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Review Paper

Sustainability Evaluation of Lignocellulosic Ethanol Production in India: A Review and Synthesis of Life Cycle Assessment Studies

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Abstract: To reduce reliance on conventional fossil fuels for transportation, ethanol is an environmentally friendly biofuel that can be blended with gasoline. Second-generation ethanol produced from lignocellulosic biomass is considered a promising option for reducing fossil fuel dependence and supporting the nation's ethanol blending targets. However, the environmental impacts of 2G ethanol production depend on the feedstock type, conversion pathways, and LCA methodologies used. This review synthesises evidence from Indian LCA studies on 2G ethanol production. Peer-reviewed literature published between 2000 and 2025 was identified through various searches and related keywords in the Indian context. The second-generation (2G) ethanol production process involves several steps, including pretreatment, enzymatic hydrolysis, fermentation, and distillation. During the process conversion, various chemical agents, such as acids, alkalis, and enzymes, along with process water and energy, are utilised. Thus, the environmental impacts of the 2G ethanol production process need to be investigated. This review provides a brief overview and analysis of the literature on the life cycle assessment (LCA) of 2G ethanol, specifically in the Indian context. The impact of electricity use can be reduced by substituting conventional coal-based electricity with bioelectricity generated from leftover lignin during the process. The 2G ethanol production in India can enhance the nation's sustainability goals, thereby reducing environmental loads by replacing the burning of lignocellulosic biomass in fields.

Keywords: Green fuels; Lignocellulosic biomass; 2G ethanol; Sustainability assessment.

1. INTRODUCTION

India's energy demand has been rising significantly over the past few years. Energy demand is broadly categorised into domestic and industrial. The primary energy demand in the transportation sector is currently fulfilled by gasoline and diesel (Dey et al. 2025; Dey et al. 2023). Transportation fuels are primarily extracted from crude oil, which places a significant burden on the nation's energy security. In fiscal year 2024-25, India imported approximately 232.5 million tonnes of crude oil, valued at $132.4 billion (Kwakye et al. 2024). The utilisation of crude oil in the transportation sector also contributes to problems such as climate change and global warming through excessive greenhouse gas emissions. India, which primarily relies on crude oil to meet its energy demands, faces challenges in mitigating these impacts. To address these issues, the Government of India launched the National Biofuel Policy (NBP) in 2018, which highlights the use of ethanol in conventional gasoline. Fuel ethanol can be easily blended with gasoline, reducing oil imports through domestic ethanol production and demand substitution (MoPNG 2018; Pattnaik et al. 2024).

Fuel ethanol can be broadly classified by the method used to produce it. First-generation (1G) ethanol is produced from edible feedstocks such as sugarcane juice, sugarcane molasses, and other food crops, including wheat, corn, and potatoes (Kurowska et al. 2020). The major setback of 1G ethanol is its competition with edible feedstocks and the trade-offs it entails between food and fuel (Kurowska et al. 2020). To overcome this issue, the second-generation (2G) ethanol is a promising option, primarily produced from non-edible feedstock, also known as lignocellulosic biomass (LCB). The LCB includes non-edible feedstock such as agricultural residues, forest residues and dedicated energy crops. These feedstocks are generally obtained after processing of 1G ethanol and are abundant and cost-effective. The LCB is composed of three main constituents, namely cellulose, hemicellulose, and lignin, with small proportions of other extractives and ash in variable proportions (Jain & Kumar**,** 2024). The intricate and complex structure of the LCB requires pretreatment to disintegrate the complex polymeric structure (cellulose and hemicellulose) into monomeric units (glucose and xylose), which can then be further converted into fuel ethanol using enzymes (Soleymani et al. 2021). Third-generation (3G) ethanol is produced from aquatic sources, such as macro- and microalgae (Joyia et al. 2024).

The biofuel sector, primarily fuel ethanol, has been a concern regarding the nation's energy security strategies and sustainable development goals. The National Biofuel Policy (2018) has emphasised the importance of blending ethanol into conventional gasoline to reduce crude oil imports from foreign nations. The Ethanol Blended Petrol (EBP) launched under NBP, 2018, has set an ambitious target of 20% ethanol blending (E20) in gasoline for promoting energy security (MoPNG, 2018; MoPNG, 2022). Ethanol can be easily blended with conventional gasoline and reduce net greenhouse gas (GHG) emissions. In recent years, ethanol production in India has expanded drastically to meet the growing demand for fuel ethanol. Currently, India relies on two production pathways for fuel ethanol: molasses-based and grain-based. Molasses-based ethanol production accounts for 426 crore litres, whereas grain-based ethanol production accounts for 258 crore litres per year (Dey et al. 2025; Raut & Patil, 2023). The current blending target of 20% ethanol (E20) in gasoline would require 10,160 million litres of ethanol (MoPNG, 2022; Sarwal et al., 2021). This represents a significant increase from current ethanol production levels, highlighting the supply-demand gap in the near future.

The indicative target of E20 blending can be achieved by expanding molasses-based ethanol from 426 crore litres to 760 crore litres and grain-based ethanol from 258 crore litres to 740 crore litres (Dey et al. 2025). This would bring the total production capacity to approximately 1,500 crore litres. Several policy frameworks have been adopted by the Indian government since 2003, with updates in 2005, 2018, and 2019. Domestic ethanol production can help reduce dependence on crude oil imports from foreign nations (Parvez et al. 2025). India has been facing several challenges, despite policy support and regulatory mechanisms, in meeting its ethanol blending targets. There is a shortfall of ethanol blending targets due to a supply-demand imbalance. India primarily relies on 1G ethanol from sugar mills, sourced from molasses and sugarcane juice. The 1G ethanol production process from sugarcane molasses and sugarcane juice is economically viable at a commercial scale. The major concern with 1G ethanol is excessive water use during production and harvesting. There are certain regions in India, such as Uttar Pradesh and Rajasthan, where irrigation demands still compete with the agricultural requirements (Priyanka, 2025).

The 2G ethanol pathway is a promising approach that utilises agricultural residues and addresses the food-versus-fuel competition. While 2G ethanol can significantly reduce GHG emissions compared to fossil fuels, its overall climate performance depends on feedstock management, energy sources, co-product credits, and life-cycle assessment assumptions. The forecasted ethanol target of 10,160 million litres can be easily fulfilled by 2G biorefineries through efficient biomass valorisation and agricultural waste management techniques (Maga et al. 2019; Thaha et al. 2025). The 2G biorefineries can not only produce biofuels such as ethanol but also produce biochemicals from a single lignocellulosic feedstock. The production process of 2G ethanol consumes energy and process water. Thus, the issue of energy and water use during the production process needs to be addressed in terms of its environmental and ecological impacts across various aspects. The comprehensive framework for evaluating the environmental impacts of a product's production process across its entire life cycle is Life Cycle Assessment (LCA). The LCA considers the entire life cycle of the process or product, starting with the extraction of raw materials used in production (including pretreatment, enzymatic hydrolysis, fermentation, distillation, and purification) (Maga et al. 2019). The LCA is primarily divided into four main parts: defining the goal, scope, and boundaries of the project; collecting primary and secondary data for the system's inputs and outputs; evaluating environmental impacts; and interpreting results.

