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Carbon Footprint Analysis of Sugarcane Syrup-derived Ethanol Production in an Indian Distillery

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***Abstract*: This study presents a cradle-to-gate assessment of the carbon footprint (CFP) of an ethanol distillery utilizing sugarcane syrup (70° Brix) as the primary feedstock. The evaluation encompasses greenhouse gas emissions from cultivation, fermentation, distillation, dehydration, and associated operations. The total CFP was estimated at 4.42 kg CO_2eq per liter of ethanol, including biogenic carbon, and 1.48 kg CO_2eq/L when excluded. The incineration boiler—used to combust concentrated spent wash and bagasse—emerged as the largest emission source (2.18 kg CO_2eq/L). Fermentation contributed 0.755 kg CO_2eq/L, primarily from biogenic CO_2, while sugarcane cultivation accounted for 0.7 kg CO_2eq/L, based on an emission factor of 55 kg CO_2eq per ton of cane. Additional emissions were associated with electricity use in distillation (0.0375 kg), molecular sieve dehydration (0.0101 kg), multi-effect evaporation (0.5487 kg), and CO_2 capture operations (0.0934 kg CO_2eq/L). Transport-related emissions remained below 0.01 kg CO_2eq/L. The study identifies emission hotspots and proposes mitigation strategies, including the adoption of hybrid pumping systems, renewable energy integration, and CO_2 valorization. These findings contribute to the development of carbon intensity benchmarks and support India's ethanol sector in achieving decarbonization goals in line with Sustainable Development Goal 7, particularly targets 7.2 (renewable energy share) and 7.3 (energy efficiency). The results further underscore ethanol's potential as a scalable and economically viable clean energy alternative within India's transition framework.**

Keywords: CO_2eq, distillery, Green Economy, Incineration boiler, Sustainable development goals

I. INTRODUCTION

Climate change is now recognized as one of the most critical challenges facing humanity, driven largely by rising concentrations of greenhouse gases (GHGs) in the atmosphere. Global climate frameworks such as the Kyoto Protocol, 1997, and the Paris Agreement, 2015, have emphasized the need for immediate and scalable emission reduction strategies. However, despite such efforts, global carbon emissions remain on the rise, especially in emerging economies such as India, where energy demand and agricultural intensity continue to increase [1]. The COVID-19 pandemic led to a brief decline in emissions due to limited transportation and industrial operations, yet post-pandemic recovery has reignited economic activity, causing emissions to rebound [2,3]. This scenario highlights the pressing need to transition towards a green economy, which aims to foster economic growth while reducing environmental risks and ecological scarcities [4]. In this context, bioethanol production from renewable agricultural feedstocks represents a key intervention point. As a cleaner-burning alternative to fossil fuels, ethanol has the potential to reduce carbon emissions when produced sustainably. India, being the second-largest producer of sugarcane, plays a pivotal role in this transition through its Ethanol Blending Program (EBP). Under this initiative, traditional molasses-based distilleries are now shifting toward direct juice or syrup-based ethanol production, aligned with the green economy principles of resource efficiency and low-carbon growth [5]. Despite policy support, there is a noticeable gap in quantifying the carbon footprint (CFP) associated with syrup-based ethanol distilleries in India. Emissions in such systems originate from multiple stages, including sugarcane cultivation, syrup extraction, energy-intensive distillation, and transportation. For instance, per hectare GHG emissions from sugarcane fields are estimated at 4273 kg CO_2-eq ha^{-1}, contributing to an annual total of 1616.53 thousand tons CO_2-eq in India [6].

Furthermore, with over 95% of India's electricity still coal-based, the energy consumption of ethanol plants becomes a major source of emissions [1]. According to the All-India Distillers Association, 2024 [7], 392 distilleries are now operating with diverted cane syrup (≥70° Brix) under government guidelines. However, variations in feedstock quality, energy sources, process design, and technology adoption cause substantial variability in plant-wise carbon footprints [8]. This assessment of the CFP of distilleries directly aligns with the United Nations Sustainable Development Goals (SDGs), particularly: SDG 7: Affordable and Clean Energy, SDG 9: Industry, Innovation, and Infrastructure, SDG 12: Responsible Consumption and Production, and SDG 13: Climate Action. Accurately assessing these emissions is vital not only for improving process sustainability but also for integrating Indian ethanol production into global carbon credit markets, thereby strengthening the green economy narrative. Moreover, such evaluations can guide the development of low-carbon technologies, resource-efficient supply chains, and eco-friendly policies aligned with India's National Action Plan on Climate Change (NAPCC). Hence, this study aims to provide a comprehensive carbon footprint assessment of bioethanol production from high Brix cane syrup, offering insights into its environmental impacts and potential for decarbonization under green economy frameworks

II. MATERIALS AND METHODS

The distillery under evaluation for CO_2-equivalent emissions has a production capacity of 131 kiloliters of ethanol per day and is located in the Lakhimpur Kheri district of Uttar Pradesh, India. It operates for 320 days annually, including production from molasses, with approximately 45 days allocated for maintenance. In compliance with the Central Pollution Control Board (CPCB) norms, the distillery maintains zero liquid discharge by recycling water through its in-house treatment facilities. Besides its primary output of bioethanol, the distillery also generates spent wash, which is processed into slop for combustion in the incineration boiler to produce energy, as well as fermented sludge used for composting and rectified spirit as a by-product [9]. The data used for the Carbon Footprint (CFP) assessment includes several parameters: energy consumption during ethanol production, steam usage in the manufacturing process, quantity of raw materials utilized, direct CO_2 emissions from fermentation, and the quantity of yeast and chemicals added to enhance fermentation (e.g., urea, diammonium phosphate, magnesium salts). Additionally, the fuel (gasoline) consumed by vehicles used for employee transport and ethanol delivery to depots has been accounted for. It is important to note that emissions from the Condensate Polishing Unit (CPU) are excluded from this analysis. The carbon footprint is expressed in terms of CO_2-equivalent emissions per liter of bioethanol produced. The general procedure followed by the distillery is given in Figure 1.

