

Life cycle assessment for circular biomanufacturing of lactic acid from sugarcane bagasse

Kumar Raja Vanapalli^{a,*}, Naseeba Parveen^a, Sunil K. Maity^{b,*}, Roberto Parra Saldivar^c, Samuel Jacob^d, Gopalakrishnan Kumar^e, Vinod Kumar^{c,f,*}

^a Department of Civil Engineering, National Institute of Technology, Mizoram, Aizawl, Mizoram, 796012, India

^b Department of Chemical Engineering, Indian Institute of Technology Hyderabad, Kandi, Sangareddy, 502284, Telangana, India

^c Magan Centre for Applied Mycology, Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield, MK43 0AL, UK

^d Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu, 603203, India

^e School of Civil and Environmental Engineering, Yonsei University, Seoul, 03722, Republic of Korea

^f Department of Engineering Technology, Cullen College of Engineering, University of Houston, Sugarland, TX 77479, USA

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ABSTRACT

Lactic acid (LA) is a top platform chemical with diverse applications in various industrial sectors. Sugarcane bagasse (SCB) is a significant waste stream during sugarcane processing. Our previous work was focused on the biomanufacturing of LA using fermentable sugars from SCB and techno-economic analysis. The current study evaluated the life cycle assessment (LCA) of SCB-based LA manufacturing for three different routes using the process models based on industrial-scale biorefinery – acid pretreatment & fermentation integrated with reactive distillation (ARD), alkali pretreatment & fermentation integrated with reactive distillation (AkRD), and alkali pretreatment & fermentation integrated with distillation (AkD). The environmental impacts were evaluated using attributional and consequential life cycle assessment (aLCA and cLCA). While aLCA was used to identify process hotspots by proportionally allocating environmental impacts, long-term impacts were assessed through cLCA by accounting for avoided products and additional burdens resulting from the upstream and downstream consequences of the processes. The aLCA analysis indicated that ARD had a 30–36 % superior environmental performance compared to AkRD and AkD, based on midpoint & endpoint impacts. The cooling water (45–47 %) and steam (27–29.1 %) during distillation, along with chemicals (18.4–24.2 %) in pretreatment and fermentation, were identified as environmental hotspots, with the respective values representing their proportionate contributions to the midpoint impacts across all scenarios. The cLCA depicted that LA recovered from the processes could offset environmental impacts by 34–44.2 %, emphasizing the long-term benefits of replacing the conventional LA manufacturing process. Moreover, valorisation of CO₂, gypsum, and steam as by-products could significantly reduce environmental impacts. The process heat integration pinch technology further reduced steam and cooling water demands, cutting the impact by 26–27.5 %. These findings emphasize the importance of water recycling and energy integration for improving the overall sustainability of SCB to LA valorisation.

Abbreviations

LA	Lactic acid
SCB	Sugarcane bagasse
LCA	Life cycle assessment
aLCA	Attributional life cycle assessment
cLCA	Consequential life cycle assessment
AD	Anaerobic digestion
ARD	Acid pretreatment & fermentation integrated with reactive distillation

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AkRD	Alkali pretreatment & fermentation integrated with reactive distillation
AkD	Alkali pretreatment & fermentation integrated with distillation
TEA	Techno-economic assessment
MW	Megawatt
MT	Metric ton
SDG	Sustainable development goals
NOx	Nitrogen oxides
CO ₂	Carbon dioxide

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* Corresponding authors.

E-mail addresses: kumar.ce@nitmz.ac.in (K.R. Vanapalli), sunil_maity@che.iith.ac.in (S.K. Maity), vinod.kumar@cranfield.ac.uk (V. Kumar).

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CHP	Combined heat and power
H ₂ SO ₄	Sulfuric acid
Ca(OH) ₂	Calcium hydroxide
FE	Freshwater ecotoxicity
FEu	Freshwater eutrophication
FPMF	Fine particulate matter formation
FRS	Fossil resource scarcity
GW	Global warming
HCT	Human carcinogenic toxicity
HNCT	Human non-carcinogenic toxicity
IRAD	Ionizing radiation
LU	Land use
ME	Marine ecotoxicity
TA	Terrestrial acidification
TE	Terrestrial ecotoxicity
MEu	Marine eutrophication
MRS	Mineral resource scarcity
OF, H	Ozone formation, Human health
OF, T	Ozone formation, Terrestrial ecosystems
SOD	Stratospheric ozone depletion
SI	Supplementary Information
WC	Water consumption
ISO	International Standards Organisation.

1. Introduction

Sugarcane is the largest cultivated crop globally, accounting for 21 % of the world's crop production (FAO, 2022). The processing of sugarcane generates sugarcane bagasse (SCB) as a major waste stream, with approximately 0.3 tons of SCB produced per ton of crushed sugarcane (Huang et al., 2020). As the world's second-largest sugarcane producer after Brazil, India generates over 100 million tons of SCB annually (Agrawal and Kumar, 2023). Conventionally, SCB is combusted for combined heat and power (CHP) generation to meet the sugar mill's energy demands and export surplus electricity (ISWA, 2022; Kabeyi and Olanrewaju, 2023). However, this practice results in significant emissions, including 34–311 ppm of CO, 8–80 ppm of Nitrogen oxides (NOx), and 6000–26,000 ppm of CO₂ for 18 kg/h SCB feed rate (Costa et al., 2023). As a fibrous and inexpensive source of fermentable sugars (Cardona et al., 2010), SCB is now a promising non-edible feedstock for biofuels and value-added renewable chemicals, such as lactic acid (LA).