A structured literature review was conducted to identify the studies on LCA of 2G ethanol production in India. The peer-reviewed literature was retrieved from Scopus, Web of Science, ScienceDirect, and Google Scholar using keywords such as ‘Life cycle assessment’, ‘2G ethanol’, ‘lignocellulosic ethanol’, ‘India’, etc. The search covered the studies published between 2000 and 2025. The inclusion criteria were limited to peer-reviewed journal articles reporting the environmental assessment of lignocellulosic ethanol production under Indian operating conditions. The selection of peer-reviewed literature was based on the use of Indian feedstocks, inventory datasets and scenarios. After screening and applying the inclusion criteria, 20 studies were selected for detailed review.

This review comprehensively describes the various approaches of LCA methodologies for 2G ethanol production in the Indian context. The various steps in the entire LCA methodology include defining the goal, scope, and system boundaries; functional units; primary and secondary data sources; software tools used; and environmental impact assessment. The various environmental impacts of 2G ethanol production from various feedstocks, pretreatment methods, and fermentation on various components of the ecosystem, including air, water (aquatic) and land (terrestrial), have been organised to convey a clear and unified perspective. This review provides a comprehensive understanding of the potential of 2G ethanol to advance the nation's sustainable development goals. To the best of our knowledge, no such review has been conducted based on an India-centric database.

2. APPROACH AND METHODOLOGY FOR LCA

The LCA is a comprehensive tool that evaluates the environmental impact of a product or process throughout its entire life cycle. The environmental impacts included in LCA are GHG emissions, fossil fuel depletion during the resource recovery stage, acidification, eutrophication, ozone layer depletion, and various toxicity effects, which are evaluated at the product stage (Jiménez et al. 2022). The drawbacks of the LCA are the availability of primary and secondary process data and the selection of the proper methodology. The primary steps involved in the LCA studies include defining the goal, scope, functional unit and system boundaries for the production process (Xicotencatl et al. 2023). The primary goal and scope of the biofuel production process are to evaluate its environmental load. The functional unit is generally set based on the end user of LCA, for example, 1 litre of ethanol produced, 1,000 kg of ethanol produced, 1,000 kg of biomass processed, etc (Borrion et al. 2012). The second step after goal and scope is to define the system boundaries and collect primary and secondary data sets related to the input and output of the production process. The system boundaries are set limits or a range of the project that are generally based on the functional unit. The system boundaries in LCA are as follows: cradle-to-grave, cradle-to-gate, gate-to-gate, and cradle-to-cradle, respectively. The cradle-to-gate approach utilises the raw materials extraction part, along with the production process, up to the factory gate. The gate-to-gate approach encompasses only one stage of the production chain, whereas the cradle-to-grave approach encompasses the entire life cycle of the product or process. The waste materials from the process are recycled back into the production process in a cradle-to-grave approach (Borrion et al. 2012; Xicotencatl et al. 2023). The LCA of the 2G ethanol production process steps, including biomass production (harvesting) and ethanol production (pretreatment, enzymatic hydrolysis, fermentation, and distillation). The biomass production stage includes seeding crops, biomass growth throughout the life cycle, and harvesting. A short overview of the subsystem is as follows:

2.1. *Biomass production and harvesting*

The primary steps in biomass production and harvesting include soil preparation using mechanised tractors and other farm equipment, followed by seed sowing, application of organic and inorganic fertilisers and other pesticides and herbicides. The final step is harvesting of the crops and crop residues (Shakelly et al. 2023). The crucial factor that impacts the overall emission from the system is crop yield per hectare. In India, more than half of crop residues are utilised for daily household purposes, such as animal fodder, combustion fuel, and soil quality enhancement. The remaining 50% of the biomass is then made available for the 2G ethanol production process (Mandade et al. 2015).

2.2. Bioethanol production process

The primary steps in ethanol production from 2G feedstock are biomass washing and drying, followed by size reduction. The size-reduced biomass is then conveyed to the pretreatment process, which uses acids, alkalis, or other agents to efficiently remove the cellulose and hemicellulose fractions. The majority of the lignin is removed during the pretreatment stage, and the pretreated biomass is subsequently loaded with an enzyme mixture containing cellulases and hemicellulases. The enzymatic hydrolysate is fed to the fermentation process, where fermenting microorganisms, such as yeast or fungi, convert it into ethanol. The final step in the ethanol production process is separation and purification, during which excess water is removed to obtain fuel-grade ethanol (Borrion et al. 2012; Morales et al. 2015; Ryan & Yaseneva, 2025). The lignin obtained after pretreatment can also be utilised for various biochemicals production and other value-added products. Figure 1 presents the generalised steps for 2G ethanol production, along with bioelectricity production from the leftover lignin.

