaboration with sugar factories ensure the availability of quality seeds to the growers. Specialised seed nurseries in farmers fields, seed villages for production of quality seeds of improved varieties, entrepreneur development programmes, etc., are some of the strategies that are being taken up to ensure the availability of seeds of improved varieties. ICAR-Sugarcane Breeding Institute, Coimbatore, distributed about 124.5 tons of breeder seed to trained farmers for quality seed production in 2020. Around 1200 tons of quality seed were supplied to the sugar mills of Tamil Nadu. More than 1,62,200 tissue culture raised plantlets were distributed to sugar factories and to the progressive farmers during the year (ICAR-SBI Annual Report 2020). ICAR-IISR Lucknow also has a well-established quality seed production programme at Lucknow, and every year approximately 8000 quintals of quality seed of the major sugarcane varieties are being produced and distributed. Besides, entrepreneurship development programmes for quality seed cane production are being conducted regularly wherein the progressive sugarcane farmers are being trained for seed production. Approximately, 20 ha is being brought under this programme annually. With the collaboration of Government of Bihar, a quality seed production programme in sugarcane is being carried out by ICAR-IISR, Lucknow, for making quality seed available to the sugarcane growers of Bihar. An area of 65.0 ha under five sugar mills of Bihar state was earmarked in the first phase, and this initiative has entered its second phase. Around 30,000 quintals of seed of the major sugarcane varieties were produced and distributed to the farmers in Bihar during 2019 (ICAR-IISR Annual Report 2019). Such programmes are being carried out by the other R&D organizations also, in areas under their jurisdiction.

Thus, the sugar industry has a well-planned seed production programme within the sugar mill command areas that satisfies the lion-share of seed demand of its stakeholders. Even in the face of unforeseen problems, the sugar mills are in a position to cater to their demand for quality seeds of improved varieties and are not dependent on outside agencies. Simultaneously, the sugarcane growers in these command areas get timely training and scientific inputs from the R&D organizations, and this helps them improve their seed production strategies and methods.

Sugarcane Production Technologies

The sugarcane research institutes have developed many location-specific technologies for improvement in sugarcane and sugar productivity, enhancement in resource use efficiency, irrigation management, profitable intercropping, integrated management of pests and diseases, post-harvest management, etc., which are being used by sugarcane farmers. These are also popularized by Sugarcane Development Departments of states, and various incentives and subsidies are available to farmers. Precision agriculture through site-specific management forms a major component of bio-intensive environment-friendly production package. In the sugarcane production system, it starts right from field preparation and planting, with innovative planting methods and planting materials being utilized.

Modified Planting Material

Single bud planting, primed cane node/bud chip technology and use of other compact forms of planting material in sugarcane, with suitable handling protocols, are cost-effective, with a substantial saving of planting material. Raising settling nursery from any of these starting material and transplanting to the field at the appropriate stage reduces the seed requirement by almost 80%, ensures a

good crop stand and thereby good cane and sugar yield. This also reduces the challenges in logistics and transport of the seed material. The technology has been widely adopted, especially in the tropical sugarcane growing zone of the country (https://www.thehindubusinessline.com/economy/agri-business/bud-chip-technology-catching-on-among-sugarcane-farmers/article30502981.ece). In the wake of the COVID pandemic, the sugar mills and state cane departments of different states have taken advantage of this technology to a great extent. Women Self Help Groups (SHGs) and other collaborative ventures were formed at the grass root level involving the sugarcane growers in many states like Uttar Pradesh in the sub-tropical India, and the members were imparted training for raising single bud settlings. Around 812 SHGs were constituted across 36 districts in the state of UP and more than 9100 entrepreneurs have been trained. As per official records, using this bud chip technology, till January 2021, 3.51 crore settlings were planted (https://www.socialnews.xyz/2021/01/09/up-making-women-self-reliant-with-bud-chip-method-of-cane-plantation/). Such collective programmes can cater to the demand for planting material in the adjoining sugarcane growing areas, without being dependant on external agencies. This will be cost-effective and can save other resources including labour, besides employment and income generation to these entrepreneurs. Moreover, there will be minimum effect on accessibility to resources even when there are restrictions on mobility and transport and other bottlenecks, as was being witnessed during COVID pandemic. Mechanization for mass production of planting material and use of machinery like settling transplanter for transferring settlings to the field have aided in a better adoption of the technology (https://sugarcane.icar.gov.in/index.php/en/home/1193-settling-transplanter; https://sugarcane.icar.gov.in/index.php/en/home/1194-quatro-sugarcane-single-bud-cutter).

Bio-intensive Nutrient Management

An integrated nutrient management strategy is important in sugarcane, keeping in mind the declining soil health in many of the sugarcane growing areas in India. In many parts of the country, the organic C content in the sugarcane growing soil is low, below 0.4% in some areas. Micronutrient deficiencies have also been reported in these soils. Approximately 9–10 million tons of nutrients (N, P_2O5, K_2O) are imported annually to meet the nutrient demand in the agricultural sector as per FAI estimates (https://www.faidelhi.org/general/Prodn-imp-cons-fert.pdf). A major share of these chemical nutrients can be substituted with organic sources in an integrated manner. A detailed study conducted in the state of Bihar reported an enhanced B: C ratio of 2.4 with integrated nutrient application over that with the conventional method (1.8) (Thakur et al. 2012). Green manuring (including in situ incorporation of green manure crops during land preparation), crop residue incorporation and trash mulching, use of bio-fertilizers and other organics like FYM, sugar industry by-products like bagasse and pressmud are gaining importance in sugarcane too (Shukla et al. 2019).

Microorganisms like *Gluconacetobacter*, *Azospirillum*, *Azotobacter*, *Pseudomonas*, *Aspergillus,* etc., are some of the microbes that form the components of biofertilizer/microbial consortia. Field trials have indicated that integrating microbial consortium and NPK fertilizer application proved effective in improving soil organic carbon, soil microbial population, microbial biomass carbon, microbial biomass nitrogen, and soil respiration, as well as the cation exchange capacity of the soil (Shukla et al. 2020). Several R&D organizations have their own units for large-scale bio-fertilizer production, and these units provide training to the sugarcane growers for mass production of bio-fertilizers. The sugar mills in India also have their own mechanism of bio-nutrient production from industry by-products, and these are supplied to the growers and other stakeholders. There are collaborative linkages among the sugarcane growers, sugar mills and R&D organizations for mass production and distribution of bio-fertilizer and microbial consortia and such linkages help in easy accessibility of the material to the farmers, besides facilitating employment and resource generation. The vast microbial diversity present in the soil and plant parts ensures a steady supply of starting material for large-scale consortia production.

These units established by many sugar mills in their command areas have made the sugarcane growers and other stakeholders self-sufficient in terms of the nutrient requirement, since these organic fertilizers can supplement the chemical fertilizers. Many of the sugar mills and associated research organizations have their own bio-compost units (http://www.kmsugar.com; http://www.bannari.com; https://renukasugars.com; https://manasindustry.com; https://www.vsisugar.com) that make use of sugar factory by-products along with microbial culture to produce their own trademark bio-fertilizers (*Moti Super* from KM Sugars, Uttar Pradesh, *Bannari Compost* from Bannari Amman Sugars, Tamil Nadu, to name a few); thus, the dependency on other sources for these bio-nutrients is done away with. Collective initiatives like out growers' model of cane cultivation and SHGs can play an active role in such ventures that can overcome many of the challenges in situations where restrictions and regulations are imposed on movement of goods, people and transport. A small portion of the field of selected farmers can be kept apart for bio-composting, and this can serve as a source of organic nutrients to the other sugarcane growers too. Earmarking

specific fields in the mill command area itself for growing green manure crops like *Sesbania* can help in easy availability of seeds. These can be of help in timely green manuring of the fields. Entrepreneurship development for large-scale bio-nutrient production and related management techniques in the field will help in easy accessibility of the technology for the stakeholders and employment generation, along with cost-effectiveness. Even though these initiatives are already being taken up, an intensification of efforts for bio-based nutrient management through establishment of production units and capacity building to facilitate location-specific production at large scale is making the sugar industry self-reliant, even at the grass root level.