Measurement of carbon footprint

The Carbon Footprint (CFP) analysis was conducted in accordance with the IPCC 2006 guidelines [10], while the energy consumption related to bioethanol production was assessed using the Life Cycle Assessment (LCA) methodology. The study adopts a cradle-to-gate boundary, encompassing all stages from raw material acquisition to final ethanol production and storage. According to the IPCC framework, greenhouse gas (GHG) emissions are classified under three scopes. Scope 1 includes direct emissions from sources owned or controlled by the distillery, such as internal combustion vehicles and emissions from incineration boilers. Scope 2 captures indirect emissions associated with the use of externally supplied electricity and steam. Scope 3 encompasses all other indirect emissions that occur in the value chain, including those from upstream agricultural operations and downstream product distribution. Emission factors used for CFP calculations were derived from region-specific literature and databases. The CFP for each operational segment was estimated by multiplying these emission factors by the corresponding activity data. Direct carbon dioxide emissions were calculated from known stoichiometric conversions in bioethanol fermentation. Other emissions, such as SO_2, though formed in trace quantities, were considered negligible and excluded from calculations. Steam consumption was included as a critical factor in both fermentation and distillation processes. During fermentation, steam was employed for sterilizing vessels, pre-fermenters, and fermenters. In distillation, high-pressure steam was utilized for ethanol separation, whereas low-pressure steam was used in multi-effect evaporation units to concentrate spent wash into slop. Chemical inputs such as crotonaldehyde, used for denaturing ethanol as per excise standards, were also accounted for. The scope of this cradle-to-gate study spans sugarcane cultivation, harvesting, syrup extraction, fermentation, distillation, dehydration, and ancillary operations, along with upstream and downstream logistics. It is broadly segmented into two stages: (i) material acquisition and preprocessing, and (ii) ethanol production. Special attention was paid to quantifying energy inputs and GHG outputs at each stage, contributing toward a holistic carbon accounting system for renewable energy integration in alignment with SDG 7. To facilitate better understanding, the system boundary considered in this study is illustrated in the accompanying Figure 2.

Material Acquisition and Pre-processing

The bioethanol production process at the reported distillery begins with the cultivation of sugarcane, which serves as the primary feedstock. Once matured, the sugarcane is harvested and transported to the sugar factory, where it is crushed to extract juice. This juice is subsequently concentrated in a multi-effect evaporator, reaching a Brix value of approximately 70 after passing through four stages of evaporation. The resulting high-Brix syrup is then transferred to the distillery through a pipeline system equipped with a mass flow meter to monitor the exact volume entering the ethanol production facility. The analysis specifically excludes the transportation of sugarcane from farms to the mill, as it has already been comprehensively covered in a previous carbon footprint study of the sugar sector [11]. However, upstream emissions associated with the delivery of dry yeast to the distillery are included, particularly those arising from gasoline-based transportation. Although wastewater generated during processing is recycled using an independent condensate polishing unit (CPU), its associated carbon footprint is beyond the current study's boundary and is proposed for separate analysis. In the fermentation section, both electricity and steam are extensively utilized. Steam is required for sterilization and various thermal processes, while electricity powers equipment such as pumps, agitators, and control systems. Additionally, a range of chemicals is introduced during fermentation to optimize yeast activity and ethanol yield. These energy and material inputs contribute significantly to the total carbon footprint during the preprocessing and conversion stages.