The LA production from SCB is especially gaining attention as a sustainable alternative to food-based sugars, offering a low-cost, renewable carbon source for microbial fermentation (Oyewole et al., 2023). LA is a versatile platform chemical with diverse applications across packaging, medical, food, and pharmaceutical sectors (Alves de Oliveira et al., 2018), driving a global market forecasted to reach \$2.43 billion by 2028 (Haris et al., 2025). Notably, the current LA production relies heavily (~90 %) on starchy and sugar-rich edible feedstocks (Agrawal and Kumar, 2023). This increasing demand conflicts with Sustainable Development Goals (SDG), specifically SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), by diverting agricultural land and resources away from food production. Integrating non-edible SCB into LA production facilities in India presents a sustainable opportunity, helping to decarbonize the industry. Moreover, it can help reduce India's dependency on LA (along with its esters and salts) imports, which reached approximately 6391.12 Metric tons (MT) in 2023 (WITS, 2024). Considering the absence of industrial-scale SCB-to-LA manufacturing facilities in India, developing economically feasible production pathways using abundant SCB can be a sustainable opportunity.

LA production from lignocellulosic SCB involves multiple integrated steps: pretreatment, enzymatic hydrolysis, fermentation, and downstream separation (Li et al., 2021). Previous techno-economic assessments (TEA) have explored various configurations, such as acid/alkali/thermal pretreatments (van der Pol et al., 2015), acid/enzymatic hydrolysis (F. and Shastri, 2016; Zhang et al., 2022), neutral pH/low pH

fermentation (Daful et al., 2016; Gezae Daful and Görgens, 2017), and distillation/reactive distillation (Gezae Daful and Görgens, 2017; Munagala et al., 2021). Our previous TEA study focused on comparing these options, including dilute acid or alkali pretreatment and conventional or reactive distillation for downstream purification (Maity et al., 2025). Aspen Plus software was utilized to develop detailed process design models based on state-of-the-art experimental data, followed by a profitability analysis for return on investment (ROI) estimation and to assess the economic viability of these technologies. While TEA assesses economic viability, Life Cycle Assessment (LCA) is the necessary tool to determine the relative environmental performance and identify key process hotspots (Vanapalli et al., 2023).

Previous LCA studies have evaluated the environmental effects of SCB valorisation into electricity across many countries (Meghana and Shastri, 2020). Studies focusing on SCB-to-LA have identified sugarcane cultivation and energy-intensive LA separation as primary hotspots. However, most studies were conducted outside the Indian geographical context using region-specific resource and energy databases (Daful et al., 2016; Farzad et al., 2017; Munagala et al., 2021). Additionally, recent LCA studies on LA production from lignocellulosic and waste-derived feedstocks have continued to highlight the dominance of energy-intensive pretreatment and purification stages (Li et al., 2021; Senila et al., 2024; Yankov, 2022). However, existing assessments lack a comprehensive framework that combines process-scale modelling with both attributional and consequential LCAs. This limits their ability to capture regional environmental trade-offs and the system-wide benefits of process integration. Particularly, a consequential life cycle analysis (cLCA) considering the long-term environmental impacts of diverting SCB in India has not been conducted previously. Furthermore, the environmental benefits of heat integration through pinch analysis to mitigate energy-intensive separation steps remain unexplored in this context.

Therefore, the current comprehensive study aims to address these critical gaps by defining the most environmentally robust and sustainable pathway for SCB-to-LA production within the Indian context. The major objective is to evaluate the relative environmental performance of three distinct process routes, namely acid pretreatment & fermentation integrated with reactive distillation (ARD), alkali pretreatment & fermentation integrated with reactive distillation (AkRD), and alkali pretreatment & fermentation integrated with distillation (AkD). Achieving this requires a multi-dimensional approach: (i) Employing an attributional LCA (aLCA) to identify immediate process-level environmental hotspots; (ii) Conducting a cLCA to assess long-term environmental consequences, factoring in avoided burdens from replacing conventional LA and the additional burdens from SCB diversion; and (iii) Evaluating the environmental improvements achievable via thermal efficiency enhancement using pinch technology. Additionally, sensitivity and uncertainty analyses were performed to determine the consistency of the impacts. The findings are expected to provide valuable, context-specific insights for policymakers and LCA practitioners.

2. Methodology

2.1. Attributional life cycle assessment

2.1.1. Goal and scope

The goal of this LCA study was to quantitatively evaluate and compare the relative environmental performance of three distinct microbial conversion routes of SCB to LA and to identify the key environmental hotspots across each process. The three routes evaluated in the study were: (i) saccharification of SCB using acid pretreatment plus enzymatic hydrolysis followed by bacterial fermentation and reactive distillation (ARD), (ii) saccharification of SCB using alkaline pretreatment plus enzymatic hydrolysis followed by bacterial fermentation and distillation (AkD), and (iii) reactive distillation (AkRD). SCB was selected for this study due to its abundance as a by-product of India's

major sugarcane industry (Agrawal and Kumar, 2023). Further, its favourable composition (cellulose: 40–50 %, hemicellulose: 25–35 %, and lignin: 20–30 %) makes it an inexpensive source of fermentable sugars for valorisation through biochemical routes (Cardona et al., 2010; Konde et al., 2021). A cradle-to-gate aLCA considering all material and energy inputs/output streams from the sub-processes was conducted. This included sugarcane collection, processing, SCB recovery, transport, shredding, pretreatment, enzymatic hydrolysis, neutralization, fermentation, and downstream separation for the recovery of LA and other by-products. Through this aLCA, environmental burdens associated with the overall process were evaluated by proportionally allocating impacts based on material and energy flows. This approach enables the identification of specific stages, sub-processes, and resource inputs that contribute most significantly to the overall environmental impacts of the process. The scope of the study was confined to the plant capacities and processes described in Section 2.1 and depicted in Fig. 1. The functional unit for the LCA was defined as ‘processing of an equivalent 83333.34 kg of SCB for LA production’. This value corresponds to the hourly input feed rate, based on our previously developed process models with a daily wet SCB processing capacity of 2000 MT (Maity et al., 2025).