Carbon sequestration through trash mulching, rhizosphere engineering and residue incorporation is also an indirect component of nutrient management in this crop which is being practised by sugarcane farmers (Shukla et al. 2017). It is estimated that 181 kg C ha^{-1} yr^{-1} is sequestered by sugarcane crop (Parr and Sullivan 2005). Thus, the practice of growing sugarcane itself leads to maintenance of soil health and enhancement of soil properties, bringing in an element of self-reliance into the whole process of sugarcane cultivation and processing. The regular addition and recycling of plant residues, green manuring and related processes add to this aspect of self-sustenance.

Irrigation Management to Enhance Water Availability

Sugarcane is a crop that requires timely irrigation at the critical stages and a proper management of the available water can help in enhanced water availability. There are several techniques that are being practiced like skip furrow irrigation and micro irrigation systems. It is estimated that out of the total irrigated land in India only less than 20% is under micro-irrigation (Gulati and Mohan 2018; https://www.thehindubusinessline.com/data-stories/data-focus/sikkim-andhra-pradesh-karnataka-and-maharashtra-lead-is-usage-of-drip-irrigation/article34075327.ece). Twenty seven states have only less than 30% of the net cultivated farm lands under micro-irrigation and a few have only 15% of the total cultivated lands under micro-irrigation. Uttar Pradesh the largest sugarcane growing state, has only 1.5% of the land under micro-irrigation. With the present pattern of water consumption, almost half of the demand will remain unmet in 2030. On an average, approximately 32% of water saving can be accomplished with micro-irrigation, with an average income enhancement of 48.5% to the farmer (https://www.thehindubusinessline.com/data-stories/data-focus/sikkim-andhra-pradesh-karnataka-and-maharashtra-lead-is-usage-of-drip-irrigation/article34075327.ece). Economic water productivity (EWP) of sugarcane in Bihar and UP is as high as Rs. 36 and Rs. 30 per cubic metre of irrigation water applied, whereas in the tropical states like Maharashtra, Tamil Nadu, Andhra Pradesh and Karnataka, EWP is as low as Rs. 10.7, Rs. 9.3, Rs. 8.3 and Rs. 8.7, respectively, per cubic metre of irrigation water. Similarly, on comparing the economic water productivity across major crops in Maharashtra except sunflower, all other crops produce higher value of output than sugarcane, per unit of irrigation water applied in one hectare (Gulati and Mohan 2018). Thus, the use of micro-irrigation systems is necessary in sugarcane especially with the fast depleting ground water table. The situation in states like Maharashtra is an ample proof for this fact. The Government of India implemented Centrally Sponsored Scheme (CSS) on Micro-irrigation in 2006, which was modified on July 1st 2015 to include micro irrigation as a component (per drop more crop) under the PMKSY (*Pradhan Mantra Krishi Sinchayee Yojana*) scheme. At least 10% of the command area created using PMKSY—*Har Khet ko pani* component—must be covered under micro/ precision irrigation. Other such programmes for water harvesting like *Jal Shakti Abhiyaan: Catch the Rain* initiative, *Atal Bhoojal Yojna* are also concerted efforts towards self-sufficiency with respect to water availability.

Apart from the use of micro-irrigation and other agro-techniques, many sugar mills are initiating water harvesting mechanisms in their command/neighbouring areas, that can help in recharging the ground water, at the same time facilitating availability of water for irrigation and other purposes. In a programme on Improving Natural Resources through Integrated Water Resources Management Approach at Sangareddy District, in the Telangana State of South India, Trident sugars, Ltd., has funded a watershed project in which eight water harvesting structures were completed in May 2020, to benefit around 2000 small-holder farmers. The work was supported by ICRISAT, Hyderabad, and also by the International NGO network, Solidaridad. The work continues with more areas being targeted (https://www.icrisat.org/icrisat-natem-watershed-project-in-south-india-marches-ahead-despite-covid-19/). Such initiatives will facilitate availability of water round the year and make the beneficiaries self-reliant with respect to water to a great extent. Another example of such a water harvesting initiative has been reported from Uttar Pradesh, the sugarcane growing belt of sub-tropical India. The distillery division of the Seorahi Chini Mill, Seorahi, Uttar Pradesh, has adopted one pond in a village to initiate rain harvesting (www.dainikjagran.com). These are small steps towards making the sugarcane growers and thereby the sugar industry, self-sufficient in water management.

Bio-intensive Crop Protection

The use of inorganic plant protection chemicals has not been very effective in controlling the major diseases and insect pests of sugarcane. Thus, along with the development of resistant/tolerant varieties against the biotic stresses, integrated management including biocontrol of pests and diseases has been an important strategy in this crop. The application of bio-agents for biotic stress control has resulted in a saving of crores of rupees to the government exchequer (https://ppqs.gov.in). Bio-agents like *Trichogramma, Cotesia* and *Epiricania* are being reared on a large scale and released into the field, and this has been successful against borer complex, *Pyrilla*, white fly and other pests (Srikanth et al. 2016). *Trichoderma* and other bio-agents have been reported to be effective in managing diseases to some extent, apart from facilitating crop growth (Viswanathan 2018, 2021; Viswanathan and Malathi, 2019). Many of the sugar mills and R&D organizations have their own mass rearing facilities for the bio-agents, to rear and release them directly in the fields or to distribute to farmers. Entrepreneurship to facilitate mass-rearing of bio-agents has resulted in training a large number of entrepreneurs in rural areas. These innovative farmers in turn, produce bio-agents on a large scale and distribute it among the growers/stakeholders in a particular area. The rural entrepreneur model of EID Parry is an example (Sankar 2014) of how the sugar industry is making use of technology and the available resources to be self-reliant. Apart from the tested bio-agents, the locally available rich biodiversity of Lepidopteron insects/pupae can also be studied for their suitability for use in biological control. This adds another dimension to the concept of a self-sustaining sugar industry.

Mechanization of Sugarcane Agriculture

Perhaps, the most sought after technological advancement that can add to the self-reliance in the sugarcane growing sector, especially in the wake of COVID-19 pandemic-related restrictions, is mechanization, which can supplement the manual interventions in crop production and management. A rough estimate indicates that sugarcane cultivation demands on an average, 375 man hours/ha of the crop (Singh et al. 2020). A well-planned and executed mechanization programme in sugarcane cultivation can help in reduction of manual labour with timely and proper field operations, thereby sustaining the crop in the field in adverse situations. This can also minimize human interventions. Even in normal circumstances, mechanization can overcome the labour scarcity and high cost of manual labour, thereby making the cultivation of this labour-intensive crop cost effective. In the wake of second and third waves of the pandemic, at many farms, there would have been the engagement of a new set of labour-force, replacing those who have migrated back to their hometowns and this would also have reduced the efficiency and timeliness of the activities to some extent. Use of machinery has helped to overcome this challenge to a limited level but the extent of mechanization is still not enough for a perfectly smooth and timely conduct of all these operations, in the face of such an unprecedented adversity.

Studies indicate that on an average, the extent of mechanization in sugarcane agriculture is less than 40% in our country, and a lot more needs to be done in this area of adoption of mechanization. But when it comes to the development of machinery, our country has an impressive line-up of R&D organizations (https://iisr.icar.gov.in; https://sugarcane.icar.gov.in) and other engineering groups like M/s Mahindra & Mahindra, Tractors and Farm Equipment Ltd. (TAFE), M/s Deccan Farm Equipments, M/s Eicher Tractors M/s VST Tillers and many others, with a wide range of machinery suited for sugarcane agriculture, ranging from manual and machine operated seed/sett cutters to tractor-operated planters with multiple attachments, RMD, etc., to suite specific needs (Table 1). The wide range of sugarcane planters and inter-culture equipment from ICAR-IISR, Lucknow, and the sugarcane transplanter, sett treatment device and other equipments from ICAR-SBI, Coimbatore, demand special mention. Manufacturers like M/s Shaktiman have developed sugarcane harvesters for Indian situations, apart from other farm implements (https://www.shaktimanagro.com/). Besides, there are small scale innovators who are engaged in developing equipment like mechanical precision sugarcane sett cutting devices and bud planters (https://nif.org.in/innovation/sugarcane-bud-planting-machine/796). These machines if used extensively in the sugarcane cultivation, have been estimated to result in a saving of more than 60% of manual labour along with a reduction in cost of cultivation to the tune of 50–60%.