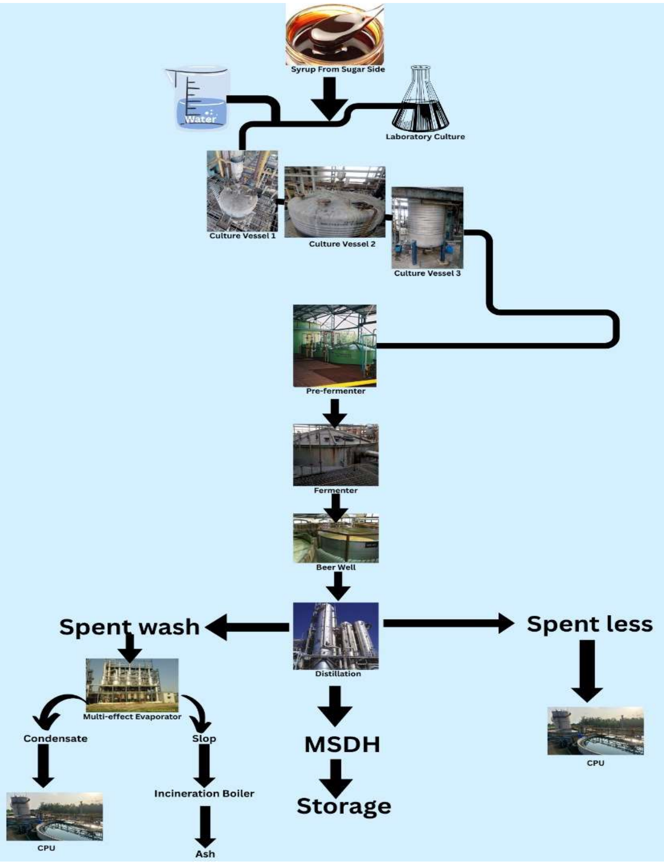

Fig. 1 Process flowchart for the production of Bio-ethanol from syrup

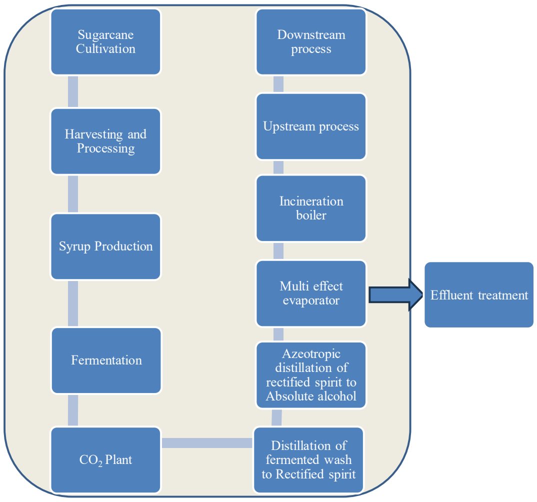

Fig 2. Study Boundary for CFP of the distillery

Ethanol Production

The ethanol production phase relies heavily on electricity and steam. Electrical energy is used across multiple units, including pumping systems, lighting, filtration, vacuum pumps, and process instrumentation. Steam is primarily consumed during the distillation process, where ethanol is separated from the fermented wash. This step also includes the concentration of the residual spent wash to form slop, which is later incinerated in a boiler. The incineration process not only manages waste but also contributes to internal electricity generation, albeit while releasing various combustion gases, thereby influencing the overall carbon footprint. Biogenic CO_2 emissions occur at two distinct points in the system: first, during sugarcane cultivation, and second, from the fermentation process itself. The direct CO_2 emitted from fermentation is of biogenic origin and is therefore treated distinctly under the IPCC guidelines. Prior to multi-effect evaporation, a pre-treatment step is implemented to separate suspended solids from spent wash. This solid-liquid separation enhances the operational efficiency and longevity of the evaporator unit but adds to the energy demand and, consequently, the carbon footprint. During distillation, the ethanol-rich fraction is separated from water, and the condensate is routed to the central processing unit for additional treatment. The distillation column itself, being energy-intensive, is a major contributor to the facility's energy and emissions profile. In the post-production stage, ethanol is stored in designated tanks. These storage units are equipped with electrically operated pumps that further add to the facility's energy consumption. The energy and emission contributions from these auxiliary systems are included within the cradle-to-gate boundary to ensure a holistic estimation of the process-related carbon footprint. This combined cradle-to-gate assessment framework enables a detailed understanding of emissions and energy consumption associated with each phase of bioethanol production. The approach is in alignment with SDG 7, promoting cleaner energy alternatives through transparent carbon accounting and resource efficiency. Following distillation, waste generated from the process is managed through incineration in a specially designed boiler. This step not only helps in reducing the waste load but also enables partial energy recovery by utilizing the heat released during combustion. Finally, both upstream and downstream processes contribute to the system's cumulative environmental burden. Upstream processes include the supply of raw materials and chemicals, while downstream activities involve product handling, storage, and utilities. Together, these stages form an integral part of the cradle-to-gate life cycle assessment.

Sugarcane cultivation

According to previous studies, it has been reported that the production of every ton of sugarcane results in the release of 55 kg of CO_2 equivalent into the environment [12]. The analysis of sugarcane syrup revealed a Brix value of 70 degrees. Data from the factory indicates that, on average, one ton of sugarcane yields 700 liters of juice with a Brix level of 16 degrees. Therefore, when calculating for syrup with a Brix of 70 degrees, one ton of cane produces approximately 160 liters of cane syrup. Furthermore, it is noted that 3640 quintals, equivalent to

364 tons of cane syrup, are required to produce 131 kiloliters of ethanol daily. By converting 364 tons into liters, using the density of cane syrup at 1.35, the resulting volume is 269,629 liters of syrup.

CPF by sugarcane = Quantity of sugarcane x Emission factor

Fermentation

The fermentation process in this study involves the microbial breakdown of fermentable sugars present in the sugarcane syrup. These sugars—primarily glucose and fructose—undergo anaerobic fermentation to yield ethanol and carbon dioxide in a 1:1 molar ratio. Based on stoichiometric calculations, one mole of glucose (180 g/mol) yields two moles each of ethanol (46 g/mol) and CO_2 (44 g/mol). Considering the density of ethanol as 0.789 kg/L, the theoretical carbon dioxide emission was determined to be approximately 0.755 kg of CO_2 per liter of pure ethanol. The ethanol produced in the distillery was analyzed in the quality control laboratory and found to possess 99.89% purity, ensuring precise quantification of emissions from this unit process.

Chemicals used in the fermentation section

In the fed-batch fermentation process of cane syrup, various chemicals are incorporated as micronutrients to promote optimal yeast growth and enhance the efficiency of bioethanol production. The selection and application of these chemicals are based on established industry practices. Emission-related data associated with the use of these chemicals have been sourced from relevant scientific studies to support the life cycle inventory and carbon footprint assessment conducted in this work.