The phases of product logistics, downstream processing, end-use, and end-of-life management for the recovered LA were excluded from the current LCA system boundary. This decision was based on the wide functional diversity of LA and its derivatives across multiple industrial sectors, including bioplastics, solvents, cosmetics, pharmaceuticals, food preservation, and biodegradable coatings (Alves de Oliveira et al., 2018). Further, the end-of-life pathways for these products, such as composting, incineration, recycling, or landfilling, depend strongly on regional techno-economic conditions, infrastructure availability, and waste management practices (Fredi and Dorigato, 2021; Parveen et al., 2024). Due to this variability, incorporating downstream use or end-of-

life scenarios would not represent the overall system accurately and could lead to misleading interpretations of environmental impacts. Therefore, the gate-to-grave phase was excluded from the current study. The geographical scope was limited to India, as it hosts the world’s second-largest sugarcane industry after Brazil (USDA, 2025).

2.1.2. Process description

The LCA was conducted for an industrial-scale biorefinery with a processing capacity of 2000 MT (wet)/day SCB for fermentative bacterial (*Bacillus coagulans*) LA production based on optimized process models from our previous TEA study (Maity et al., 2025). The process simulation was conducted using Aspen Plus, utilizing its databases and property estimation methods. Optimized lab-scale experimental data on reaction conditions and process parameters for the bioconversion of SCB to LA were used as inputs for the simulation work (Baral et al., 2024; Mo et al., 2011; Shaji et al., 2022). These data were then applied to simulate the industrial-scale process models, which were used to determine the associated energy, material, and elementary flows. Based on these simulation data, the environmental performance of three different processing scenarios for biological conversion of SCB to LA were compared. The detailed process flows of ARD, AkD, and AkRD scenarios are depicted in Fig. 1.

The processes commenced with the pre-processing of SCB, which included mechanical size reduction to particles smaller than 2 mm, followed by dilute acid or alkali pretreatment coupled with enzymatic hydrolysis and downstream separation by distillation/reactive distillation.

2.1.2.1. Acid pretreatment. The size-reduced SCB was treated with 0.015 L of sulfuric acid per kg of dry SCB at 170 °C and 11 bar for 15 min. Steam and recycled hot water were added to the pretreatment reactor in a specific ratio to maintain the desired reactor temperature. The

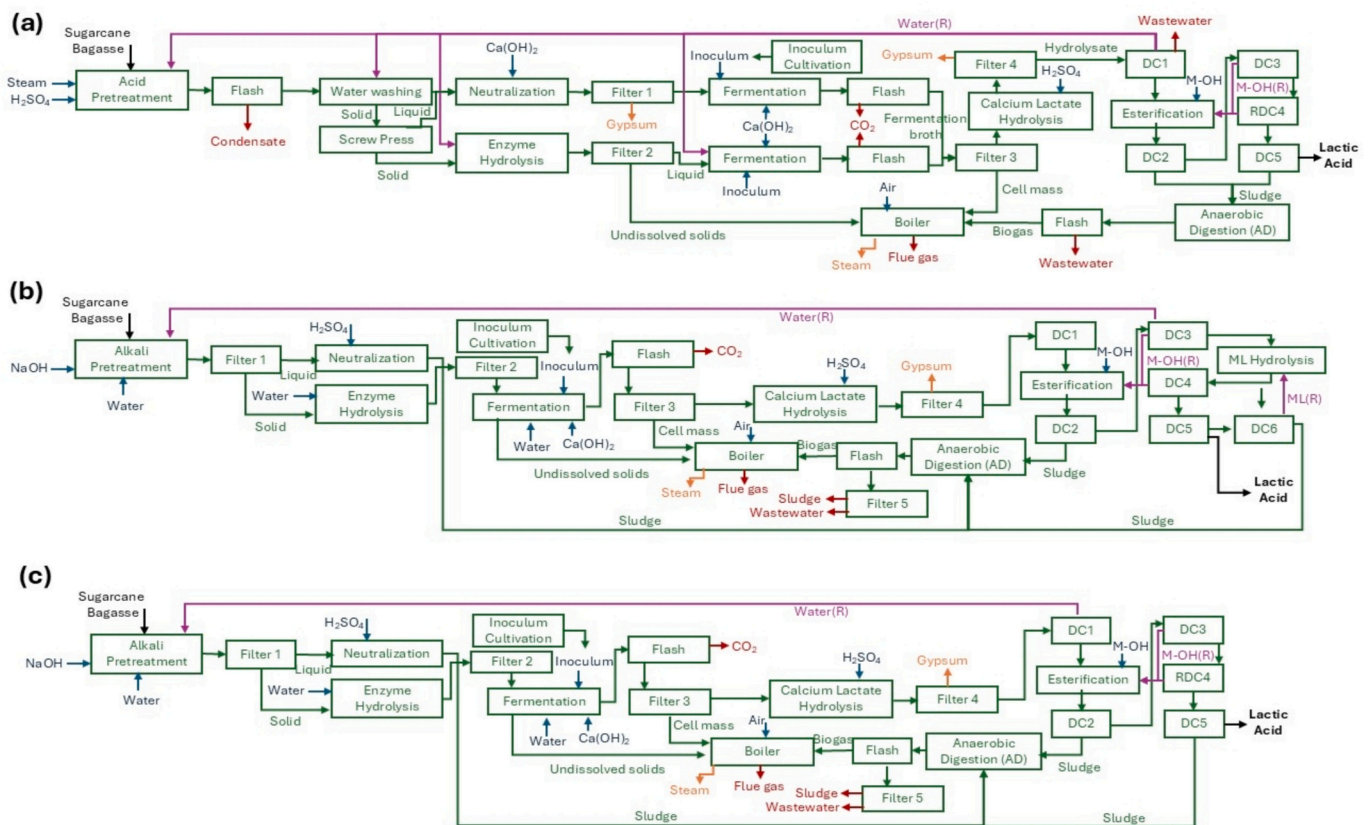


Fig. 1. Process flow diagrams for SCB valorization to LA. (a) ARD: acid pretreatment, enzymatic hydrolysis, fermentation, and reactive distillation, (b) AkD: alkali pretreatment, enzymatic hydrolysis, fermentation, and distillation, and (c) AkRD: alkali pretreatment, enzymatic hydrolysis, fermentation, and reactive distillation.