The rich resources we have in terms of farm mechanization enable us to be self-reliant in carrying out the various on-farm operations. Indian manufacturers have linkages and collaborations abroad and sugar industries in many countries around the world have taken advantage of the expertise of the manufacturers in sugarcane mechanization. This in turn, has enabled our manufacturers/mechanization experts to sharpen their skills and delve into new avenues, thereby making valuable additions to the Indian mechanization scenario. Thus self-reliance through linkages and collaborations is being realized to a great extent through mechanization, by the Indian sugar industry.

Table 1 Components of self-reliance in Indian sugar industry

Component	Technology/Resources	Source
Varietal development	Improved high sugar, high yielding, stress resistant, location-specific sugarcane varieties	https://sugarcane.icar.gov.in https://iisr.icar.gov.in https://www.vsisugar.com http://www.upcsr.org State Agricultural Universities
Quality Seed production	Quality seed production of improved varieties, including *in-vitro* practices	https://iisr.icar.gov.in https://sugarcane.icar.gov.in https://www.vsisugar.com http://www.upcsr.org State Agricultural Universities Seed production units in sugar mills State sugarcane departments
Improved planting techniques	Improved planting material like single cane node, transplanting of settlings, etc.	https://iisr.icar.gov.in https://sugarcane.icar.gov.in https://www.vsisugar.com http://www.upcsr.org State Agricultural Universities State sugarcane departments
Bio-intensive nutrient management	Use of green manures, biofertilizers, sugar mill by-products as components of INM	https://iisr.icar.gov.in https://sugarcane.icar.gov.in https://www.vsisugar.com http://www.upcsr.org State Agricultural Universities State sugarcane departments Biocomposting units in sugar mills
Water management	Micro-irrigation and other water-conserving techniques	https://sugarcane.icar.gov.in https://iisr.icar.gov.in https://vsisugar.com http://www.upcsr.org https://pmksy.gov.in https://www.icrisat.org State Agricultural Universities State sugarcane departments www.netafimindia.com http://www.jains.com https://www.solidaridad.org
Bio-intensive disease and pest management	Use of bio-agents, like *Trichogramma* spp., *Cotesia* spp. *Epiricania*, *Dipha, Micromus*, insect traps and pheromones, *Trichoderma* and fungal/microbial pathogens	https://iisr.icar.gov.in https://sugarcane.icar.gov.in https://www.vsisugar.com http://www.upcsr.org https://pmksy.gov.in https://www.nbair.res.in State Agricultural Universities State sugarcane departments

Table 1 continued

Component	Technology/Resources	Source
Mechanization	Machinery for sugarcane cultivation	https://iisr.icar.gov.in
		https://sugarcane.icar.gov.in
		https://nif.org.in/innovation
		https://www.shaktimanagro.com
		www.kuboto.co.in
		www.mahindra.com
		https://www.mam.co.jp
		https://farming-machine.com
		https://www.caseih.com
Process Mechanization	Mill machinery	https://www.shrijee.com
		https://www.isgec.com/sugar-plant
		https://thyssenkrup-industries-india.com/
		https://www.trivenigroup.com
		https://www.nsi.kanpur
Information Technology	User-friendly mobile-based/ computer-based applications	https://iisr.icar.gov.in
		https://sugarcane.icar.gov.in
		https://krishi.icar.gov.in
		https://plantix.net
		https://ww.upcane.gov.in
Capacity building	Training to national and international stakeholders including sugarcane growers, sugar mill personnel, process machinery personnel and others	https://iisr.icar.gov.in
		https://sugarcane.icar.gov.in
		https://www.nsi.kanpur
		https://www.vsisugar.com
		http://www.upcsr.org
		State Agricultural Universities
		State sugarcane departments
Product diversification	Diversification to products other than sugar Biorefinery/Sugar Agro-complex	Various sugar mills across the country
		https://www.nsi.kanpur
		https://www.vsisugar.com

ICT in Sugarcane Agriculture

India is a major sugarcane growing country in the world with different zones having different climatic and other features. Therefore, the requirements for raising a good crop will vary to some extent in these zones. Location-specific packages are needed, and these should be developed in such a way that these are user-friendly. The application of Information & Communication Technology (ICT) has been a significant step towards enhanced productivity and profitability in this crop. This has also facilitated an optimal and timely utilization of resources like human resources, nutrients and water, thereby taking care of the sustainability factor also.

A very significant advancement in the sugar industry has been the GPS-based sugarcane crop area survey initiated by the Indian Sugar Mills Association (ISMA) and other agencies. From 2011 onwards, ISMA has been carrying out sugarcane area survey and estimation using GPS. This helps in timely and more precise estimation and also reduces the requirement of manual intervention. Instead of a minimum of 4–5 personnel needed for sugarcane area survey pre-2011, the GPS-based hand-held machine can work even with a single operator (http://www.indiansugar.com).

GPS-based techniques have helped in assessing the location-specific soil nutrient requirements of the sugarcane growers. There are mobile applications developed by different organizations (e.g. Cane Advisor developed by ICAR-SBI, Coimbatore) that are very user-friendly and help in nutrient management. Water management is also one area where the ICT is playing a major role. The mobile-based applications developed help in scheduling irrigation, based on the requirement of the crop. "*Ikshu-Kedar*" a mobile-based application for irrigation scheduling, developed by ICAR-IISR, Lucknow is one such

intervention (https://krishi.icar.gov.in). This, along with proper management practices, helps in timely and need-based irrigation and nutrient management, thereby aiding resource conservation and minimum human interventions. Another such initiative is by the ICAR-Sugarcane Breeding Institute Coimbatore through its Soil Moisture Indicator that has contributed to a highly efficient water utilization by the stakeholders (https://sugarcane.icar.gov.in/images/sbi/announcements/mobile_app.pdf). This innovation bagged the National Water Award-2019 for its contribution towards the water conservation.

Several sugar mills have also developed such apps in collaboration with other agencies, e.g. *Meetha Sona* an interactive App by DSCL Sugars Ltd. (https://www.amarujala.com/uttar-pradesh/hardoi/meetha-sona-ap-for-sugercane-farmers-hardoi-news-knp5706703180). The stakeholders can themselves schedule irrigation in the crop using these applications. Mobile-based diagnostic tools like CaneDES from ICAR-IISR, Lucknow, 'Plantix' developed by PEAT, Germany, in collaboration with ICRISAT, India and Acharya NG Ranga Agricultural University, Andhra Pradesh, India, help in disease/disorder diagnosis and management of these stresses (https://iisr.icar.gov.in/iisr/download/publications/newsletter/NewsLetterJuly2014.pdf ; https://plantix.net).

Apart from the on-farm ICT solutions, post-harvest activities like marketing have also benefitted immensely from this technology. The Sugarcane Information System (SIS) developed by the Government of Uttar Pradesh is a typical example of how this e-governance platform has made the sale, procurement and marketing of sugarcane easier, along with several other advantages (https://economictimes.indiatimes.com/news/economy/agriculture/sugarcane-farmers-benefit-through-sis-system-in-uttar-pradesh/articleshow/12019911.cms.from=mdr; Krishnan 2019). The key benefits include transparency in transactions, elimination of middle men, saving of time and resources for frequent travels by the growers, proper weighing of canes and related benefits. Such mobile-based user-friendly applications have been of immense help for sugar industry in challenging times as that was witnessed during the global COVID-19 pandemic. These initiatives are best solutions in overcoming the hurdles of restricted mobility or other such regulations, thereby making the growers also self-reliant.