TABLE 1
Chemical dosing in the Fermenter

Fermenter Dosing	Quantity	Emission factor	Process value (kg CO_2 eq)	Ref
1st Dosing				
Urea	100 Kg	0.2Kg CO_2eq /Kg	20	[a]
Zinc Sulphate	6.0 Kg	3.8 kg CO_2eq / kilogram	22.8	[13]
Magnesium Sulphate	6.0 Kg	0.18kg CO_2eq /kg	1.08	[14]
2nd Dosing (75/80 m3)				
Urea	100 Kg	0.2Kg CO_2eq /Kg	20	[a]
3rd Dosing (At Set up)				
Urea	100 Kg	0.2Kg CO_2eq /Kg	20	[a]
4th Dosing (After Set up)				
Urea	50 Kg	0.2Kg CO_2eq /Kg	10	[a]

[a] IPCC default Carbon footprint factor

Yeast Production

For the production of bioethanol from cane syrup, the distillery employs 100% dry yeast, which is more economically feasible compared to cultivating yeast cultures in vessels using additional raw materials. The dry yeast is directly added to the pre-fermenter, which contains water and syrup with a sugar concentration of 8–10%. A total of 30 kg of dry yeast is utilized daily for producing 131 kiloliters of ethanol. The emission factor for dry yeast, based on consumption, is 3.373 kg CO_2-equivalent per kilogram, as reported by [15]. The CFP is calculated by the following equation.

Emissions Factor = Yeast as dry matter X 3.373 Kg CO_2eq /kg consumption of yeast

Distillation section

The fermented wash is distilled under the distillation section, which consists of seven columns that are operated by direct high-pressure steam and 8 bodies of multi-effect evaporator operated by low-pressure steam. The distillation section consist of two section the first section contains columns i.e. analyzer column from where first distillate came out having 55% strength of alcohol and residue known as spent wash is fed to Multi effect evaporator which concentrate it to make slop having brix of 55-60 burned in the incineration boiler, rectified spirit column which rectify the 55% pure ethanol to 95%, the second section have the MSDH body and MSDH bed, in MSDH body the 95% pure ethanol is converted into superheated steam and fed to MSDH bed which works on the principle of adsorption and convert the 95% of ethanol vapors into 99% to make t suitable for blending with gasoline. All these columns have suction pumps, vacuum pumps, and other types of pumps operated by electricity. The electricity consumption by these two sections is mentioned in the energy footprint. The CO2eq of direct steam is not considered, as the steam used in the distillery comes from the incineration boiler, which generates its energy by incinerating the slop with Bagasse. The CO2eq by the incineration boiler is calculated separately as per IPCC guidelines.

CO2eq due to the Incineration boiler

The spent wash that came out of the analyzer column is concentrated with the help of a multi-effect evaporator to 55-60 ° brix, and then it is burned in the incineration boiler for energy conversion with other material called Bagasse, which is also a byproduct of the sugar industry. The incineration boiler installed has having capacity of producing steam 80TPH, with having pressure capacity of 45 kg/cm2, the boiler is a travelling grate type. The slop is fed to the furnace at the rate of 34TPH, and the Bagasse at the rate of 10TPH. As per **[16],** the emission of CO_2eq by burning one ton of Bagasse for producing energy is 0.1160/ton of Bagasse. So, per day CO_2eq due to burning of Bagasse is 27.84-ton CO_2eq or 278840 kg CO_2eq (alone from Bagasse). The slop is burned at the rate of 34 TPH, as per the IPCC guideline, the calculation for the CO_2eq. Of slop is as follows

As per the IPCC guideline:

CO_2 EMISSION FROM INCINERATION OF LIQUID WASTE

$$CO_2 \text{ Emissions} = \sum(AL_i \bullet CL_i \bullet OF_i) \bullet 44/12$$

Where:

CO2 Emissions = CO2 emissions from the incineration of fossil liquid waste,
ALi = amount of incinerated fossil liquid waste type i,
CLi = carbon content of fossil liquid waste type i, (fraction)
OFi = oxidation factor for fossil liquid waste type i, (fraction)
44/12 = conversion factor from C to CO2

Upstream transportation/indirect emission

The syrup was pumped directly to the distilleries; hence, no transportation is needed, but the yeast and other chemicals used in the fermentation are considered. Dry yeast is coming to the distillery from Delhi, and the distillery is 501km away from it. Taking the average fuel consumption of trucks, i.e.10km/l of diesel, the fuel consumption is 50.10 liters, so the CPF from it is 3.6 x 50.10= 180.36 kg CO_2eq for 500 kg of dry yeast

CFP by the Downstream Process

The distillery stores the ethanol in the storage section, from where it is transported to the different depots of refinery companies. The distillery has tenders from the companies HPCL, BPCL, and IOCL. These companies have different depots located in various parts of India. As per excise data, the ethanol is transported to Kanpur-U.P India, Banthra-Unnao U.P., Meerut U.P., India, Gwalior-M.P. India, Bhopal, M.P., India, and Indore, M.P., India.