combined mass of these inputs was equivalent to a 5 wt% sulfuric acid. The resulting acid-treated SCB slurry was transferred to a flash drum, facilitating condensate separation ($\approx 9\%$). The remaining slurry was cooled and water-washed, removing 50 % of the soluble fraction, with 137 g/L sugar concentration. The recovered solid underwent screw pressing, which extracted 47 % of xylose sugars as a liquid. The combined xylose-rich liquid from the washer and press was then neutralised using calcium hydroxide, resulting in gypsum as a by-product. The solution was then heated to 50 °C and transferred to the fermenter. The recovered solid from the press was mixed with recycled hot water at 50 °C and subjected to enzymatic hydrolysis. The xylose sugar-rich liquid hydrolysate was sent to the fermenter, while the undissolved solids were filtered and transferred to the boiler. Along with inoculum, calcium hydroxide was added to both the fermenters containing liquid streams from neutralization and enzymatic hydrolysis for pH control. The fermentation broth containing calcium lactate was subjected to hydrolysis with sulfuric acid to regenerate LA with gypsum as a by-product. Meanwhile, the cell biomass contained in the fermentation broth was filtered and sent to the boiler for combined heat and power (CHP) generation. After filtering out the gypsum, the fermentation broth was forwarded to downstream separation. The LA yield after fermentation was 0.336 kg/kg of wet SCB and 0.517 kg/kg of dry SCB.

2.1.2.2. Alkali pretreatment. The size-reduced SCB was treated with 0.13 kg NaOH per kg of biomass in an autoclave at 121 °C for 30 min, with a total solid loading of 15 % (w/v). The alkali-pretreated slurry was filtered to separate solids, which were then hydrolysed enzymatically at 50 °C for 48 h using Cellic CTec3 enzyme, with a 20 % solid loading and 12.5 mg/g glucan protein loading. The filtered liquid from the slurry was neutralised with H₂SO₄, and the resulting neutralised black liquor was transferred to anaerobic digestion (AD) to generate biogas. The resulting concentrated hydrolysate was diluted with water and transferred to the fermenter to obtain 100 g/L equivalent LA titer with CO₂ as the by-product stemming from microbial respiration. The unconverted solids from the enzymatic hydrolysis and the cell biomass from the fermentation were individually separated by filtration and transferred to the boiler for steam co-generation. Additionally, the fermentation broth was processed in an H₂SO₄-mediated calcium lactate hydrolysis reactor at 50 °C to regenerate LA, with gypsum filtered as a by-product. The final yield of LA after co-fermentation was 0.356 kg/kg wet SCB, equivalent to 0.548 kg/kg dry SCB, which was slightly higher than that of acid pretreatment.

2.1.2.3. Downstream LA separation processes. The LA-regenerated hydrolysate from calcium lactate hydrolysis was concentrated using an evaporator equipped with a preheater and a distillation column (DC1). This step facilitated the better equilibrium conversion of LA to methyl lactate (ML) during esterification and reactive separation (Fig. 1). The concentrated LA stream from DC1 was then cooled to 96 °C and mixed with recycled methanol at a 3:1 M ratio. The resulting mixture was transferred to a fixed-bed esterification reactor, where approximately 85 % of the LA was converted to ML. The reactor effluent was conveyed to DC2, where a mixed liquid stream of excess methanol, ML, and water was separated from the unreacted LA and sugars. The latter stream was directed to anaerobic digestion (AD) for biogas generation. The surplus methanol from the distillate of DC2 was separated in DC3 and subsequently recycled back to the esterification reactor.

The subsequent stages of downstream LA separation were carried out using one of the two configurations: distillation or reactive distillation. Distillation configuration (D) involves hydrolysing ML in a fixed-bed reactor, separating LA from the product mixture by traditional distillation, and recycling unreacted ML. Therefore, a combined stream of water and ML from DC3 was mixed with another stream of recycled ML and water and then directed to a fixed-bed ML hydrolysis reactor. Methanol from the outlet stream of the hydrolysis reactor was distilled

in DC4 and then recycled back to the esterification reactor. In addition to the recycled methanol from DC3 and DC4, a small amount of additional makeup methanol was added for the losses during separation. From the DC4 stream, polymer-grade LA (99.99 %) was separated via vacuum distillation in DC5, yielding 0.30 kg per kg of wet SCB or 0.47 kg per kg of dry SCB. The recovered LA was then cooled to room temperature and transferred to a storage tank. The distillate from DC5, containing a mixture of unconverted ML and water, was transferred to DC6, where the water-rich ML stream was separated, cooled, and recycled to the ML hydrolysis reactor. Further, the low boiling azeotropic mixture of excess water and ML was separated from DC6 and directed to AD for generating biogas.