Process Engineering/Machinery

India has a galaxy of machinery manufacturing and installing companies who have a strong group of extremely capable and experienced technical experts, facilitating an efficient network at the domestic and international level. These manufacturing units are spread all over India and are largely responsible for installation and commissioning of sugar plants, distilleries, co-generation plants and other ancillary facilities for the sugar industry (Table 1). They constitute some of the world's leading suppliers of turnkey sugar factories, refineries, distilleries, ethanol plants, power transmission systems, water and waste-water treatment plants, manufacturers of steam turbines, etc. These engineering units have made their mark in installation and commissioning of state-of-the-art sugar industry related facilities both within India and in countries abroad (https://www.shrijee.com; https://www.trivenigroup.com; https://www.isgec.com; https://thyssenkrup-industries-india.com; https://www.usipl.com; https://ssngineers.com and other related groups).With their expertise and vast experience in their field, these companies have a widespread network all over India and also in other countries, where they take up consultancy, installation and commissioning of the latest technological facilities for the sugar industry. To mention a few, the Uttam Sucrotech International Pvt. Ltd., the international arm of Uttam Sugar Group, has projects in Kenya, Indonesia, Sudan, Uganda, Columbia, Ethiopia and many other countries. The Shrijee group has its presence in more than 30 countries across the globe in the form of consultancies, installations and supply of equipment. This is apart from their services that cater to the sugar processing units all over India. The Triveni Engineering Group, ISGEC Heavy Engineering Ltd., SS Engineers, etc., are some of the other sugar machinery and equipment manufacturers who have linkages and collaborations in India and abroad. The list is very lengthy, and the industry has been constantly evolving in this area with newer facilities to meet the ever changing demands of the clientele. The National Sugar Institute, Kanpur, is also having a major role as an advisory and consultancy provider, facilitating linkages among the service providers and stakeholders. The institute provides technical assistance to the sugar mills with an aim to improve their efficiency.

Capacity Building

The entire R&D network of the sugarcane and sugar research organizations are well-equipped with the conventional as well as the modern technologies to provide skill and knowledge enhancement to the students, sugarcane farmers, sugar mill personnel and other stakeholders. Training in sugarcane production and management practices, entrepreneurship development for different technologies like seed production, application of bio-control practices, farm machinery related technologies, skill development in sophisticated techniques including laboratory analyses, molecular biology related techniques, etc., are provided by these organizations as per the demand at regular intervals (Table 1). During 2019–20220 around 680

farmers, 80 developmental personnel and 570 students were trained at ICAR-IISR, Lucknow (ICAR-IISR Annual Report 2019). Such training programmes and interactions are held in other organizations also. Research teams from many sugarcane growing countries like Sri Lanka, Bangladesh, Thailand, Vietnam, Kenya visit these organizations for getting trained in various aspects of sugarcane production and management including mechanization. This is apart from the short visits for specific interactions and deliberations that are regularly organized by these institutions and organization.

Diversification in Sugar Industry: A Step Towards Self-Reliance

Sugarcane and other sugar crops like sugar beet and sweet sorghum are excellent biomass feed stocks for renewable fuel and green energy, apart from several other main and by-products. The major advantage with the sugar crops including sugarcane over the grain crops is the less level of processing required due to the fermentable sugars present in their juice. The fluctuating sugar markets, the demand for alternative bio-based fuels and increased consumer demands for bio-based products are significant factors that drive the global sugar industry towards diversification for sustainability. The continued reliance on fossil fuel energy will deplete the world reserves, and a shift to biomass-based renewable energy will also be environment-friendly, with a reduction in emission of associated greenhouse gases (GHG). With a high biomass and high conversion efficiency, sugarcane has emerged as a very attractive option for diversification to bio-based products. Sugarcane is a major source of bio-energy, and the main energy chains from this crop include bio-ethanol from molasses & juice, cogeneration from bagasse and bio-CNG from press mud and spent wash (Mohan and Kanaujia 2021).

Bio-ethanol

In India, there cannot be a more ideal time for the sugar industry to move towards self-reliance, through a sugarcane based bio-economy. A record domestic sugar output in the recent years (32 million metric tons in 2020–21) fluctuating global sugar markets and the demand for green and clean energy, along with the formulation of National Biofuel Policy (NBP) in 2018, has given ample impetus for the sugar industry to divert towards bioethanol. As per the NBP, a blending target of 20% is to be achieved by 2030. The recent reforms in this scenario like E-100 pilot project have led to the government setting new ethanol blending targets (https://pmindiawebcast.nic.in/2021/5jun21.html). From the present ethanol blending of approximately 8.5%, a 20% ethanol blending is to be achieved by 2025 and this will drive the diversion of excess sugar/sugarcane juice/molasses towards ethanol production. On June 5, 2021, the Prime Minister of India inaugurated three ethanol dispensing stations at Pune. This E100 pilot project aims to set up a network for ethanol production and distribution across the nation. From around 38 crore litres of ethanol purchased in 2013–14 by the Oil Marketing Companies (OMCs), the amount has increased to 332 crore litres and this approximately eightfold increase in procurement has benefitted the sugarcane farmers to a great extent (https://pmindiawebcast.nic.in/2021/5jun21.html Sarwal et al. 2021). The blending % by PSU OMCs has also increased from 1.53% to 8.5%. With the demand for clean and green energy steadily increasing, the country need to be assured of sufficient supply of bioethanol to meet the future demands in the context of the Ethanol Blending targets. The report of the *Expert Committee on Roadmap for Ethanol Blending in India by 2025*, has also highlighted a major role of sugar industry in E 20 blending program (https://www.niti.gov.in/expert-committee-roadmap-ethanol-blending-india-2025). Sugar sector capacity is being augmented to produce 550 crore litres for 20% blending by 2025–26. Molasses-based distilleries can produce 20% additional ethanol if sugar rich feed stocks like B-heavy molasses, syrup and cane juice are used, as the same capacity can cater to the higher demand of ethanol.

Co-generation

Self-reliance in terms of energy demand is vital for the development of any country. India being one among the fastest growing economies of the world, is presently the third largest energy consuming country and is entering a very dynamic period with respect to energy scenario. India has already provided electricity connections to the majority of its citizens, along with the adoption of several energy saving measures. Government has also initiated the massive expansion of renewable energy program of 175 GW by 2022.

Since 2000, India's per capita energy demand has grown by $> 60\%$. Electricity consumption nearly tripled in the past two decades. The expanding economy and the large scale urbanization and industrialization point towards a huge demand for energy in the times to come. With the co-existence of shortage and abundance of conventional energy sources in the country, there is ample scope of utilization of renewable energy. Co-generation by the sugar mills is an important source that satisfies the energy demand of the country (Mohan and Swain 2018; Mohan and Kanaujia 2021). Bagasse from sugar processing produces high pressure steam and electricity. The excess power generated after use for running the sugar mill is sent to the national power grid. According to World Alliance

for Decentralized Energy, bagasse-based power generation in sugar mills has the potential to meet up to 25% of the present-day power demand in the sugar producing countries of the world.