TABLE 2
Distance covered in product delivery

Place	Distance(Km)	Average(Km)
Kanpur	180	580
Banthra	170	
Meerut	400	
Gwalior	300	
Bhopal	800	
Indore	850	
Paradip	1380	

Energy Footprint

The electricity consumption of the distillery can be differentiated in 10 parts based on use in the different section-fermentation, distilling rectified spirit, redistilling rectified spirit to ethanol of 99.89% pure(absolute alcohol), Multi effect evaporator for concentrating the spent wash, Boiler and TG, Dry ice plant, Firefighting and other utility consist of the power consumed in the taking syrup from the sugar factory etc. the emission factor for calculation of CFP by electricity consumption is taken from the table given in the [12]. Descriptive statistical evaluation was conducted to assess the variability and consistency of energy consumption across different process units during November 2024. The overall mean consumption across all sections was 110,516 units/day, with a standard deviation of 6,402 units and a coefficient of variation (CV) of 5.79%, indicating moderate day-to-day variation. Among individual units, Boiler, TG, and Distillery Utilities demonstrated the most stable energy profiles, with CVs of 2.92% and 2.35%, respectively. Core production units such as Fermentation (CV: 6.56%), MEE (CV: 5.23%), and Rectified Spirit (RS) (CV: 7.33%) showed acceptable operational consistency. However, the CO_2 Plant recorded a markedly higher variability (CV: 42.93%), pointing to irregular energy demand, potentially due to intermittent operation. Lower-load areas like Lighting and Fire Fighting exhibited relatively high CVs due to their small base consumption. These findings highlight areas for energy optimization, particularly where high variance suggests potential inefficiencies or inconsistent operations. To further quantify inter-sectional differences, a one-way analysis of variance (ANOVA) was performed. The test revealed statistically significant variation in mean energy consumption across sections ($F = 4033.11$; $p < 0.001$), confirming that operational units differ markedly in their energy demands. This supports the need for tailored energy optimization strategies based on section-specific requirements

TABLE 3
Statistical analysis of one month of data on electricity consumption

Section	Mean Energy Use	Standard Deviation	Coefficient of Variation (%)
Total	110516	6389.24	5.78
Boiler and TG	43503	1270.12	2.92
Fermentation	13937	838.15	6.01
CO2 Plant	15116	6490.72	42.93
MEE	8926	472.64	5.29
RS	6651	420.22	6.32
CPU	3209	442.57	13.79
Fire Fighting	351	23.45	6.68
Distillery Utilities	19259	453.06	2.35
Lighting	299	26.03	8.71
AA	1675	163.67	9.77

Fermentation section- the fermentation section consist of six fermenters each fermenter is having agitator, two pumps, digital level indicator, resistance temperature detector, mass flow meter for water and syrup, load cell, flow meter at load cell instruments connected to it for showing data in PLC room, lightening lamps, beer well having two pumps for transferring the fermented wash to the distillation section, beer well agitator and plate type heat exchanger in each fermenters. All this equipment consumes electricity. Sections per day consumption is noted down for a month, and the average is calculated, which is 10128 kWh/day, taking the emission factor from table 1, i.e., 0.81kg CO_2eq $kWh^{-1,}$ multiplying it

CFP by the fermentation section on energy consumption
=10128 x 0.81
=8203 CO2eq
= 0.07731 Kg CO2eq /liter

Distilling Rectified spirit- The fermented wash from fermentation section is pumped to the distillation first column known as analyzer column which consist of pumps, sealing pumps, level indicator, temperature detector, flow meters of fermented wash feed, flow meter of spent wash, flow meter of condensed product and from here the separated alcohol of 55% strength is fed to rectified spirit column where all instrument describe earlier is installed consumes electricity. The one-month data of electricity consumption is collected, and an average of 6079 kWh of electricity is consumed per day for the production of 138 KL of Rectified spirit having 95% alcoholic strength. It produces 4924 CO_2eq per day. 0.0375 kg CO_2eq /liter of ethanol. From RS (rectified spirit) to AA (Absolute alcohol)_– to produce the absolute alcohol of strength above 99%, it is necessary to remove water content from rectified spirit. For this, the distillery is using a molecular sieve dehydration system, which works on the principle of adsorption [17]. For this, the above-mentioned instruments are used in the same way, but the operating method has changed. The average of one month of data has been taken, which is 1646 kWh/day; its CFP is 1333 CO_2eq.

=0.0101 CO_2eq /liter of ethanol

Multi-effect evaporator_– the distillery has a total of 8multi-effectt evaporators, in which 4 are falling film type and four forced circulation type. At one time, 6 were in operation, and two were under CIP. The energy consumption for it is 8876 x 0.81, i.e., 7189 CO_2 eq or 0.5487/liter of ethanol.

CO_2 plant- the distillery has one CO_2 plant, which converts the CO_2 gas into dry ice. Its electricity consumption and its CFP given to the environment are as follows

Average consumption of CO_2 plant is 15116 x 0.81= 12243 CO_2eq or 0.09345/liter
Firefighting and lighting of the distillery

The total of the two units' averages yielded a CFP of 1051 CO_2eq, which is converted to per liter of i.e., 0.008022 Kg.