In the reactive distillation (RD) configuration, reaction and product separation occur in a single unit. This is an effective method to address the equilibrium limitations of an ML hydrolysis reaction. Although RD reduces capital investment and energy consumption compared to conventional methods, its key limitation lies in balancing reaction kinetics with vapor–liquid equilibrium in one operating unit (Maity et al., 2025). Therefore, the combined stream of water and ML from DC3 was directly sent to the RD column, where complete hydrolysis of ML was achieved. This results in the recovery of methanol as distillate which was recycled back to the esterification reactor. The output mixed stream of LA along with excess water was routed to DC5, where LA was recovered through vacuum distillation. The distillate from DC5, comprising a mixture of water and a small quantity of ML, was sent to AD for generating biogas. The biogas generated from the AD of all the liquid waste streams was burnt in the boiler together with the unconverted solids and cell biomass using air to generate high-pressure steam as a by-product. The undigested lignin and ash separated after AD by filtration in alkaline pretreatment processes can have applications as biofertilizers.

2.1.3. Life cycle inventory

The life cycle inventory (LCI) of SCB valorization was prepared using the high-quality inventory data generated from comprehensive process models (Maity et al., 2025). Table 1 lists the four stages of SCB valorization, detailing the input consumption, recycled materials, major output, and the outflows of byproducts and emissions. This inventory includes raw materials, byproducts, emissions, outputs, energy flows like electricity and heat, and capital goods (plant infrastructure). The mass and energy flows in various unit operations/processes of the biorefinery (Fig. S1, in the SI) were derived from the process simulation designed using Aspen Plus software. Aspen Plus is widely used for process design due to its extensive property database and robust thermodynamic models that ensure accurate mass and energy balance calculations. Process modelling for pretreatment, enzymatic hydrolysis, and fermentation stages was based on either laboratory-scale experimental data or established industry methods with mass balance closure, as detailed in our previous techno-economic analysis paper (Maity et al., 2025). For downstream LA separation, the commercial distillation process was compared with reactive distillation using a validated kinetic model. All end-to-end process scenarios were designed in Aspen Plus with validated thermodynamic models. Consequently, the material and energy balance data for the specified plant capacity represent deterministic outputs derived from fixed design and modelling assumptions. It is important to note that all the nutrients utilized during the inoculum cultivation phase were incorporated into the fermentation process of LCI. Additionally, the electricity demands of all unit operations were collectively represented as electricity (in kWh) by the individual processes. The ancillary data on the environmental footprints of the materials and processes involved in the LCI were obtained from the EcoInvent 3.10 databases (Table S1, in the Supplementary Information (SI)). The detailed LCI of the SCB recovery phase from sugarcane cultivation in the cLCA, along with the avoided products and additional burdens, is provided in Table S2, in the SI. Additionally, the following assumptions were made while compiling the LCI data.

Table 1

Life cycle inventory data for fermentative LA production using acid/alkali pretreated SCB at an input feed of 83,333.34 kg SCB integrated with fermentative distillation/reactive distillation processes.

Process	Category	Input/output				
		Item	Unit	ARD	AkD	AkRD
Pretreatment	Input	Sugarcane bagasse (SCB)	kg	83,330	83,330	83,330
		Steam (Medium pressure)	kg	8700	63,060	63,060
		H ₂ SO ₄	kg	1460	8630	8630
		NaOH	kg	–	7040	7040
		Process water	kg	–	3.370×10^5	3.370×10^5
		Lime	kg	812	–	–
		Enzyme	kg	899	1310	1310
		Electricity	kWh	1470	1540	1540
		Cooling water	kg	6.751×10^6	1.782×10^7	1.782×10^7
		Capital goods	kg	0.39	1.23	1.23
		Gypsum	kg	1880	–	–
		Condensate	kg	10,640	–	–
		Lime	kg	11,500	12,200	12,200
		H ₂ SO ₄	kg	14,900	16,200	16,200
	Output – byproduct	Process water	kg	–	1.411×10^5	1.411×10^5
		Nutrients	kg	6520	6880	6880
		Cooling water	kg	2.696×10^6	2.772×10^6	2.772×10^6
		Steam (Medium pressure)	kg	3220	5755	5755
		Electricity	kWh	329	433	433
		Capital goods	kg	0.45	0.27	0.45
		CO ₂ (from Fermentation)	kg	970	856	856
		Gypsum	kg	26,800	28,400	28,400
		Methanol (makeup)	kg	8.7	8.8	2.6
		Cooling water	kg	4.180×10^7	4.740×10^7	4.297×10^7
Fermentation	Input	Steam (Medium pressure)	kg	3.970×10^5	4.480×10^5	4.309×10^5
		Steam (High pressure)	kg	29,390	57,490	31,130
		Electricity	kWh	185	103	82.9
		Capital goods	kg	5.8	7.1	6.1
		Lactic acid	kg	23,880	25,210	25,200
		Water	kg	21,400	–	–
		Lignin	kg	–	–	–
		Gypsum	kg	–	–	–
		H ₂ SO ₄	kg	1.1×10^{-16}	–	–
		Lactic acid	kg	4.9	–	–
	Emission	Methanol	kg	–	–	–
		Air (0.79 N ₂ + 0.21 O ₂)	kg	2.351×10^5	1.37×10^5	1.340×10^5
		Cooling water	kg	1.179×10^6	2.013×10^6	2.003×10^6
		Electricity	kWh	1370	819.8	803
		Capital goods	kg	0.76	0.76	0.76
		Steam (Medium pressure)	kg	2.545×10^5	1.243×10^5	1.465×10^5
		Steam (High pressure)	kg	29,390	57,490	31,130
		Sludge	kg	–	9510	9510
		Water	kg	2497	5.071×10^5	5.072×10^5
		Lignin	kg	1.3×10^{-4}	0.84	0.84
	Output – byproduct	Ash	kg	–	0.11	0.11
		Gypsum	kg	2.7	3.3×10^{-3}	3.3×10^{-3}
		H ₂ SO ₄	kg	0.03	–	–
		Na ₂ SO ₄	kg	–	12,500	12,500
		Lactic acid	kg	–	–	–
		Methanol	kg	0.96	5.2	5.2
		Water	kg	23,860	14,830	14,830
		O ₂	kg	5.1	0.63	0.63
		N ₂	kg	1.804×10^5	1.051×10^5	1.051×10^5
		CO ₂	kg	61,435	38,510	38,510
Downstream separation	Emission -wastewater	Water	kg	–	–	–
		Lignin	kg	–	–	–
		Gypsum	kg	–	–	–
		H ₂ SO ₄	kg	1.1×10^{-16}	–	–
		Lactic acid	kg	4.9	–	–
		Methanol	kg	–	–	–
	Input	Air (0.79 N ₂ + 0.21 O ₂)	kg	2.351×10^5	1.37×10^5	1.340×10^5
		Cooling water	kg	1.179×10^6	2.013×10^6	2.003×10^6
		Electricity	kWh	1370	819.8	803
		Capital goods	kg	0.76	0.76	0.76
		Steam (Medium pressure)	kg	2.545×10^5	1.243×10^5	1.465×10^5
		Steam (High pressure)	kg	29,390	57,490	31,130
Anaerobic digestion	Output – byproduct	Sludge	kg	–	9510	9510
		Water	kg	2497	5.071×10^5	5.072×10^5
		Lignin	kg	1.3×10^{-4}	0.84	0.84
		Ash	kg	–	0.11	0.11
		Gypsum	kg	2.7	3.3×10^{-3}	3.3×10^{-3}
		H ₂ SO ₄	kg	0.03	–	–
	Emission -wastewater	Na ₂ SO ₄	kg	–	12,500	12,500
		Lactic acid	kg	–	–	–
		Methanol	kg	0.96	5.2	5.2
		Water	kg	23,860	14,830	14,830
		O ₂	kg	5.1	0.63	0.63
		N ₂	kg	1.804×10^5	1.051×10^5	1.051×10^5