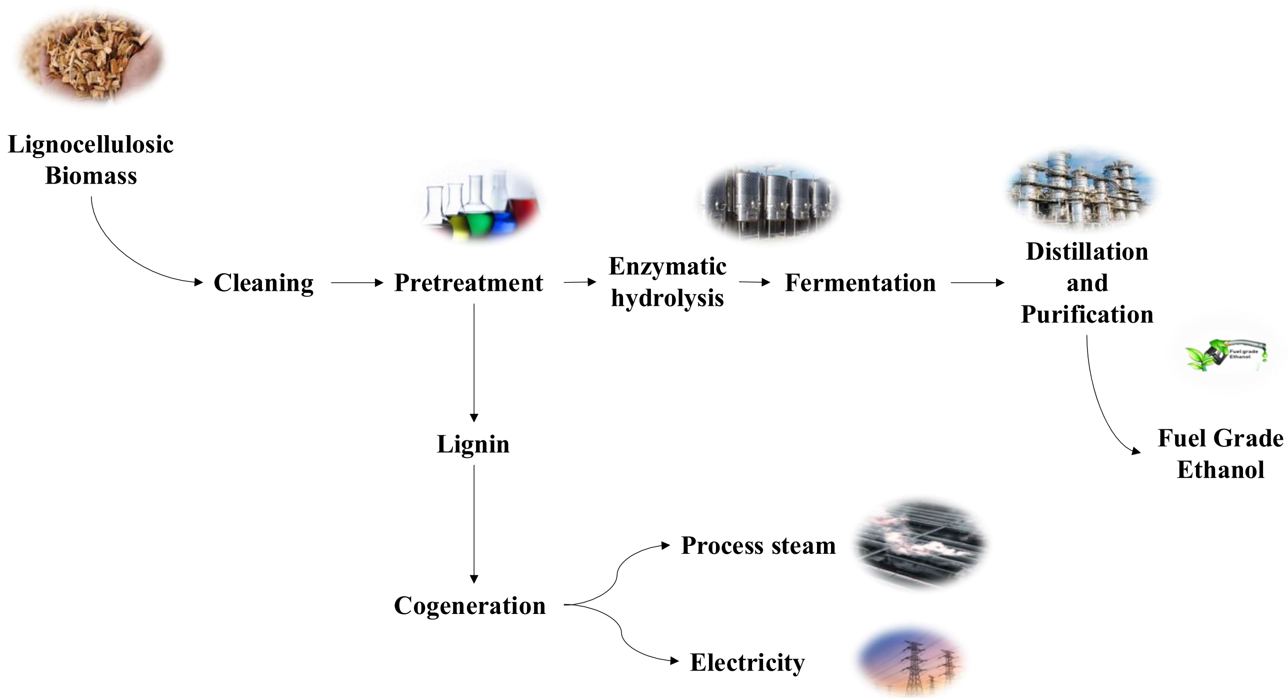

Figure 1: Detailed block flow diagram for generalised 2G ethanol production process

3. LIFE CYCLE ASSESSMENT FRAMEWORK FOR 2G ETHANOL

3.1. Goal and Scope Definition

The primary purpose of the LCA is to assess the environmental performance of 2G ethanol production in the Indian context. The major 2G feedstocks available in India include rice straw, sugarcane bagasse, and corn stover. The main objectives include quantifying the GHG emissions associated with 2G ethanol production and identifying environmental hotspots throughout the entire production chain. The scope definition includes a consistent basis for comparison, for example, 1 kg of 2G ethanol or 1 ton of 2G ethanol production, respectively.

3.2. *System Boundaries and Functional Units*

The system boundaries are the set limits of the production system, encompassing the product's various life cycle stages, as well as the processes and flows within the system. The system boundaries encompass the start and end points of the LCA, as well as interactions with the environment, including energy, emissions, waste generation, and water use, among others. The typical system boundaries in LCA are classified as cradle-to-gate, cradle-to-grave, gate-to-gate, cradle-to-cradle, well-to-tank, tank-to-wheel, and well-to-wheel (Borrion et al. 2012; Xicotencatl et al. 2023). The cradle-to-gate approach involves LCA from raw materials extraction to the production factory gate; cradle-to-grave is the entire LCA of a production process till the end usage of the product; the gate-to-gate approach includes a single process, for example, an enzymatic hydrolysis step alone; the cradle-to-cradle approach is basically used where the materials are recycled back into the production process. Figure 2 represents the detailed block flow diagram of system boundaries for the 2G ethanol production process.

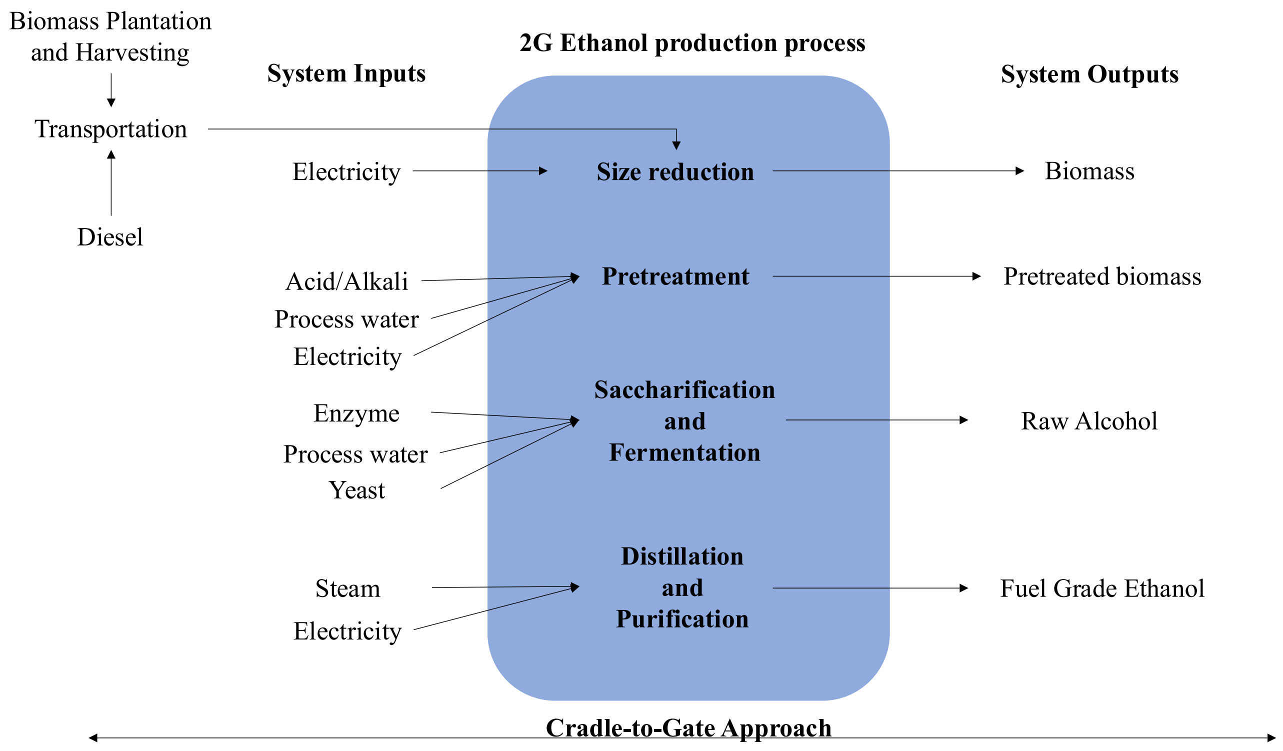

Figure 2: Detailed block flow diagram of system boundaries for 2G ethanol production

3.3. Life Cycle Inventory (LCI) and Data Sources

The LCI is the collection of primary and secondary data, i.e., inputs and outputs of the product system, associated with the product life cycle. The complete dataset for each unit process is required within the set system boundary, for example, pretreatment, enzymatic hydrolysis, fermentation, distillation and purification of 2G ethanol. The important task in LCI is data validation; consistent, complete, and accurate primary and secondary data are required at this stage of LCA. The allocation is another important step in LCI, dividing the system's environmental impacts among multiple products and by-products from the production process. Three types of allocation are widely used in LCI: mass allocation, energy allocation, and price or economic allocation (Borrion et al. 2012). The mass allocation divides the environmental impacts based on the mass of 2G ethanol production. In contrast, the energy allocation divides them by energy content, and the economic allocation distributes the environmental burden in proportion to the market value of products and by-products.