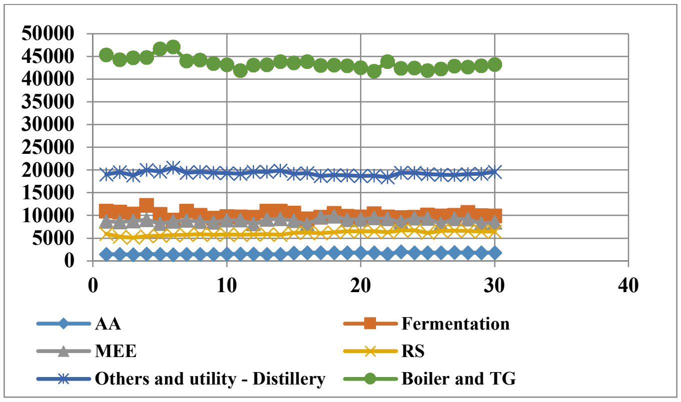

Fig. 3 Electricity consumption of different unit operations for one month

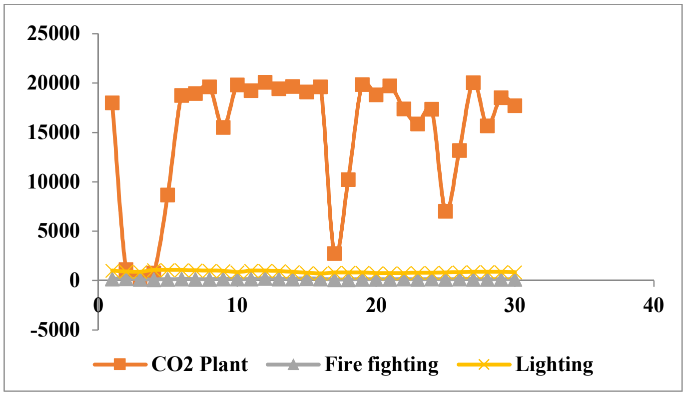

Fig. 4 Electricity consumption of different unit operations for one month

TABLE 4
Emission factor of different products

Sr. No.	Resources	Carbon emission		Energy Input/output	
1.		Emission factor	Unit	Energy factor	Unit
2.	Diesel	3.6	kg CO_2eq L-‘diesel	56.31	MJ L-1
	Fertilizers				
	N	6.69	kg CO_2eq kg-1	56.30	MJ ha-¹
	P2O5	0.71	kg CO_2eq kg-1	7.50	MJ ha-¹
	K2O	0.46	kg CO_2eq kg-1 K2O	7	MJ ha-¹
3.	Water	0.000086	kg CO_2eq kg-1Water	0.00036	MJ ha-¹
4.	Electricity	0.81	kg CO_2eq kWh	11.93	MJ ha-¹
5.	Trash				
6.	CH4	0.0027	kg CH_4 kg-1 trash	-	-
7.	N2O	0.00007	kg N_2O kg-1 trash	-	-
			Output resource		
1.	Sugarcane/ Sugar	0.017	kg CO_2eq kg-1 sugar	5.3	MJ ha-¹
2.	Trash	-	-	15	MJ ha-¹

III. RESULTS AND DISCUSSION

Carbon Footprint from Sugarcane Cultivation (Cradle Stage

The cradle-to-gate assessment identified sugarcane cultivation as one of the major contributors to overall emissions. To sustain a daily ethanol output of 131 KL, approximately 364 metric tons of sugarcane syrup were required. Considering the syrup density of 1.35 g/cm³, the calculated daily volume was 269,629 L. To obtain this volume, nearly 1,685 metric tons of sugarcane were required, based on a syrup yield of 160 L per ton of cane at 70° Brix. Using an established emission factor of 55 kg CO_2-eq per metric ton of cane, the carbon footprint attributable to cultivation was 92.7 t CO_2-eq per day. When normalized to ethanol output, the agricultural stage contributed 0.70 kg CO_2-eq/L of ethanol, emphasizing the need for sustainable farming practices to support SDG 7 goals.

Fermentation-Related Emissions (Biogenic and Chemical Inputs)

Fermentation contributed substantially to industrial emissions. The microbial conversion of fermentable sugars resulted in 98.9 t CO_2-eq/day, classified as biogenic CO_2. Additional emissions were associated with chemicals used for fermentation efficiency. For a fermenter capacity of 910 m³ producing 122,850 L ethanol at 13.5% v/v, chemical inputs contributed 93.88 kg CO_2-eq, equivalent to 0.000764 kg CO_2-eq//L. Yeast addition (30 kg/day; emission factor 0.360 kg CO_2-eq/kg) resulted in a further 0.0000879 kg CO_2-eq/L. Although individually small, these emissions collectively form a significant component within the material acquisition and processing stage.

Boiler and Slop Incineration Emissions

The boiler system emerged as the most carbon-intensive unit. Approximately 35 t/h of slop were incinerated, with laboratory tests indicating 22% carbon content and 8% retention in fly ash. The computed oxidation factor enabled accurate estimation of released CO_2. Combined emissions from slop and auxiliary bagasse firing amounted to 11.94 t CO_2-eq/h. Over 24 hours, the boiler generated 286.56 t CO_2-eq/day, corresponding to 2.187 kg CO_2-eq per Liter of ethanol. This makes the boiler the dominant point source in the industrial phase, highlighting the necessity for improved combustion efficiency or alternative renewable fuels.

Emissions from Transportation Logistics

Annual ethanol production (41,920 kL) required approximately 1,677 tanker trips of 25,000-L capacity each. With an average distance of 580 km and diesel consumption of 10 km/L, annual diesel usage was 97,266 L. Using an emission factor of 3.6 kg CO_2-eq/L of diesel, the transportation footprint was 350.16 t CO_2-eq/year, equivalent to 0.00835 kg CO_2-eq/L. Although comparatively low, these emissions remain relevant to cradle-to-gate reporting.