1. The inoculum preparation was assumed to be under neutral pH conditions (Tiwari et al., 2023; Vanapalli et al., 2023).
2. The nutrient calculation was based on previous studies (Cox et al., 2022; Mailaram et al., 2023), which determined that a total of 0.273 kg of nutrients was required to produce 1 kg of LA. This quantity was further divided into various major and minor nutrients based on the proportions specified previously (Vanapalli et al., 2023).
3. The purity of LA recovered was considered >99 %, and all other input materials involved in the LA production were assumed to be of high purity (>99 %) on a mass basis.
4. The unit operations and material and energy flow involved in producing SCB from sugarcane cultivation and processing (Table S2, in the SI) were directly assigned to the parameter ‘SCB’, depicted as input in pretreatment. The environmental impacts of SCB as an input

5. The necessary equipment for processing 83,333 kg/h of sugarcane into SCB has been determined based on commercially available sugarcane crushing and SCB drying machines. Considering the specifications of sugarcane milling machines (53–100 hp. operating at 80 % efficiency (Patel Manufacturing Company, 2025)) and the bubbling bed SCB dryer (0.0173 kWh/ kg (Dongding Machinery, 2022; Manohar and Velraj, 2015)) for reducing the moisture content were calculated by following economic allocation based on the current market prices of SCB (3135 INR/ton $\approx$ 36 USD/ton) (Vatsyayan, 2021), the unprocessed sugarcane juice in India (39,391 INR/ton $\approx$ 452 USD/ton) (PM FME, 2023), and their quantities generated post-processing (83,333 kg of SCB and 228,758 kg of sugarcane juice) (Daful et al., 2016; Farzad et al., 2017; MERC, 2019).

from 50 % to 35 %, it was estimated that 53 sugarcane crusher machines and 40 dryer machines were required. The energy consumption of these machines was subsequently calculated, and a weight of 25 tons per machine was assumed for the calculation of capital goods.

6. As KH_2PO_4 , MgCl_2 , and $\text{Na}_2\text{PO}_4 \cdot 6\text{H}_2\text{O}$, were not available in the EcoInvent 3.10, their demand was calculated from stoichiometric calculations of corresponding substitutes: (H_3PO_4 and KOH with H_2O as by-product), (MgO , H_2O , and HCl), (Na_3PO_4 , HCl , and H_2O with NaCl as by-product), respectively (Thanahiranya et al., 2023; Vanapalli et al., 2024, 2023).
7. All material and energy data inputs into the LCA model were derived from Indian averages as provided in the databases of EcoInvent 3.10. For any data not available specific to India, the rest of the world averages were considered.
8. The electricity mix was modelled based on the southern Indian grid. This region grid was selected because it is one of the areas where the target industry is concentrated, with sugarcane cultivation and bagasse production being predominant there.
9. The capital goods were determined by calculating the amount of steel (kg) utilized in the infrastructure and equipment manufacturing based on the dimensions derived from the Aspen Plus simulation model (Maity et al., 2025). The equipment's design life was assumed to be 20 years, and the average hourly capital goods were calculated accordingly. It is important to note that the installation, land usage, maintenance, and decommissioning phases of the capital goods were excluded from the scope of the LCA model due to limitations in data availability within the database of EcoInvent 3.10 (Tiwari et al., 2023; Vanapalli et al., 2024; Vinardell et al., 2023). Although this represents a conservative estimation of the capital goods related environmental impacts, it was supported by previous research reporting that environmental effects of infrastructure for large-scale processes with very long lifecycles are negligible (Li et al., 2022).
10. For the recycled streams of water, methanol, and ML, only the net masses added as surplus were included as inputs in the individual subprocesses for simplified LCI analysis.
11. The gypsum and steam generated as by-products of the process were treated as avoided products in the LCA model based on system expansion approach, negating their environmental impacts from the total impact of the processes.
12. To account for significant logistical variability in the Indian sugar industry (where farm-to-mill distances can exceed 100 km) (Yogesh Bhatt et al., 2021) and to model a nascent biorefinery supply chain, a conservative transportation distance of 150 km was assumed for both the phases: SC from the field to the mill, and SCB and other raw materials from the industry to the biorefinery.
13. The characteristics of condensate from acid pretreatment in the ARD process were compared to wastewater (available in the EcoInvent database), with a total organic carbon (TOC) of 0.1091 kg/m^3 , chemical oxygen demand (COD) of 0.42534 kg/m^3 , biochemical oxygen demand (BOD) of 0.20572 kg/m^3 , and a density of 1000 kg/m^3 (Rhee et al., 2021).
14. As lignin, a component of wastewater from the AD process, was not available in the EcoInvent 3.10 database, an equivalent amount of TOC was used in the LCA model.