3.4. Life Cycle Impact Assessment (LCIA) Methods

The LCIA is the phase of the LCA that evaluates the potential environmental impact associated with the inputs and outputs of the production process. In simple terms, it provides a brief overview of emissions in various categories, including CO_2, NO_x, CH_4, and others. There are various LCIA methods based on impact categories developed regionally, such as CML, ReCiPe, TRACI, IMPACT 2002+, ILCD, GREET, and Eco-indicator (Borrion et al. 2012; Jiménez et al. 2022).

4. REVIEW OF INDIAN CASE STUDIES

4.1. LCA of 1G ethanol

1G ethanol in India is primarily produced from sugarcane juice, molasses, and edible feedstocks. Several LCA studies have evaluated the environmental impacts of these production pathways and reported reductions in GHG emissions compared with conventional gasoline. Although these studies provide insights into the Indian bioethanol sector, they are not directly representative of 2G ethanol production and are therefore considered contextual background in this review.

Tsiropoulos et al. (2014) investigated a comparative LCA of ethanol production from sugarcane in India and Brazil. The study primarily focused on Uttar Pradesh and South-Central Brazil. The primary feedstock for ethanol production was sugarcane juice and molasses. The approach used was cradle-to-gate, along with economic allocation. The LCIA method selected was IMPACT 2002+. From the results obtained, Indian ethanol produces lower GHG emissions, ranging from 0.09 to 0.64 kg CO_2 eq. per kg of ethanol production, whereas Brazilian ethanol produced 0.46 to 0.63 kg CO_2 eq. per kg of ethanol production. Water usage in the Indian ethanol industry is comparatively higher, at 543 L per kg of ethanol, whereas the Brazilian ethanol industry uses just 28 L per kg. The major reason for higher water consumption is unrestricted groundwater use for irrigation. The Indian ethanol industry can minimise environmental impacts by avoiding excessive use of certain pesticides and by avoiding the dumping of untreated stillage into freshwater bodies. **Soam et al. (2015)** investigated the LCA of fuel ethanol from sugarcane molasses in India. The study was primarily focused on the northern and western parts of India. The functional unit selected was 1 tonne of fuel-grade ethanol produced with a cradle-to-grave approach. Four types of allocation were selected: no allocation, mass, energy, and market price. From the results obtained, the estimated GHG emissions ranged from 543.3 to 8219.8 kg CO2 eq for various allocations in northern India, and from 552 to 7382.4 kg CO2 eq/tonne of ethanol produced in the western part of India. The net energy ratio (NER) ranged from 0.39 to 3.39 for the northern region and from 0.48 to 4.23 for the western region. The major contributor to GHG emissions was the usage of fossil-based electricity during the production process. This environmental load can be further reduced by altering the fossil-based electricity with bioelectricity production in India. Integrated sugar mills with distillery units can also reduce overall GHG emissions by increasing the energy efficiency of ethanol production.

Sujata et al. (2021) investigated LCA of ethanol production from sugarcane molasses to identify strategic locations for ethanol production facilities in India. The major objectives of the study were to identify strategic locations for processing molasses into ethanol in major sugarcane-growing states such as Uttar Pradesh, Maharashtra, and Karnataka. The expected outcome was to identify the most economical and environmentally friendly solution for ethanol production. The study considered well-to-pump using the ecoinvent database. The functional unit was set to 1 ton of ethanol production using mass allocation. Three scenarios were investigated, considering molasses transported to the distillation unit, ethanol transported to the refinery, and molasses transported to the refinery, with ranges of 2.25 km to 1250 km, respectively. The selected impact assessment method was IMPACT 2002+ to identify environmental impacts from the process. Based on the results, estimated GHG emissions ranged from 820 to 1230 kg CO2 eq per ton of ethanol produced across different states. **Hiloidhari et al. (2021)** investigated the LCA of ethanol production from sugarcane, including other by-products such as sugar and cogeneration electricity. The approach used from farm to factory gate, i.e., cradle-to-gate, with functional unit for energy MJ/kg for sugar, MJ/kWh for electricity and MJ/L for ethanol production, along with carbon footprint accounting kg CO_2 eq./kg for sugar; kg CO_2 eq./kWh for electricity and kg CO_2 eq./L of ethanol produced, respectively. Mass, energy, and economic allocation were used to assess the environmental impacts of various products. From the results, the estimated energy footprints for ethanol production were 4.59 MJ/L of ethanol, 6.13 MJ/kg of sugar, and 0.77 MJ/kWh of electricity. The energy return on investment for sugar production was estimated at 2.6, for ethanol production at 4.26, and for electricity generation at 4.63. The estimated carbon footprint for sugar, ethanol and electricity was 0.401kg CO_2 eq./kg of sugar; 0.295 kg CO_2 eq./L of ethanol and 0.042 kg CO_2 eq./kWh.

Uppalapati et al. 2024 investigated the LCA and energy balance for ethanol production from sugarcane molasses in southern India. The software tool used was the GREET model. The primary data were collected from Gayatri Sugar Mill in Telangana. Two scenarios were investigated: sugarcane trash utilised for mulching and for conventional field burning. The functional unit was set to 1 ton of sugarcane processed. The estimated GHG emission for the cultivation stage was 43.86 kg CO_2 eq., 45.98 kg CO_2 eq. for the transportation stage, 69.05 kg CO_2 eq. for cane trash burning and 6.37 kg CO_2 eq. during ethanol production, respectively. The overall energy yield was 15.79 MJ/MJ of ethanol produced. The largest carbon footprint was observed during sugarcane farming. Using sugarcane trash for mulching can significantly reduce carbon footprints and enhance soil fertility. **Harde and Ojha (2025)** investigated the LCA of ethanol-gasoline blends in India. The study focused on blending ethanol into conventional gasoline at E10, E20, and E30 levels. The blended fuel was compared with conventional gasoline fuel. The functional unit was set to 1 kg of fuel combusted in BS-VI engines using a cradle-to-gate approach. Based on the results, the estimated GHG emissions ranged from 0.32 to 0.35 kg CO_2 eq per kg of blended fuel used in BS-VI engines. Ethanol blends at mid-levels, i.e., E20-E30, provide environmental benefits and lower GHG emissions. Table 1 summarises the major findings of LCA from previous literature on 1G ethanol in the Indian context.