Electricity-Related Emissions Across Industrial Units

Fermentation Section

The fermentation section included six fermenters equipped with instruments such as agitators, pumps, flow meters, sensors, and PLC systems. Average electricity consumption was 10,128 kWh/day, contributing 8.2 t CO_2-eq/day or 0.077 kg CO_2-eq/L.

Distillation Section

Analyzer and rectified spirit (RS) columns consumed 6,079 kWh/day, corresponding to 4.9 t CO_2-eq/day or 0.0375 kg CO_2-eq/L.

Molecular Sieve Dehydration (MSDH)

The MSDH system consumed 1,646 kWh/day, contributing 1.3 t CO_2-eq/day, equivalent to 0.0101 kg CO_2-eq/L.

Multi-Effect Evaporator (MEE)

The MEE system (six operational evaporators) used 8,876 kWh/day, generating 7.2 t CO_2-eq/day. This corresponds to 0.5487 kg CO_2-eq/L, making it the highest electricity-related contributor.

CO_2 Recovery Plant

The CO_2 recovery unit consumed 15,116 kWh/day, contributing 12.2 t CO_2-eq/day or 0.0935 kg CO_2-eq/L.

Auxiliary Utilities

Additional systems (lighting, fire-fighting pumps, general utilities) contributed 1.05 t CO_2-eq/day, equivalent to 0.008 kg CO_2-eq/L.

Comparative Emissions: Material Acquisition vs. Production Phases

Material acquisition and processing—including cultivation, fermentation, chemicals, and yeast—contributed a total of 1.456 kg CO_2-eq/L of ethanol. The fermentation section formed the largest share, contributing 0.775 kg CO_2-eq/L, as shown in Table 6. On the production side, emissions were dominated by the incineration boiler, contributing 2.18 kg CO_2-eq/L, as summarized in Table 7. Electricity-related emissions from various unit operations amounted to 0.775082 kg CO_2-eq/L (Table 8), with the MEE unit alone contributing 0.5487 kg CO_2-eq/L.

Accounting for Biogenic Carbon and Net Carbon Footprint

Biogenic CO_2 was primarily released during fermentation and slop incineration. Since this carbon originates from biomass and is reabsorbed during sugarcane growth, its exclusion provides an adjusted perspective of environmental burden. When biogenic CO_2 emissions were excluded, the net cradle-to-gate carbon footprint reduced to 1.48 kg CO_2-eq/L of ethanol. This dual reporting approach reflects global LCA recommendations and demonstrates the strong potential for near-carbon-neutral operation through improved biomass management and increased cane productivity.

Implications for Sustainability and SDG 7

Results clearly identify sugarcane cultivation, slop incineration, and fermentation as the major emission contributors. Adoption of more efficient agricultural practices, advanced boiler technologies, optimized energy management, and sustainable logistics can significantly improve environmental performance.

The findings substantiate the role of sugarcane-based ethanol as a viable contributor to clean and affordable energy (SDG 7) and emphasize the scope for further emission reductions through process optimization.

The slightly elevated carbon footprint reported in Table 5 in this study (1.48 kg CO_2-eq/L) is primarily a result of the comprehensive system boundaries employed. In contrast to earlier studies that often adopt narrower scopes limited to core production stages, this analysis uses a cradle-to-gate boundary, encompassing all relevant upstream and operational activities. Specifically, many previous assessments—such as those by Tsiropoulos [18]—exclude auxiliary systems such as multi-effect evaporators, CO_2 capture units, steam generation details, yeast propagation, and minor utilities (e.g., lighting, safety infrastructure). These omissions can significantly underestimate the total greenhouse gas emissions associated with bioethanol production. In this study, emissions were estimated for:

- Agricultural activities (fertilizer production and use, field emissions, diesel use)
- Process energy (boiler operations, even when using Bagasse)
- Chemical and yeast production,
- Evaporation and distillation systems, and
- Scope 2 emissions from electricity and steam, where applicable.

Moreover, actual plant-level consumption data were used instead of idealized or modeled values, ensuring higher accuracy but also reflecting real-world inefficiencies. This methodological choice aligns with global standards such as the GHG Protocol and ISO 14067, making the analysis more robust and policy-relevant. Therefore, the higher footprint is not a methodological error but a reflection of a more detailed and complete carbon accounting approach, providing valuable insights for mitigation strategies across the ethanol production value chain.

TABLE 5
Comparison of findings of different studies

Reference	Process Details / Sections	CO_2eq / L Ethanol	Remark
Current Study (2025)	Adjusted CFP (excluding biogenic CO_2 from fermentation and incineration boiler using Bagasse and spent wash as fuel)	1.48	More accurate after excluding biogenic emissions and assuming renewable boiler fuel
	(Originally estimated total with incineration boiler and biogenic CO_2 from fermentation)	4.42	Initial overestimation due to baggage-based boiler and fermentation CO_2 count
[18]	LCA of sugarcane ethanol in India vs. Brazil	1.03	Comprehensive boundary-based LCA comparison study
[19]	Mixed feedstocks; plant-level comparisons	0.89–1.31	Higher in the molasses route
[1]	Corn-based global industrial average	1.35	Fossil-intensive feedstock and grid