2.1.4. Life cycle impact assessment

The LCIA was conducted using the ReCiPe 2016 (H) method, analysed at both midpoint and endpoint levels with SimaPro software (v9.6 PhD) (SimaPro, 2025). ReCiPe 2016 was selected because it is one of the most comprehensive and widely used LCIA methods for bio-based chemical production systems. Compared to other LCIA frameworks

such as CML, TRACI, and ILCD, ReCiPe 2016 offers harmonised and updated characterisation factors. While CML and ILCD focus mainly on midpoints, TRACI is specific to U.S. conditions, whereas ReCiPe provides globally applicable factors that are suitable when region-specific methods are unavailable. Its impact pathways effectively represent the key environmental mechanisms of biorefinery systems, including biochemical conversion, energy-intensive separation, and agriculture-based supply chains (Rybczewska-Błażejowska and Jezierski, 2024). Its midpoint–endpoint framework is particularly relevant for biorefineries, where understanding both resource use and long-term impacts on human health and ecosystems is crucial for informed decision-making. Midpoint indicators represent intermediate measures of environmental impact reflecting changes in the natural environment that allows detailed assessment of contributions from individual process stages and identification of trade-offs across categories. Endpoint indicators, by contrast, aggregate these midpoints into broader areas of protection providing a higher-level view of sustainability outcomes (Fiorani et al., 2024). Evaluating both levels ensures a balanced perspective, where midpoint results enable precise diagnosis of environmental hotspots within the processes, while endpoint results can translate these findings into decision-relevant outcomes. According to the ReCiPe methodology, all 18 midpoint impact categories, as well as 3 endpoint impact categories (human health, ecosystems, and resources), were considered. The list of midpoint and endpoint impact categories, along with their units as per ReCiPe2016(H), is depicted in Table S3, in the SI. Additionally, the study applied the ‘system expansion and substitution’ approach for allocation of impacts for major by-products, as recommended by International Standards Organisation (ISO) 14,044. The midpoint and endpoint impacts were aggregated into normalized values and single-point scores from individual characterisation values across various categories. This process involved normalizing characterisation scores to a common unit before weighting them based on their relative importance. These weighted scores were then aggregated to produce a final single score (M.A.J. Huijbregts et al., 2016). Based on the results, the hotspot impact categories of concern, as well as the related unit processes/subprocesses and material and energy flows contributing to these impacts, were identified.

2.2. Consequential life cycle assessment

Our baseline scenario involved an attributional approach, where environmental impacts were shared between the products/processes based on the proportionate allocation of individual material and energy flows required for processes. However in the cLCA, we employed a ‘system expansion approach’ (Alvarenga et al., 2013), accounting for avoided products and additional burdens as potential upstream and downstream consequences of the process. This allowed the evaluation of long-term and indirect impacts, providing a broader systems perspective that extends beyond the immediate system boundaries. It also enabled the assessment of potential trade-offs arising from product or technological substitutions, along with any additional process-related burdens. For instance, the conventional use of SCB was to cogenerate heat and electricity to fulfil the energy demands within the sugarcane processing plant, while the surplus electricity was exported to the Indian national grid. However, considering that SCB will be diverted to LA production as an upstream consequence of the current study, this cogeneration becomes unfeasible. Consequently, to compensate for the resulting electricity deficit in both the sugarcane plant and the Indian national grid, an additional burden was introduced in the cLCA. The additional electricity burden was calculated based on the assumption that the CHP generation from burning 1.8 kg of SCB is equivalent to 1 kWh of electricity (C. Dinakaran et al., 2016; Purohit and Michaelowa, 2007; TERI, 2022), and the plant operates at $80\% \eta$ (Michael and Casten, 2004). The resultant air emissions from SCB burning at the co-generation plant (CO_2 (1618 g kg^{-1}), CO (5.7 g kg^{-1}), CH_4 (2.29 g kg^{-1}), PM_{10} (1.81 g kg^{-1}), and $\text{PM}_{2.5}$ (1.19 g kg^{-1}) of SCB) (Mugica-Álvarez et al., 2018), which

were eliminated as a result of this diversion, were added as avoided emissions. Further, the ash from burning SCB (15 kg of ash per ton of SCB) in co-generation plants (Ramjeawon, 2008) was traditionally used to partially supplement the cement demand (4:1 cement to ash ratio) (Jamsawang et al., 2017). Therefore, an equivalent amount of cement to be additionally produced due to the diversion was added as an additional burden in cLCA.