Table 1: Summary of major findings of previous literature on LCA on 1G ethanol in the Indian context

Feedstock	Functional unit	System boundary	Allocation method	LCIA method	GHG emission (kg CO_2 eq.)	Key findings	Reference
Sugarcane	1kg of ethanol	Cradle-to-gate	-	IMPACT 2002+	Brazil: 0.46 to 0.63 India: 0.09 to 0.64	The Indian ethanol industry can minimise environmental impacts by avoiding excessive use of certain pesticides.	Tsiropoulos et al. (2014)
	1 ton of ethanol	Cradle-to-gate	W/o; Mass; Economic; Energy	-	0.552 to 8.219	The major contributor to GHG emissions was the usage of fossil-based electricity during the production process.	Soam et al. (2015)
	1 ton of ethanol	Well-to-Pump	Mass	IMPACT 2002+	0.82 to 1.23	Identify strategic locations for processing molasses into ethanol in major sugarcane-growing states such as Uttar Pradesh, Maharashtra, and Karnataka.	Sujata et al. (2021)
	MJ/kg; MJ/L and MJ/kWh	Cradle-to-gate	Mass; Economic; Energy	CED	Sugar: 0.401/kg; Ethanol: 0.295/L; Electricity: 0.042/kWh	LCA of ethanol production from sugarcane, along with other by-products, including sugar and cogeneration electricity.	Hiloidhari et al. (2021)

1 ton of SC	Cradle-to-Gate	Mass	-	Sugarcane cultivation: 0.04386 Transportation: 0.04598 Ethanol: 0.00637	The largest carbon footprint was observed during sugarcane farming.	Uppalapati et al. (2024)
1 kg of ethanol combusted in BS-VI	Cradle-to-Grave	-	-	0.32 to 0.35/L of blended fuel	E20-E30, provide environmental benefits and lower GHG emissions.	Harde and Ojha (2025)

4.2. LCA of 2G ethanol

2G ethanol is mainly produced from lignocellulosic biomass, such as sugarcane bagasse, rice straw, wheat straw, corn stover, and other agricultural residues. The reviewed studies mainly focused on evaluating the environmental performance of these feedstocks under Indian conditions/databases. The key environmental indicators include GHG emissions, energy balance, water footprint, acidification potential, eutrophication potential, and related metrics, providing insights into the sustainability of 2G ethanol production pathways.

Kadam (2002) investigated the LCA of 2G ethanol production from sugarcane bagasse and associated blending in conventional gasoline in India. The software tool used for LCA was TEAM (Tools for Environmental Analysis and Management), developed by Ecobalance, Maryland, USA. The functional unit selected was 1 ton of dry sugarcane bagasse for ethanol production. The pretreatment method employed was dilute acid, and the impact categories were IPCC and CML. Two scenarios were investigated: sugarcane bagasse burning and gasoline use, ethanol production, and E10 fuel use. From the results obtained, the estimated GHG emissions were 582 kg CO_2 eq. and -152 kg CO_2 eq. for scenarios 1 and 2, respectively. Ethanol production from sugarcane bagasse has a lower environmental burden than burning it for cogeneration. **Mandade et al. (2015)** investigated LCA of six feedstocks, namely cotton stalk, rice husk, wheat stalk, sorghum stalk, sugarcane bagasse and molasses in India. The cradle-to-gate approach was selected for LCA, along with mass and economic allocation for products. From the results, the estimated GHG emissions ranged from 0.13 to 1.8 kg CO2 eq per litre of ethanol produced. The major sources of GHG emissions are the use of fertilisers and pesticides, and the use of electricity for irrigation. The estimated GHG emission from sugarcane-based ethanol production was 0.39 to 0.61 kg CO_2 eq per litre of ethanol production. The energy return on investment ranged from 1.59 to 8 across different allocations. The sorghum stalk has lower GHG and the lowest energy and water usage in the Indian context. The rice husk has a maximum water consumption and relatively higher GHG emissions. Sorghum stalks in India are primarily used as animal feed and thus cannot serve as a major feedstock for cellulosic ethanol.

Soam et al. (2016) investigated LCA of GHG emissions and energy use for 2G ethanol production in India. The pretreatment methods employed were dilute acid and steam explosion, followed by separate hydrolysis and fermentation. The functional unit selected was 1 ton of paddy straw and 1MJ of transportation fuel production. The estimated ethanol yield was 239 and 253 L per ton of paddy straw for dilute acid and steam explosion, respectively. These results were based on a process developed by the 2G ethanol plant by Indian Oil Corporation Ltd, Panipat. The energy input estimated for 2G ethanol production was 1736 and 1372 MJ per ton of paddy straw for dilute acid and steam explosion, respectively. The estimated energy requirements for the 2G ethanol production process were 2,660 MJ for dilute acid pretreatment and 2,471 MJ for steam explosion pretreatment. The estimated net energy ratio ranged from 2.3 to 2.7 for both pretreatment processes. The energy balances for dilute acid pretreatment and steam explosion were 14.9 and 16.3, respectively. Enzyme production has the highest GHG emissions, accounting for 54% and 57% of total GHG emissions for dilute acid and steam explosion pretreatment, respectively. Environmental impacts can be reduced through techniques such as recycling, enzymes, or on-site enzyme production. The steam explosion process is considered a greener alternative to dilute acid pretreatment, providing an environmentally friendly route to second-generation (2G) ethanol production. **Soam et al. (2018)** investigated the life-cycle costing of conventional dilute-acid and modified dilute-acid pretreatment for ethanol production in India. The process parameter data for pretreatment were collected from Indian Oil Corporation, Ltd, Faridabad. The major objective of this study was to reduce enzyme use and enhance ethanol productivity. The rice straw was selected as a 2G feedstock, with dilute acid concentration ranging from 0.2 to 0.5%. The biomass was initially pre-soaked in the hot water at 60 °C. The functional unit selected was 1 litre of ethanol produced with a well-to-gate approach. Three system boundaries were selected: feedstock acquisition, ethanol production and ethanol transportation. The LCIA method selected was CML 2; the modified pretreatment method involved pre-soaking biomass in hot water at 60 °C. From the results obtained, the estimated GHG emissions ranged from -0.26 to -0.58 kg CO_2 eq per litre of ethanol. The estimated life-cycle cost of ethanol production ranged from 49 to 58 rupees per litre. The enzyme loading was 8 FPU per gram, and the estimated ethanol yield was 242-267 litres per tonne of biomass.