In India, the total utility electricity sector has about 25% of the total installed capacity being met by newer renewable power plants, which amounts to ~ 94.4 GW (Mohan and Kanaujia 2021). 11% of the total installed Renewable Energy Source is contributed by biomass-based co-generation (~ 10 GW). There has been an increase of around 130% in the installed biomass power generation capacity during the last 5 years. This is about 10.15 GW in 2021 (https://mnre.gov.in). The sugar industry is an important source of power generation with 275 sugar factories having the facility for co-generation. The current estimate of the exportable energy from sugarcane bagasse from these mills is 3500 MW. This accounts for ~ 1.0% of the total electricity generated in the country. Considering the high-pressure co-generation systems and the latest technologies that are being utilized by the sugar mills, the surplus energy generated can be manifold and this can be exported to the national grid. The present potential of the sugar industry is estimated to be 12.5GW of exportable power generation and this can go up to 14.0 GW with improvements in the infra-structure in the sugar mills (Mohan and Kanaujia 2021). The mills will have an improved capacity to produce up to 250 kWh/ton cane against the present generation of around 150 kWh/ton cane. The proper utilization of the sugarcane plant residues in the existing cogeneration units, along with bagasse can help in realizing a higher level of cogeneration in the sugar mills (Mohan and Swain 2018). This will help in sustaining the sugar industry and making the industry as well as the country self-reliant in terms of power generation and accessibility to the energy produced.

Bio-gas and Bio-CNG

Compressed bio-gas is another source of bio-energy from sugar industry, which has a significant role in bringing in self-reliance in the energy sector for the country. The anaerobic digestion of filter cake results in the production of bio-gas/compressed bio-gas. Approximately 1 kg of CNG can be produced from 25 to 30 kg of filter cake, which makes the process lucrative. Apart from providing bio-energy this is a value-addition of the industry by-product. Out of the total compressed bio-gas potential of the country (approximately 62.0 million tons), around 3% (around 2.0 million tons) can be produced from sugar industry by-products like spent-wash/filter cake/press mud. Spent wash/vinasse, an effluent from ethanol production process can also be a valuable source of bio-energy. It is estimated that around 500 MW power can be produced from the present available alcohol production (3000 million litres in a year).

Apart from the self-reliance contributed by these value added products, the additional revenue that can be earned by the sugar mills through value addition can contribute to the sustainability of the sugar mills (Table 2), as estimated in detail (Mohan and Kanaujia 2021).

Sugarcane can be considered as the best green crude for a bio-based industry, giving rise to an efficient and sustainable bio-based economy. The C_4 route of photosynthesis taking place in the plant, suitability to the tropical environments, ready-to-use source of soluble carbohydrate, the utilization of the whole crop as source of various products, with a very positive energy balance and the lowest carbon foot print, etc., make this crop the best choice for an efficient bio-based economy (Solomon and Swapna 2019). Sugarcane provides the raw material for food, fodder, bio-fuel, green energy, bio ethanol, bio-plastics, pulp and paper, particle boards, kitchenware, bio-detergents, bio-molecule coated fabrics, etc. The textiles industry also make use of bagasse based products for manufacturing nature friendly garments). All these contribute towards a self-reliant economy where the dependence on other sources is reduced to a great extent.

Sugarcane-Based Bio-refinery

The biorefinery concept is gaining more importance in India with great investment potential and has been identified as one of the most promising routes for economic sustainability, employment and creation of new industries. The upcoming concept of bio-refinery with sugarcane as the feed stock is an excellent means by which different bio-products can be integrated into the same physical space. The processes for producing sugars, biofuels, co-generation, bio-based products several chemicals (sugar-based or ethanol based) can be undertaken within the same space using different chemistries. The biomass can be converted into high value chemicals that can replace the petroleum-based products. A typical example of a sugarcane based refinery is presented here (Fig. 1), and many sugar mills are producing these value added products.

An excellent example of product diversification into bio-based chemicals while obtaining social, environmental, and financial sustainability gains, is Godavari Biorefineries Ltd., in India (https://godavaribiorefineries.com/). Starting with sugarcane, Godavari manufactures refined sugar, ethanol, and chemicals including ethyl acetate, croton-aldehyde, 1,3-butanediol, and even flavour and fragrance ingredients. From bagasse, electricity is cogenerated and used to power the sugar and chemicals factories and plants. The company's bio-based chemicals are produced so efficiently that they are able to compete pricewise against

Table 2 Estimated additional revenue generation through value addition of sugar industry by-products. (Source: Mohan and Kanaujia 2021)

By- product	Value Added product	Revenue earned (INR)	
		Primary By-product	After Value-addition*
Bagasse (saved 7.0% on cane and 9.0% on cane resp.)	Power	119.00	151.50
Molasses (@ 4.5% cane)	Ethanol	180.00	371.00
Press Mud (@3.5%on cane)	Bio-gas	8.75	33.00
Total (per ton of sugarcane)		307.75	555.55

*Net Revenue considering the additional cost of conversion

the same chemical produced from fossil sources (https://godavaribiorefineries.com/). Many sugar companies such as The Simbhaoli Sugar Mills, Mawana Sugar works, Harinagar Sugar Mills, Balrampur Chini Mills and Bajaj Hindustan, Ltd., are using sugarcane and its co-products and employing cleaner chemical processes to make environmentally preferred products to satisfy consumers who are becoming increasingly aware of sustainability issues.

The Indian sugar industry like other progressive sugar producing countries is increasingly implementing sustainable ways to produce and supply natural sweeteners (Eggleston and Lima 2015) such as cane sugar, jaggery, unrefined raw/brown sugar, syrups following a circular approach which spans the entire product life cycle.

Sugarcane Industry and Carbon Footprints

Several studies have been carried out all over the world., esp., in the sugarcane growing countries like Brazil about the sustainable green technologies in terms of CO_2 emissions, carbon and water footprints, methane emissions, etc., that can be adopted in sugarcane agriculture. Sugarcane cultivation and processing practices as a way towards reduction of carbon foot prints has assumed great significance in the present scenario of environmental friendly sustainable options. Land management, nutrient management, plant residue incorporation and green harvest are some of the practices which have grabbed the attention of researchers in this regard (Solomon and Swapna 2019). Estimation of C footprint in the sugar production chain has been reported under different situations in major sugar producing countries/regions like Brazil, Australia and Philippines (Rein 2010; Renouf et. al. 2010; de Oliveira Bordonal 2018; Mendoza 2014, 2017). In India, sugarcane-based cropping system (Sugarcane-Ratoon-Wheat) was observed to sequester 1.42 mg/ha/yr carbon and with the residue incorporation along with application of *Trichoderma*, a sequestration up to 2.45 mg/ha/yr of carbon could be achieved (Shukla et al. 2017). A longer sustainability of soil C level, crop productivity and production efficiency was documented by the group under these conditions. BONSUCRO through its Better Sugarcane Initiative Standards have also estimated net carbon footprint for sugar production. As a base value, within specific conditions and with the assumption of 10 MW power exported from co-generation, an estimated value of 307 kg CO_2 equivalent/ton of sugar (0.31 g CO_2 eq/g of sugar) produced has been reported by this group. Hiloidhari et al. (2021) identified some of the conditions that can lead to better environmental friendly production practices in Maharashtra in India. The carbon emission/carbon footprint values are found to depend on the country/ region of study and the variables used in the estimations. Increasing the efficiency of agricultural operations in the field and processing in the factories using bio-intensive practices will invariably lead to reduced carbon footprint.

Transition towards a "Green Smart Sugar-Agro Complex" with an emphasis to produce green energy and other bio-based products, apart from sugar is the hallmark of the present-day sugar factories. Improved technologies like GREEN technology (Greatly Reduced Energy and Equipment Needs) for sugar refining (Tongaat Hulett Refinery, South Africa) are being practiced by the sugar mills. The potential of value addition through a better utilization of by-products is also being taken up by the sugar mills, for example, bagasse for co-generation, molasses as a source of ethanol, utilization of vinasse/spent wash for bio-electricity and also for soil health management, to name a few. A bio-refinery with the mandate of "Wealth from waste" encourages the sugar mills to utilize "anything and everything from the sugarcane plant" to be processed for an enhanced profitability and sustainability of the industry (Fig. 1).