TABLE 6
Carbon Emissions during Material Acquisition and Processing

Section	Sugarcane cultivation	Fermenter co_2	Fermentation chemicals	Yeast production
CO_2 eq /L	0.7	$7.55 X 10^{-1}$	$7.64 X 10^{-4}$	$8.236 X 10^{-4}$

TABLE 7
Carbon Emission during Production

Section	Incineration boiler	Upstream Process	Downstream Process
CO_2eq /l	2.18	$8.79 X 10^{-5}$	$8.35 X 10^{-3}$

TABLE 8
Energy Footprint

Section	Fermentation	Rectified spirit	Absolute Alcohol	Multi-Effect Evaporator	CO_2 Plant	Lighting and fire extinguisher
CO_2eq /l l	$7.731 X 10^{-2}$	$3.75 X 10^{-2}$	$1.01 X 10^{-2}$	$5.487 X 10^{-1}$	$9.345 X 10^{-2}$	$8.022 X 10^{-3}$

IV. CONCLUSION

The total carbon footprint (CFP) associated with the production of bioethanol from cane syrup in the studied distillery is estimated at 4.42 kg CO_2-eq per liter of ethanol, when including biogenic carbon emissions. Among all contributing processes, the incineration boiler was identified as the dominant source of emissions. It is therefore recommended that flue gases from the boiler be effectively managed and not released directly into the environment. In comparison, a study conducted by Soam [20] reported that the CFP for ethanol production from molasses in northern India ranged from 543.3 to 8219.8 kg CO_2-eq per ton of ethanol, equivalent to approximately 0.43 to 6.60 kg CO_2-eq per liter of ethanol. This highlights that cane syrup-based ethanol production—even when accounting for biogenic carbon—demonstrates a significant reduction in emissions, with a decrease of nearly 2.18 kg CO_2-eq per liter compared to earlier molasses-based systems. This improvement is largely attributed to technological advancements and process efficiencies.

Ways to Reduce CFP

1. Carbon Dioxide Utilization and Limitations

One potential approach involves utilizing the existing CO_2 recovery infrastructure within the distillery, which currently captures and converts gaseous CO_2 into dry ice (solid CO_2). While this process facilitates the temporary storage and repurposing of CO_2, it does not contribute to net emission reductions because the carbon is eventually re-released into the atmosphere when the dry ice sublimates. Thus, this method represents a form of carbon recycling rather than carbon sequestration or conversion [21]

To advance beyond physical transformation, emerging technologies such as carbon capture and utilization (CCU) for green hydrogen production could be explored. These technologies involve electrochemical or thermochemical conversion of CO_2 into value-added fuels or chemicals using renewable energy sources. For example, the reduction of CO_2 using water electrolysis powered by solar energy can yield hydrogen, a clean energy carrier. However, this requires substantial capital investment and energy input, making feasibility a key consideration.

2. Integration of Renewable Energy: Solar Power

Transitioning to solar energy for on-site electricity generation offers a highly effective method to reduce the distillery's dependence on fossil fuels. Solar photovoltaic (PV) systems have one of the lowest lifecycles GHG emissions among energy sources, estimated at 20–70 g CO_2-eq/kWh, compared to over 400 g CO_2-eq/kWh for natural gas and over 1,000 g CO_2-eq/kWh for coal [22]. The installation of rooftop or ground-mounted PV panels can significantly reduce Scope 2 emissions related to purchased electricity.

Moreover, designing electric pumps and processing units to operate in hybrid mode—utilizing both grid and solar electricity—can enhance energy efficiency and ensure continuity during periods of low solar insolation. These hybrid systems not only reduce operational emissions but also improve energy resilience and cost savings over time.

3. Electrification of Logistics and Mobility

Emissions from upstream (e.g., feedstock transportation) and downstream (e.g., product distribution) activities constitute a substantial portion of the distillery's indirect CFP. The deployment of electric vehicles (EVs), powered by renewable energy, can substantially reduce Scope 3 emissions. Life cycle analyses (LCA) show that EVs produce up to 70% fewer emissions over their lifespan compared to conventional internal combustion engine vehicles when charged with clean electricity [23]

4. Carbon Offsetting Through Afforestation

Given the notable release of biogenic CO_2 during the fermentation and combustion of biomass, afforestation and reforestation initiatives serve as viable carbon offset mechanisms. Trees act as carbon sinks, sequestering atmospheric CO_2 through photosynthesis and storing it in biomass and soil. It is estimated that one mature tree can absorb approximately 22 kg of CO_2 annually [24]. Therefore, strategic afforestation around the distillery premises can meaningfully offset unavoidable emissions and enhance biodiversity.

5. Bio-Energy from Distillery By-Products

Distilleries generate significant quantities of organic waste, particularly spent wash, which can be converted into biogas through anaerobic digestion. This biogas, predominantly methane (CH_4), can be used for cogeneration or electricity production. According to [25], the cumulative bio-energy potential from distillery by-products could supply up to 5% of national electricity demand if effectively harnessed. This not only contributes to waste valorization but also reduces reliance on external energy sources, promoting a circular economy.

6. Approach Towards Carbon Neutrality

Based on the above suggestions, the authors conclude that the integration of sustainable development practices—such as clean energy adoption, waste-to-energy conversion, afforestation, and electrification of transport—can significantly contribute to the distillery's goal of achieving carbon neutrality. A systems-based LCA approach is essential to evaluate the environmental performance of each intervention and ensure that reductions in one area do not lead to unintended consequences elsewhere. [26]

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