Sreekumar et al. (2020) investigated the LCA of 2G ethanol production from rice straw. The functional unit was set to 1 L of ethanol production. The process was based on a 100 KLPD plant developed by DBT-ICT, Mumbai. The pretreatment method used in the study was sodium hydroxide. The estimated rice straw required for 1 L of ethanol production was 3.27 kg, yielding 272 L per ton of rice straw. The estimated GHG emissions were 2.82 kg CO2 eq per litre of ethanol produced using economic allocation. The major GHG contributor to the process was electricity sourced from fossil fuels, and the estimated global warming potential of electricity production in India was 1.17 kg CO_2 eq per kWh when coal was used. From the results obtained with no allocation, the estimated GHG emissions were 3.78 kg CO_2 eq. per litre of ethanol production, whereas with the physical allocation it was 1.493 kg CO_2 eq. per litre of ethanol production. The physical allocation used electricity sourced from hydroelectric power, resulting in a global warming potential of 0.520 kg CO2 eq per litre of ethanol produced. The estimated energy return on investment for ethanol was 1.59, whereas the estimated water footprint was 27.11 litres per litre of ethanol produced. **Hassan et al. (2021)** investigated the LCA of 2G ethanol production from Indian rice straw. The pretreatment method considered for the study was dilute acid and steam explosion, along with electricity production. The functional unit selected for the study was 1 ton of rice straw. The estimated ethanol production was 239 and 253 litres from dilute acid and steam explosion pretreatment, respectively. Ethanol and bioelectricity production were estimated based on the surplus rice straw available in the country. Based on the results, the forecasted 2G ethanol production from major rice-growing states was estimated at 11,165 million litres for the year 2030-31. The estimated GHG reduction potential was 11,498 and 14,498 kiloton of CO_2 eq. for dilute acid and steam explosion, respectively. **Murali and Shastri (2022)** investigated the LCA of 2G ethanol production from sugarcane bagasse in India. Eight different pretreatment methods were investigated, namely, dilute acid, liquid hot water, steam explosion, ammonia fibre explosion, wet oxidation, ionic liquid and lime, respectively. The functional unit was set to 1 MJ of energy derived from ethanol production. From the results obtained, the estimated GHG emission from 1 MJ of ethanol production was 0.132 kg CO_2 eq; whereas for 1 litre of ethanol production, the estimated GHG emission was 3.144 kg CO_2 eq. The estimated water footprint was 232 litres per litre of ethanol produced from dilute acid pretreatment. The majority of water usage occurred during the farming stage. The pretreatment with the highest water footprint was lime, estimated at 672 litres per litre of ethanol produced. The majority of water use was attributed to lime production at manufacturing facilities. Dilute acid pretreatment is one of the environmentally friendly options for producing 2G ethanol from sugarcane bagasse. **Pati et al. (2023)** investigated the LCA of 2G ethanol production via co-gasification and syngas fermentation using Indian lignocellulosic biomass. The feedstock used was sugarcane bagasse and wheat straw. The functional unit selected was 1 kg of ethanol production using the cradle-to-gate approach. From the results, the estimated GHG potential of 2G ethanol production was 1.40 kg CO2 eq per litre. Three conversion routes were investigated: co-gasification and fermentation, enzymatic hydrolysis and fermentation, and sugar fermentation. The enzymatic hydrolysis and fermentation route has greater environmental impacts than the other two routes.

Patel and Singh (2024) presented an LCA of 2G ethanol production using rice straw and municipal solid waste in India. The functional unit was 1 litre of ethanol produced using the cradle-to-gate approach. The pretreatment methods used were dilute acid for rice straw and calcium hydroxide for municipal solid waste. Based on the results, the estimated GHG emission from rice straw was 2.19 kg CO_2 eq. per litre of ethanol, whereas for municipal solid waste it was 4.4 kg CO_2 eq. per litre of ethanol production. The major GHG emissions are due to enzyme use and electricity consumption during the process. The estimated energy demands for rice straw were 18.86 MJ and 71.5 MJ for rice straw and municipal solid waste, respectively. The environmental impact can be further reduced by switching to sustainable energy sources, such as lignin-based bioelectricity. **Patel and Singh (2024)** investigated the LCA and energy efficiency of 2G ethanol production from major agricultural residues in India. The selected feedstocks were rice straw, corn stover, and cassava straw. The functional unit selected was 1 litre of ethanol production, using a cradle-to-gate approach. Based on the results, the estimated GHG emissions for corn stover were 0.37 kg CO_2 eq. per litre of ethanol production, followed by rice straw of 0.966 kg CO_2 eq. per litre of ethanol production, and for cassava straw, it was 1.102 kg CO_2 eq. per litre of ethanol production, respectively. The cumulative energy demand for rice straw-based ethanol production was 13.62 MJ, mainly due to enzyme use. The cumulative energy demand for corn stover was 8.62 MJ, followed by cassava straw at 8.13 MJ. The estimated water footprints for rice straw, corn stover, and cassava straw were 0.14, 0.05, and 0.05 m3 per litre of ethanol production, respectively. Rice straw-based 2G ethanol production has the greatest environmental impact among the three lignocellulosic biomasses in India. The highest global warming potential was associated with cassava-based ethanol production, primarily due to the higher enzyme usage. The estimated net energy ratios for rice straw, corn stover and cassava straw were 1.2, 3.1 and 3.28, respectively. Table 2 summarises the major findings of LCA from previous literature on 2G ethanol in the Indian context.

Table 2: Summary of major findings of previous literature on LCA of 2G ethanol in the Indian context

Feedstock	Functional unit	System boundary	Allocation method	LCIA method	GHG emission (kg CO_2 eq.)	Key findings	Reference
Sugarcane Bagasse	1 ton of SCB	-	-	IPCC, CML	Scenario 1: SCB burning and gasoline use: 0.582 Scenario 2: Ethanol production and E10 use: -0.152 kg CO_2 eq.	Ethanol production from sugarcane bagasse has a lower environmental burden than burning it for cogeneration	Kadam (2002)

Indian surplus LCB feedstocks	1 L of ethanol	Cradle-to-gate	Mass, Economic, Energy	-	Cotton Stalk: 1.1 Rice husk: 1.8 Wheat stalks: 0.9 Sorghum stalk: 0.3 SCB: 0.7	Major sources of GHG emissions are the use of fertilisers and pesticides, and electricity for irrigation.	Mandade et al. (2015)
Rice straw	1 ton of rice straw	Cradle-to-gate	-	-	Dilute acid: 0.0084 Steam explosion: 0.0042	Environmental impacts can be reduced through techniques such as recycling, enzymes, or on-site enzyme production.	Soam et al. (2016)
Rice straw	1 L of ethanol	Well-to-gate		CML 2	Modified pretreatment: 0.26 to -0.58	Life-cycle costing of conventional dilute-acid and modified dilute-acid pretreatment for ethanol production	Soam et al. (2018)
Rice straw	1 L of ethanol	Cradle-to-Gate	Economic	ILCD 2011	2.818	The major GHG contributor to the process was electricity sourced from fossil fuels.	Sreekumar et al. (2020)
Rice straw	1 ton of rice straw	-	-	-	GHG reduction potential: Dil. Acid + Electricity: 11,498 kiloton CO_2 eq. Steam explosion+ Electricity: 14,498 kiloton CO_2 eq.	The forecasted 2G ethanol production from major rice-growing states was estimated at 11,165 million litres for the year 2030-31	Hassan et al. (2021)
Sugarcane Bagasse	1 MJ of ethanok	Cradle-to-Gate	Economic, Energy, Physical	ReCiPe TRACI	0.132/MJ of ethanol	Dilute acid pretreatment is one of the environmentally friendly options for producing 2G ethanol.	Murali and Shastri (2022)
Sugarcane Bagasse	1 kg ethanol	Cradle-to-Gate	Economic	ReCiPe	1.42	The enzymatic hydrolysis and fermentation route has greater environmental impacts than the co-gasification and syngas fermentation.	Pati et al. (2023)