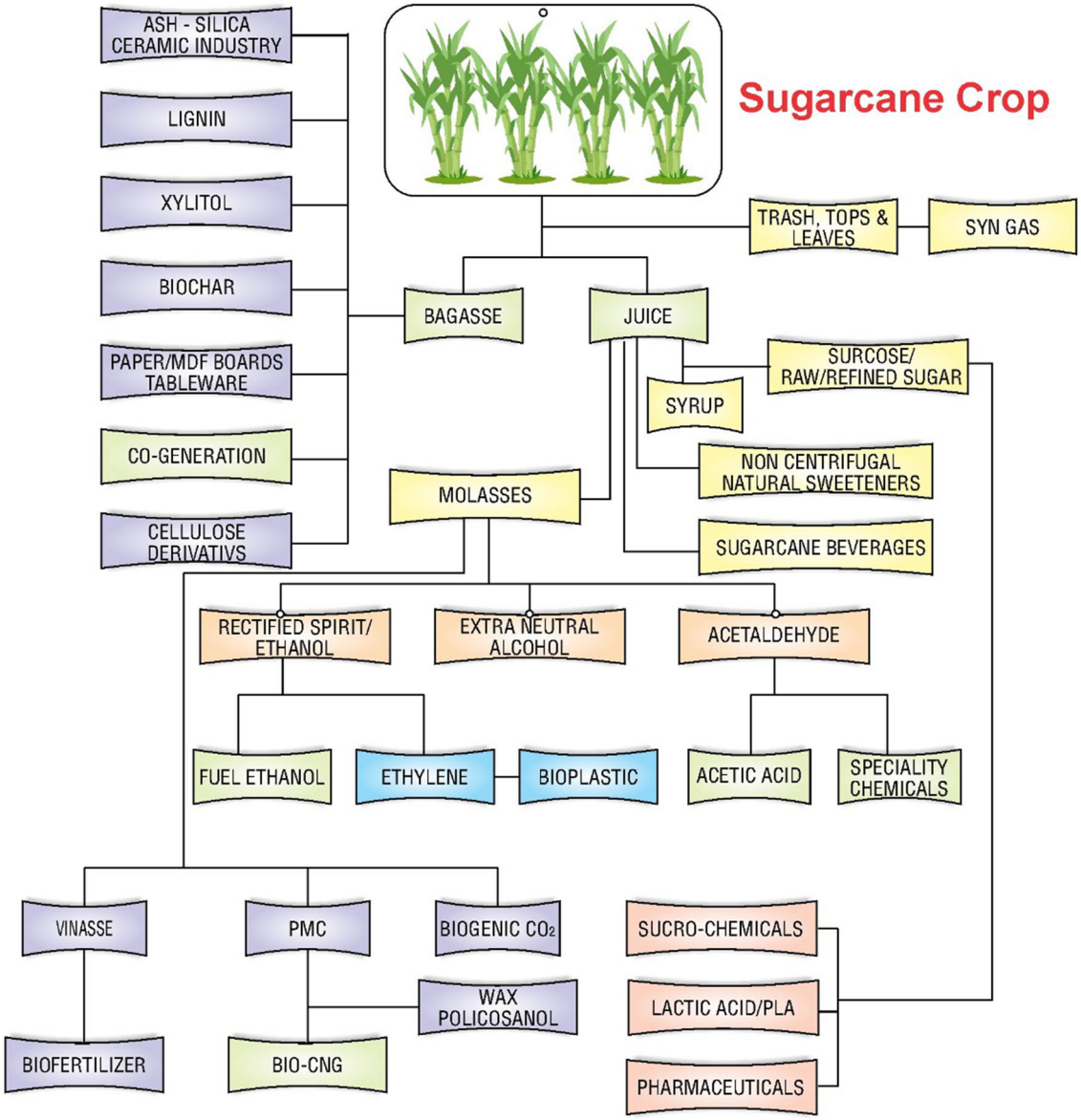

Fig. 1 Bio-refinery from sugarcane—options for Indian sugar industry

There have been investigations related to carbon footprint of bioethanol and bioelectricity production from sugarcane. A comparison of carbon footprints from US sugarcane bioethanol and Brazil sugarcane bioethanol by Mekonnen et al. (2018) reported that the Brazil bioethanol from sugarcane has a smaller carbon foot print (38.5 kg CO_2 eq/MJ) than that of US corn bioethanol (44.9 kg CO_2 eq/MJ).

The carbon foot print of bioelectricity production from sugarcane bagasse was estimated to be 0.227 kg CO_2 eq./KWh compared to that of 1.660 kg CO_2 eq/KWh electricity from diesel (Carvalho et al. 2019). Here also, the main contributors of CO_2 in the sugarcane production process were concluded to be fertilizer applied and irrigation.

The Indian sugar industry has been making use of these strategies both in the field as well as the factory in an attempt to lower the carbon foot prints. Several incentives and directives are in place to facilitate such sustainable activities aimed at reducing the carbon-footprint from the sugar industry. Of late, in the state of Uttar Pradesh, the government has mandated a 33% of afforestation through adopting Japanese *Miyawaki* technique, which is expected to bring about a major curb in the carbon emissions (https://timesofindia.indiatimes.com/city/lucknow/uttar-pradesh-asks-industries-to-adopt-miyawaki-method-to-reduce-carbon-footprint/articleshow/87027089.cms). Such bio-

intensive production and management techniques, carbon sequestration, micro-irrigation practices, integrated nutrient and pest/disease management, green harvesting, product diversification and other energy efficient processing practices are all a part of our efforts towards a reduction in carbon footprints.

Indian Sugar Industry and the 2030 Agenda for Sustainable Development

The 2030 Agenda for Sustainable Development Goals and its 17 Sustainable Development Goals (SDGs), provide a visionary road map for all countries and stakeholders to strive for a world of sustainable prosperity, social inclusion and equality, while at the same time preserving the planet and leaving no one behind. It embraces three dimensions of sustainability—economic, social and environmental. In order to carry forward the common vision of a sustainable, peaceful and prosperous future, sugar industry is gradually transforming toward Self-reliance to Sustainability so it can leverage new opportunities created by global shifts in sugar production and trade due to Covid-19 pandemic, as well as new options of renewable energy (ethanol, electricity, CNG), and bio-based products (bio-plastics, biochemicals, wellness products) through bio-refinery concept (Table 3). The industry has taken necessary sustainability initiatives for all its key stakeholders, resources, environment and product development through various Government departments, agencies, NGOs, CSR, etc. Many companies are implementing ISO certification/BSI/Bonsucro Production Standard—a global, metric-based standard for improving the social, environmental and economic sustainability of sugarcane farming and sugarcane derived products. Such standards are useful in strengthening the sugar mill efforts to get its sugar cane suppliers to adopt sustainable farming practices while helping it to improve workplace safety and monitoring. This has greatly helped in empowering small holders to get better cane yields through bio-intensive sugarcane production technologies, better and efficient use of resources, recycling and value addition of products, and production & economic sustainability.

Farmer Sustainability

The Indian sugar industry has a vision to create sustainable value for the farmers by improving resource efficiency, revitalizing ecosystems and uplifting rural communities. In this regard, smallholder farmers face the challenges of low returns and therefore industry is committed to teach them techniques about new & alternative ways of income generation through enhancing cane productivity, entrepreneurship and intercropping. Experts from research institutes, KVKs and NGOs share knowledge and expertise in sustainable agriculture practices in sugarcane cultivation, improved varieties, water management, biological control methods, bio-fertilizers, mechanization, marketing and pre- and post-harvest management of produce which limit any negative impact on the environment. Many progressive units also provide tools and training that make their farms more productive, efficient and profitable while preserving the long-term potential of their land for a sustainable livelihood.