Rice straw and MSW	1 L of ethanol	Cradle-to-Gate	-	IMPACT 2002+, CML	Rice straw: 2.19 MSW: 4.4	The environmental impact can be further reduced by switching to sustainable energy sources, such as lignin-based bioelectricity.	Patel and Singh (2024)
Rice straw, Corn stover, Cassava straw	1 L of ethanol	Cradle-to-Gate	-	IMPACT 2002+	Rice straw: 0.966 Corn stover: 0.371 Casavva straw: 1.102	Rice straw-based 2G ethanol production has the greatest environmental impact among the three lignocellulosic biomasses in India.	Patel and Singh (2024)

4.3. LCA of alternative biomass utilisation pathways under the biorefinery approach

In addition to ethanol production, lignocellulosic biomass, an excellent source of cellulose, hemicellulose, and lignin, can be utilised for various applications, such as bioelectricity and biogas production, as well as for value-added biochemicals such as lactic acid and xylitol. Several studies have assessed the environmental impacts of these alternative biomass utilisation pathways within the Indian context. These pathways contribute to the broader bioeconomy and biorefinery concept; they are discussed separately as they do not directly represent the 2G ethanol production system.

Soam et al. (2017) presented an LCA of paddy straw use in India. Paddy straw in India is primarily used as a fertiliser, animal fodder, and for electricity and biogas production. The functional unit selected was 1 ton of paddy straw utilisation. The major regions selected for the study were Punjab and Uttar Pradesh, as these states account for the highest rice production in India. The average rice yield in northern India was estimated at 3.5 tons per hectare, and the estimated rice straw yield was 4.2 tons per hectare. The estimated electricity production from 1 ton of paddy straw was 1,367 kWh, whereas biogas generation was 7.1 GJ. From the results obtained, 1 ton of paddy straw processed to electricity and biogas production would result in GHG emissions of 1,471 and 1,023 kg CO_2 eq., 15 and 3.4 kg SO_2 eq. and 6.7 and 7.1 kg CH_4 eq., respectively. The major benefit of utilising paddy straw for electricity production would be a reduction in coal use and associated emissions. The utilisation of paddy straw as animal fodder would reduce the major impact on eutrophication. The conventional burning practices cause excessive GHG emissions. Thus, paddy straw in India has a vast potential as a feedstock for various bioenergy production routes. **Munagala and Shastri (2021)** investigated the LCA of lactic acid production from sugarcane bagasse. The process data was obtained from a 104 TPD commercial plant at Vasantdada Sugar Institute, Pune. The functional unit selected was 1kg of lactic acid, along with sodium hydroxide pretreatment followed by enzymatic hydrolysis and fermentation. From the results, the estimated GHG emissions were 4.64 kg CO2 eq per kg of lactic acid produced. The water depletion potential was 18.89 m^3 per kg of lactic acid produced. The lactic acid production, coupled with conventional sugar mills, will drastically reduce the environmental load and provide economic benefits. The estimated cost of lactic acid production was USD 2.9 per kg.

Dasgupta et al. (2022) investigated the LCA and energy impact assessment of xylitol production from corn cob in India. The functional unit was set to the processing of 3.5 kg of corn cob for xylitol production. From the results, the estimated GHG emissions were 8.68 kg CO_2 eq. The major environmental impacts imposed were on the marine and freshwater ecosystems from the production of xylitol crystals. The estimated yield was 0.502 kg of xylitol crystals from 3.5 kg of corn cob. **Munagala and Shastri (2023)** investigated the LCA of a sugarcane biorefinery in India. Five configurations were investigated for a sugarcane biorefinery: a biorefinery that produced sugar, ethanol, and electricity from sugarcane bagasse; sugarcane bagasse diverted to lactic acid production; sugarcane bagasse diverted to succinic acid production; and sugarcane bagasse diverted to xylitol production. The functional unit selected was 1 ton of sugarcane processing using the cradle-to-grave approach. Based on the results, the estimated GHG emissions from the configuration of sugarcane bagasse diverted to lactic acid production were 111.08 kg CO_2 eq per ton of cane. The highest GHG emissions were estimated for the configuration that diverted sugarcane bagasse for lactic acid production. Sugarcane bagasse can be effectively diverted to other applications, such as 2G biofuel and biochemical production, rather than conventional electricity generation in sugar mills. Table 3 summarises the major findings of LCA from previous literature on biorefinery pathways in the Indian context.

Table 3: Summary of major findings of previous literature on LCA of 2G ethanol in the Indian context

Feedstock	Functional unit	System boundary	Allocation method	LCIA method	GHG emission (kg CO_2 eq.)	Key findings	Reference
Rice straw	1 ton of rice straw	Cradle-to-Gate	-	CML 2	Bioelectricity: 1.471 Biogas: 1.023	Conventional burning of rice straw results in excessive GHG emissions. Paddy straw in India has significant potential as a feedstock for various bioenergy production routes.	Soam et al. (2017)
Sugarcane bagasse	1 kg of lactic acid	Cradle-to-Gate	Economic	ReCiPe (H) Midpoint	4.64	SCB can be valorised for lactic acid production, instead of cogeneration	Munagala and Shastri (2021)
Corn cob	3.5 kg of corn cob for xylitol production	Cradle-to-Gate	-	CML	8.68	The major environmental impacts imposed were on the marine and freshwater ecosystems from the production of xylitol crystals	Dasgupta et al. (2022)
Sugarcane Bagasse	1 ton of SCB for lactic acid	Cradle-to-Gate	Economic	ReCiPe (H) Midpoint	0.111	Sugarcane bagasse can be effectively diverted to other applications, such as 2G biofuel and biochemical production, rather than conventional electricity generation in sugar mills.	Munagala and Shastri (2023)

5. DISCUSSION

Cellulosic ethanol, also known as 2G ethanol, is the liquid biofuel that is the primary product of 2G biorefineries. The primary feedstock for 2G biorefineries is non-food lignocellulosic biomass. The 2G biorefineries can not only produce fuels such as ethanol, biogas, butanol, and methanol, but also value-added biochemicals, including lactic acid, succinic acid, syringic acid, syringaldehyde, and vanillin. The 2G biorefineries provide an environmentally friendly option for producing fuels, chemicals and other energy products. The nation's sustainable development goals can also be achieved through efficient and effective waste management. The major drawback of 2G biorefineries is the high capital and operating costs of the production facility; other challenges include an inconsistent year-round biomass supply chain across various scales of operation. The major risk factors are uncertainty in the production process, the risk of capital investment, and immature process technology at the commercial level.