Resource Sustainability

The *i*ndustry is committed and equipped to manufacturing products using bio renewable raw materials and then ensuring that the full value of raw materials is maximized. This starts with the planning of efficient manufacturing processes that enable economic sustainability for the sugar mills through higher product yields and environmental sustainability using fewer resources and low emissions and waste. All residues and co-products (bagasse, molasses, PMC and cellulosic residues) are used as feedstock for another value added product throughout the *value chain* (bio-fuels/bio-electricity/biochemicals/bio-plastic/pharmaceuticals/feed/fodder/paper/boards/moulded products).The spent wash generated in distilleries burnt in an incinerator boiler helps in meeting the steam and power requirements of the distillery. Additionally, the ash from the boiler is used to make bricks, further benefiting to reduce the environmental pollution and disposal problem & more importantly reduces the cost of construction. The rest of the spent wash is used in the manufacturing of bio compost by utilizing press-mud received from sugar mill (using aerotillers), thereby leading to zero liquid discharge.

Environmental Sustainability

Indian sugar industry have overcome various challenges to become second largest producer of sweeteners in the world, however, in process of doing so, significant negative impacts were inflicted onto the environment, *esp*. on to the water resources. To overcome these impacts and to promote sustainable practices, Central *Pollution Control* Board (CPCB) of India introduced a charter and environmental compensation plan for the sugar industries. The CPCB guidelines is being followed in all the sugar & distillery units which has resulted in significant reduction in freshwater consumption, effluent generation, and biochemical oxygen demand load. Besides, adoption of *rainwater harvesting* practices, recycling of PMC through biocomposting and CNG production, use of *sludge* for the purpose of filling low lying areas, and consumption of used

Table 3 Agenda 2030 for Sustainable Development—Contribution by the Indian sugar industry

S. No	Sustainable Development Goals	Size and current production potential of sugar industry	Contribution of Indian sugar sector to SDG Agenda 2030
1	SDG 1: No Poverty	Sugarcane Area (M ha): 5.2	Directly or indirectly impacts the livelihood of over 5 crore farmers and their dependents and 0.5 million workers in sugar mills and another 1.0 million workers, through indirect means
		Livelihood and employment provision for > 5 crore farmers	Employment generation in various ancillary activities relating to transport, trade servicing of machinery and supply of agriculture inputs
		Engage 7.5% of rural population	Instrumental in eradicating poverty and uplifting rural communities
2	SDG 2: Zero Hunger	Number of sugar mills installed (2019–2020)	Produce 30–35 MT energy-rich sweeteners annually
		Total: 751	Cane juice and non-centrifugal sugars and sugar products are important ingredients of food/energy for rural population
		Cooperative:330	Sugarcane agriculture facilitates intercropping with many cereals, vegetables, legumes and support small holders
		Private: 378	Encourages entrepreneurship ventures like mushroom cultivation
		Public: 43	
3	SDG 3: Good Health and Well-being	Sugarcane production (MT): 385	Green Technology /Bio-intensive sugarcane agriculture and reduced use of agro-chemicals through INM & IPM
		Sugar Production(MT): 30.9	Emphasis on Zero Liquid Discharge, Green fuel(s), Best Management Practices (BMP) in agriculture and clean drinking water contributing to better health of workers
		Jaggery Production (MT): 5.6	Medicinal and nutritional value of natural sweeteners obtained from sugarcane like cane juice, jaggery, syrups
4	SDG 4: Quality Education	Number of sugar mills in operation(2019–20): 532	Providing quality education in the rural areas
			Establish and support educational institutions for educating children of farm/ factory workers, women of nearby villages utilizing the CSR funds
5	SDG 5: Gender Equality	Number of sugarcane growers(Out growers model): 7 millions	Involvement of women in seed preparations, planting, intercultural operations, harvesting, etc.
			No discrimination in employing women in sugar mills/distilleries and integrated industries
			Regular seminars to sensitize their management related to issues of gender equality, social discrimination, etc.
6	SDG 6: Clean Water & Sanitation	Number of molasses based distilleries: 388	Use of water saving devices in farm, water recycling process in the mills
		Ethanol Production: 3.2 billion litres	Development of technology to produce potable water from cane, installing water purifiers in the mill premises, adequate sanitation facilities in cane yard and milling stations
			Mandatory usage of ETP and monitoring ground water quality
7	SDG 7: Affordable and clean energy	Co-generation/Bio-electricity units(bagasse based): 275	Expanded Green Energy base by utilizing bagasse, molasses, trash, PMC and effluents
		Co-generation capacity: 6500 MW	Approximately 50% sugar units are producing electricity from bagasse/trash, using high pressure boiler and bio-CNG from press mud
		Power exported: 4700 MW	Production of bioethanol and supporting EBP to meet the target of 20% blending by 2025
8	SDG 8: Decent work and Economic Growth	Contribution to national GDP: 1.1%	Commitment to attain long-term sustainability, integration of Environment
		Contribution for Government exchequer: over ₹12,000 crore/ annum	Health and Safety (EHS) initiatives with societal development and wealth creation of its stakeholders, especially farming community. Support over 12% of the rural population directly or indirectly
		Export of Sugar: 4.0 MT(in 2018–19) valued at US$ 1.36 billion	Major economic boost to ethanol, energy, paper, boards, pharmaceuticals and many ancillary industries
			Focus on effective management, innovation and decent work culture in farms and processing units

Table 3 continued

S. No	Sustainable Development Goals	Size and current production potential of sugar industry	Contribution of Indian sugar sector to SDG Agenda 2030
9	SDG 9: Industry, Innovation and Infrastructure	Annual turnover by the sugar industry: US$ 13 billion	Annual turnover exceed US$13billion. Farm implements and machinery suited for Indian small holders such as sugarcane planters, settling planters, FIRB, RMD, thumpers, etc., have been developed
			Leader in manufacturing of process machinery for sugar, ethanol, cogeneration, and effluent treatment plants
			Innovative technologies such as reduction in steam consumption, low temperature evaporation technology, use of syrup and B-heavy molasses for ethanol production, water saving in processing, etc., have contributed to the efficiency of industry
			Developed innovative ways and means to reduce the use of water in the growing of sugarcane, these initiative include trash mulching, alternate furrow irrigation, skip furrow irrigation, subsurface drip irrigation, and transplantation of sugarcane settlings, saving around 30–40% water as compared to conventional irrigation
			Geographic Information System (GIS) mapping tracks the latest satellite images of an area and lists the growth, vegetation and non-vegetation areas
10	SDG 10: Reduce Inequalities	Agro based paper mills 60 Open Pan/ Jaggery units: > 100,000	Industry as a potential source of sugar and many value added products The tremendous employment opportunities in India and abroad by these ancillary units
			Besides sugar, other sugarcane based potential sector viz., Jaggery, Paper, MDF board, alco-chemicals, etc., have created wealth and employment opportunities in developing countries
11	SDG 11: Sustainable cities and communities	Potential of bioethanol from molasses (2025–26): 684 crore litres Ethanol sold to OMC for EBP: 332 crore litres	Incentivization of sugar mills to produce bio-ethanol for EBP from molasses, B-Heavy molasses and cane juice to meet 20% blending target by 2025
			A saving of US $4 billion per annum for the country
		Sugar mill potential to supply ethanol for EBP (2025–26): 550 crore litres	Ethanol is a less polluting fuel, and offers equivalent efficiency at lower cost than petrol
			Provision of clean electricity in the household in nearby rural and urban areas from bagasse based bioelectricity /co-generation provides thus reducing the dependence on fossil fuels
12	SDG12: Responsible consumption and production	Annual national sugar consumption: 27.5 MT Per capita white sugar consumption (Kg)/annum: 19.5	Commitment to reduce C,N, water and energy footprints, lowering the cost of sugarcane & sugar production, enhanced C-sequestration through intercropping, green manuring & bio-fertilizers
			Sugarcane is well integrated in the cropping system(s) of tropical and sub-tropical India and support industry in 10 states. About 385 MT cane produced annually is a versatile source of food, fodder, feed and bio-based products, producing enough sweeteners for domestic consumption and export
			Improve farmers income and their welfare
13	SDG 13: Climate action	Average Sugarcane productivity (2015–2020): 76 tons/ha Highest sugarcane productivity (2015–2020): 99.70 tons/ha (Tamil Nadu)	Initiation of appropriate steps to minimize emission of greenhouse gases through increased C sequestration, green technology, residue and waste recycling, ZLD, and eco-friendly crop & product diversification
			New and improved climate smart/ resilient varieties and agro-technologies to boost productivity
			Significantly reduction in the use of water, agrochemicals and fossil fuel in sugarcane/sugar production-processing
			Created additional potential for revenue generation through sale of Certified Emissions Reductions (CERs) under the Clean Development Mechanism (CDM) of the Kyoto Protocol
			These transformative steps by sugar industry will greatly help in reducing the adverse effects of climate change