Life cycle assessment is an important perspective that offers a detailed understanding of the environmental impacts associated with biofuels and biochemical production from lignocellulosic biomass. The transport sector has been a major source of GHG emissions; most previous studies have focused on the global warming potential and GHG emissions associated with 2G ethanol production. All studies have reported reductions in GHG emissions from the production of 2G ethanol in India. The major impacts are associated with the use of fertilisers, pesticides, and herbicides during the crop-growing stage, resulting in higher global warming potentials for CO_2, CH_4, N_2O, and other gases. Another major contributor to GHG emissions is the excessive use of conventional coal-fired electricity in irrigation and the entire process. Some authors have highlighted that the lignin recovered during pretreatment can be effectively utilised for both biochemical production and bioelectricity production, further reducing the environmental load of the entire process. Thus, 2G ethanol production can recycle carbon dioxide by utilising the lignocellulosic biomass, which utilises carbon dioxide during its growth phase.

The acidification and eutrophication potential associated with 2G ethanol production are important factors that can damage ecosystems through acid rain and algal bloom formation, harming terrestrial and aquatic ecosystems. Previous studies have highlighted that the acidification and eutrophication potential of 2G ethanol production is higher than that of conventional gasoline, whereas its ozone depletion potential is comparatively lower (Soam et al. 2017). Some previous studies have also highlighted the Net Energy Ratio (NER) and Energy Return on Investment for 2G ethanol production. The NER is the ratio of the total energy produced by a technology to the total energy consumed during its production. Most of the previous literature has highlighted the NER for 2G ethanol production to be greater than 1, indicating the energy-efficient and sustainable pathway for ethanol production (Morales et al. 2015; Hassan et al. 2021)

Water footprint estimates reported in the literature exhibit considerable variability due to differences in methodological approaches and system assumptions. Various factors, such as irrigation water for primary crops and agricultural residues, and water consumption during biomass conversion stages, can influence water consumption results. Therefore, comparisons of reported water-use values should be interpreted within the context of each study's specific methodologies and assumptions. The environmental performance of the 2G ethanol varies across the studies due to differences in feedstock types, system boundaries, allocation methods, and co-product credits. While most studies reported lower GHG emissions than conventional gasoline, the magnitude of these benefits depends on assumptions about the avoided burning of residues, such as lignin, and on the value of exported electricity credits. The net energy ratio alone does not imply overall sustainability, as environmental trade-offs may arise in other impact categories such as water consumption, acidification and eutrophication.

6. FUTURE CHALLENGES AND DIRECTIONS FOR 2G ETHANOL

The major challenge associated with 2G ethanol production is scaling up the technology from laboratory scale to commercial scale. The techno-economic analysis plays a crucial role in estimating the CAPEX and OPEX of the production facility. To overcome the uncertainties associated with the high costs of acids, alkalis, enzymes, and feedstocks used in the process, India needs to establish small pilot-scale or demonstration plants at major sugarcane-producing hubs, such as Uttar Pradesh, Maharashtra, Karnataka, and Tamil Nadu. Such demonstration or pilot plants can showcase economically viable 2G ethanol technologies and serve as a knowledge dissemination centre, accelerating the commercial viability of 2G ethanol across the nation. The Indian government can further introduce a regulated or benchmark 2G ethanol production cost, which provides financial stability to new entrants and encourages large-scale commercialisation. The Indian government has already made major trade-offs in terms of tax benefits and incentives for 2G ethanol production under the Viability Gap Funding (VGF) scheme, as highlighted in PM-JI-VAN (Pradhan Mantri Jaiv Indhan-Vatavatarn Anukool Fasal). The high cost of CAPEX can be considered under VGF and help boost 2G biofuel production in India.

Another issue with the LCA of 2G ethanol in India is the limited availability of an India-specific life-cycle inventory database. Most LCA databases, such as Ecoinvent, GaBi, and Agribalyse, contain global averages or data for specific European countries. Most researchers rely on such databases, leading to reduced accuracy and increased uncertainty in Indian conditions. Government agencies, research institutes, and industries should collaborate to develop an India-centric LCA database that reflects actual Indian practices. Such datasets should be standardised, integrated into major LCA software tools, and made available in open access, so that they can be widely used to perform more accurate LCA studies in India.

7. CONCLUSION

This review synthesised evidence from 20 Indian based LCA studies evaluating the environmental load of 2G ethanol from LCB in India. The 2G ethanol demonstrated the potential to reduce GHG emissions compared with the fossil gasoline, simultaneously providing a utilisation pathway for agricultural residues. India's ambitious goals for ethanol blending into conventional gasoline aim to reduce crude oil imports. India has achieved 20% ethanol blending (E20) in gasoline by 2025 under the Ethanol Blended Petrol programme of the National Biofuel Policy. India primarily relies on 1G ethanol for blending, with sugar mills as the major producers, followed by grain-based distilleries. To overcome the issues related to food versus fuel, 2G feedstocks, such as agricultural residues, play a crucial role in meeting ethanol demand. 2G ethanol shows a significant reduction in GHG emissions but has higher impacts on acidification and eutrophication potential, as highlighted by previous literature. The primary cause of acidification and eutrophication is the increased use of pesticides and herbicides during biomass cultivation. Considering the overall GHG emissions and positive NER, the 2G ethanol remains a promising option.

Enhanced and effective pretreatment technologies, reduced enzyme use through in-house enzyme production, and utilisation of lignin for value-addition through the production of biochemicals and electricity help commercialise 2G ethanol. With specific India-centric data, more comprehensive LCA studies can be conducted, highlighting major technological breakthroughs. India-specific LCA studies can guide policy for the nation's sustainable development. The vehicle efficiency, emissions, and other maintenance associated with E20 fuels might impact internal combustion engines over the long run. Therefore, the impact of internal combustion engines on E20-blended fuel should also be incorporated into LCA studies of 2G ethanol to reflect real-world conditions and inform policy and industry decisions.

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Abbreviations

1G: First generation ethanol; 2G: Second generation ethanol; 3G: Third generation ethanol; LCA: Life Cycle Assessment; LCI: Life Cycle Inventory; LCIA: Life Cycle Impact Assessment; LCC: Life Cycle Costing; kWh: Kilowatt hours; MWh: Megawatt hours; SSCF: Simultaneous saccharification and co-fermentation; GWP: Global Warming Potential; GHG: Green House Gases; CAPEX: Capital expenditure; OPEX: Operational expenditure; FU: Functional Unit; NER: Net Energy Ratio; EROI: Energy Return on Investment.

Authors' contribution

Aditya Arvind Yadav: Writing – original draft, Data curation, Investigation; **Mithilesh Kumar Jha:** Writing – review & editing, Supervision; **Sachin Kumar:** Writing – review & editing, Supervision, Investigation, Validation, Conceptualisation.

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