Table 3 continued

S. No	Sustainable Development Goals	Size and current production potential of sugar industry	Contribution of Indian sugar sector to SDG Agenda 2030
14	SDG 14: Life below water	Molasses production:13.78 MT (average 12–14 MT)	Conserving water by adopting various measures in all its operations and follow Zero Liquid Discharge (ZLD), strategies to maximize water recycling using latest technology
			Use of advanced wastewater treatment technologies to recycle, recover and re-use the treated wastewater thereby ensuring no discharge of wastewater to the environment or affect ground water quality
			The waste water treatment and other steps help in improving the quality of life below water for the under-water living organisms
			Treatment of process condensate and spent wash in a Biological Treatment Plant (BTP) and a Condensing Polishing Unit (CPU) to be re-used for process
15	SDG 15: Life on Land	Sugar Export Target (2020–21): > 6.0 MT	The sugar mills are continuously working in raising awareness among farmers to enhance sugarcane yield, use non-chemical /biological pest control and promoting use of bio-compost/biofertilizers
			Increased cane productivity and enhanced soil fertility with protection and preservation of environment from undue chemicals
			Committed to conserve all resources (specifically water and energy consumption) and biodiversity to ensure long term sustainability and minimization of environment footprint with due consideration to National & International protocols and business charters
			Helps in providing better returns to farming community. Implementation of rain water harvesting projects to conserve water and rejuvenate ground water by adopting ponds in the villages
			CSR activities focusing on priority areas like education of girl child, empowering women and communities, voluntary family planning services,
16	SDG 16: Peace, Justice and Strong Institutions	Sugarcane share in net area sown: 3.7%	Well-established linkages of the sugar mills with its local and global stakeholders to create a peaceful working atmosphere without any discrimination, social injustice and human right violation
		Value of output from crop sector: 4.2%	Promotes activities like educating and empowering women and communities, including ensuring access to voluntary family planning services through CSR
17	SDG 17: Partnership for the Goals	Sugarcane Production target (2030): 530 MT	The industry is progressive and well connected with the global sugar agro-industries and international societies like ISSCT, ASSCT, IAPSIT, WABCG, SASA, etc., for exchange of experts and technologies to enhance production efficiency and sustainability
		Sweeteners production target (2030): 52 MT	
		Average sugar recovery(2030): 10.75%	Even in the face of unprecedented challenges like COVID-19, with the lockdown and other restrictions, production, processing and export of sugar continued at normal pace due to the efficient co-ordination within the sector and with the other organizations
		(*Vision 2030, IISR, Lucknow*)	

oil with bagasse in boilers are other significant moves in the line of environmental sustainability and economical operation of sugar industries after the implementation of charter. The outcome of these initiatives has been very effective in minimizing the pollution load from sugar industries and in conserving the groundwater resources and promoting environmental sustainability. Our sugar mills and distilleries have adopted Zero Liquid Discharge (ZLD) system, an advanced wastewater treatment technology to recycle, recover and re-use the treated wastewater and effluent, ensuring no discharge of wastewater to the environment. Green energy sources like bio-ethanol, bio-electricity and bio-CNG are being promoted by Government of India through use of molasses, cane juice, bagasse, biomass and PMC. There are as many as 275 bagasse based power co-generation plants which are designed to meet their own power requirements as well as export the surplus power to grid, providing much needed power to the community and villages nearby. This process actually mitigates carbon emissions, and the industry earns Carbon Credits under the United Nations Framework Convention on Climate Change (UNFCCC).

Sustainable Valorisation

The sustainability strategy is an inherent part of sugar industry business plan and consistent with its commitment to contribute to the society. The sugar industry is an enabler of improved sustainability across value chains and manufactures many bio-based products through value addition. The industry is producing a range of renewable products that not only have lower environmental impact but also perform equivalent or superior to existing materials. The use of resources to make green power (bio-ethanol and bio-electricity), that also mitigate greenhouse gases, and the manufacture of biofuels and chemicals from ethanol also presents a model as to how a crop such as sugarcane can be used to make a host of valuable products, used in a variety of applications. Recent EBP of Government of India, where sugar industry is supplying a major chunk of ethanol shows that fossil fuels have an alternative and the green fuel produced from sugarcane is an examples of this model. The industry R & D is engaged in developing innovative ways for further valorizing residual biomass by cascading which includes the recovery of silicon from bagasse ashes, production of bio-plastic and bio-fertilizer, and valorization of biogenic CO_2 sources.

Social Sustainability

All the key stakeholders directly involved in sugar value chains viz., farmers, farm workers, sugar mills, cane societies, Cane Development and Sugar Industry Departments, companies buying sugar, civil societies and trade unions are directly or indirectly associated with the sugar units of their area. Sugarcane production in the command area is the direct responsibility of cane development department wherein a large number of farmers including women farmers are associated. Sugar mills operate many technology-enabled cane collection centres across the villages and provide convenient transportation and logistics to the farms of the partner farmers, so that the agricultural produce can be transported with ease and no added costs are incurred by the farmers. This service enables farmers to concentrate on their production activities while the industry take care of the aggregation of their agricultural produce. The harvested sugarcane is subsequently transferred to the manufacturing and processing units. The sugar mills are responsible for taking care of the farming community as per the Companies Act, 2013 by implementing CSR policy. The CSR activities of sugar mills are focused on different sectors with main emphasis on promotion of education, skill development, health care and preventive healthcare, gender equity and empowering women (Solomon et al. 2019). During Covid-19 pandemic, the industry has worked closely with government hospitals, schools, police stations and other establishments to assist in the fight against the pandemic. Many mills had arranged sanitizers, facilitated company ambulance for shifting affected patients, arranged for RT-PCR/random tests and provided other required services.

Conclusion

The global markets are in a transition phase with a relentless drive to improve the efficiency along with sustainable development. Rapid growth and growing prosperity has created an increase in demand for all the resources, including food, feed and energy. A lion-share of this demand is invariably coming from the Asian countries, with the fast growing economies like India poised to take a quantum leap with respect to economic growth. Thus, the Asian countries and the South East Asian region as a whole, are the leading players in driving the global economic growth. With a fast developing economy, the demand for food, fuel, feed and other products and resources will be more, which necessitates an increase in availability of these resources. This calls for a judicious utilization of resources along with the need for self-reliance. The unforeseen challenges like the ongoing pandemic also offer ample scope to restructure the industry with a minimum level of dependence on other sources with collaborations and linkages to strengthen the self-sufficiency. The sugar industry is a perfect example of an emerging sustainable system with ample avenues to become self-reliant. The innovative technologies in the sugarcane and sugar production system along with the scope for diversification has made the global as well as the local sugar industries, the flag bearers of the concept of sustainability and profitability with self-reliance. This is evident from the remarkable growth of the Indian sugar industry from the early 30 s till date and its transformation into a major sugar producing nation with a strong global presence. The Indian sugar industry in particular, is far ahead in this journey and has the potential to lend a helping hand to the sugar producing countries of the region so that the sugar industry in the Asia and South East Asian Region can be trailblazers in their march towards a self-reliant, sustainable, bio-based economy.

For the Indian sugar industry, this journey towards self-reliance and sustainability is a continuous one, taking along with it the various stakeholders, investors, employees and

other clientele, for the welfare and economic prosperity of the overall community.

Declarations

Conflict of interest Authors declare that they have no conflict of interest.

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