The CO₂ generated from the fermentation process was considered as an emission in the aLCA model. However, in the cLCA, the CO₂ was considered a byproduct, substituting the traditionally produced and commercially available compressed CO₂ as an avoided product (1:1 mass substitution). This included the additional burden of electricity required in CO₂ compression (110 kWh/ton of CO₂) after recovery from the fermentation process (Dees et al., 2023). The undigested lignin and ash, separated as sludge after AD by filtration in alkaline pretreatment processes, were considered as recoverable nutrients to be used as fertilizer in agriculture. Therefore, the recoverable nutrients from the filtered sludge were calculated as equivalent of total nitrogen (N), phosphorus (P), and potassium (K) contents (27.55 kg, 32.63 kg, and 5.55 kg, respectively, per ton of sludge) (Cañote et al., 2021; Tiwari et al., 2023). They were included as avoided products to substitute commercial N (NH₄NO₃), P (PO₄³⁻), and K (KCl) fertilizers in the market. The LA recovered as the main output from all the processes was considered to substitute commercial LA in the market as a downstream outcome of the process. Therefore, an equivalent amount of traditionally produced commercial LA was added as an avoided product (1:1 mass substitution). This included diverting SCB from conventional incineration and substituting recovered CO₂ and LA into commercial products (see section 2.3 and Fig. S2, in the SI). The detailed description of the assumptions, quantitative details, and data sources used for avoided products and additional burdens in cLCA is depicted in Table S4, in the SI.

2.3. Scenario analysis – integration with heat recovery and recirculation

To enhance the energy efficiency of biorefinery systems, a potential scenario of heat recovery and recirculation across various processes was considered to support the energy requirements of system. Pinch technology adopts process integration technique to strategically connect the hot and cold streams across the processes using an optimal heat exchanger network system. Pinch technology seeks to enhance the energy efficiency of biorefinery systems by facilitating efficient exchanges between recoverable internal heat energy demands using steam and in-process cooling water recycling. This thermal integration reduces the requirement for externally generated steam, thereby lowering associated resource and energy demand which can result in significant reductions in the environmental impacts. The cost-benefit analysis carried out in our previous techno-economic study depicted 10–11 % reduction in LA manufacturing costs with integration of the pinch technology (Maity et al., 2025). Therefore, the relative enhancement in the environmental efficacy of the base scenario was analysed using process integration via pinch technology to evaluate the potential for maximizing thermal efficiency and overall system performance. The LCIA depicting the energy and mass flows of processes with pinch technology is given in Table S5, in the SI.

2.4. Sensitivity and uncertainty analysis

A sensitivity analysis was conducted on the critical environmental hotspot parameters identified across the processes, varying them by ± 5 % and ± 10 % to assess the variability in their environmental impact performance. Additionally, to account for regional variability, factors such as transportation distances, electricity grid mix, and the market price of SCB were evaluated through sensitivity analysis. Additionally, an uncertainty analysis (95 % confidence range) using Monte Carlo simulations (10,000 runs) was performed in SimaPro with ReCiPe 2016

midpoint (H) method. Finally, the LCIA results obtained from SimaPro software were analysed in Microsoft 365 Excel for comparative interpretation.

3. Results

3.1. Attributional life cycle assessment

The relative environmental impacts of SCB valorization to LA using three different routes (ARD, AkD, and AkRD) are illustrated in Fig. 2. The normalized values of midpoint and endpoint impacts were used for effective comparison and cumulative impact determination. Positive values indicate the negative environmental impacts of the processes, while negative values depict avoided impacts and consequent environmental benefits. The proportionate contributions of individual sub-processes and input/output parameters to the midpoint and endpoint impacts of the three different processing scenarios were used to identify the critical environmental hotspots. The significance of these effects across impact categories was evaluated to recognize the zones of maximum potential concern.

Fig. 2a illustrates the significant variations in the midpoint impacts of ARD, AkD, and AkRD scenarios across their sub-processes, primarily influenced by differences in resource consumption, chemical inputs, and energy demand. The distillation stage emerged as the primary driver of impact within the ARD, AkD, and AkRD processes. It was responsible for a significant portion of their total normalized midpoint impact scores, accounting for 82.6 % (ARD), 61.2 % (AkD), and 59 % (AkRD) (Fig. 2c). The majority of these impacts can be attributed to the demand for cooling water (55.5–56.8 %) and steam (43–44.3 %) in the process. A similar trend was exhibited in the endpoint impact contributions (Fig. S3, in the SI) of the distillation process, reinforcing the resource intensiveness of the process. Following distillation, the pretreatment stage depicted the second-highest environmental impacts. The impacts of this stage were majorly contributed by H₂SO₄ and enzyme consumption (47.8–48.4 %), followed by cooling water utility (31.6–35.3 %) during the process.

In contrast, fermentation was the least resource-intensive step. Chemicals were the significant input factor, representing 74–74.2 % of the impacts of the fermentation stage, followed by cooling water utility (18.5–19.6 %). Other input parameters, including transportation, SCB production, electricity consumption, and CO₂ emissions and wastewater release played a minimal role in the observed environmental impacts. Considering the endpoint impacts, human health was the highest affected impact category due to fermentation, followed by ecosystem and resources (Fig. 2d). Notably, the AD supported by the boiler stage contributed the most substantial environmental benefit, particularly in the impact categories of terrestrial ecotoxicity, fossil resource scarcity, and marine ecotoxicity. The steam generated as a byproduct played a key role in reducing overall emissions, offsetting the environmental footprint of other input parameters. ARD benefited the most from steam as a by-product, effectively offsetting the emissions by 18.9 % and reducing overall environmental impact (Fig. 2b).

Based on the overall midpoint and endpoint impact analysis, ARD was identified as the environmentally preferable option, followed by AkRD and AkD, considering their overall environmental performance. Alkali-based processes exhibited significantly higher environmental impacts due to relatively higher H₂SO₄ and enzyme consumption, along with the additional impacts imparted by the NaOH demands of the process. Specifically, ARD demonstrated significantly lower environmental impacts, ranging from.

32–35.7 % at the midpoint and 30–34.5 % at the endpoint, compared to the other two process configurations. The major environmental hotspots identified were cooling water and steam used in the downstream separation process and chemicals used in pretreatment and fermentation processes across all the systems. Specifically, H₂SO₄ (pretreatment and fermentation) and enzymes (pretreatment) significantly contributed to

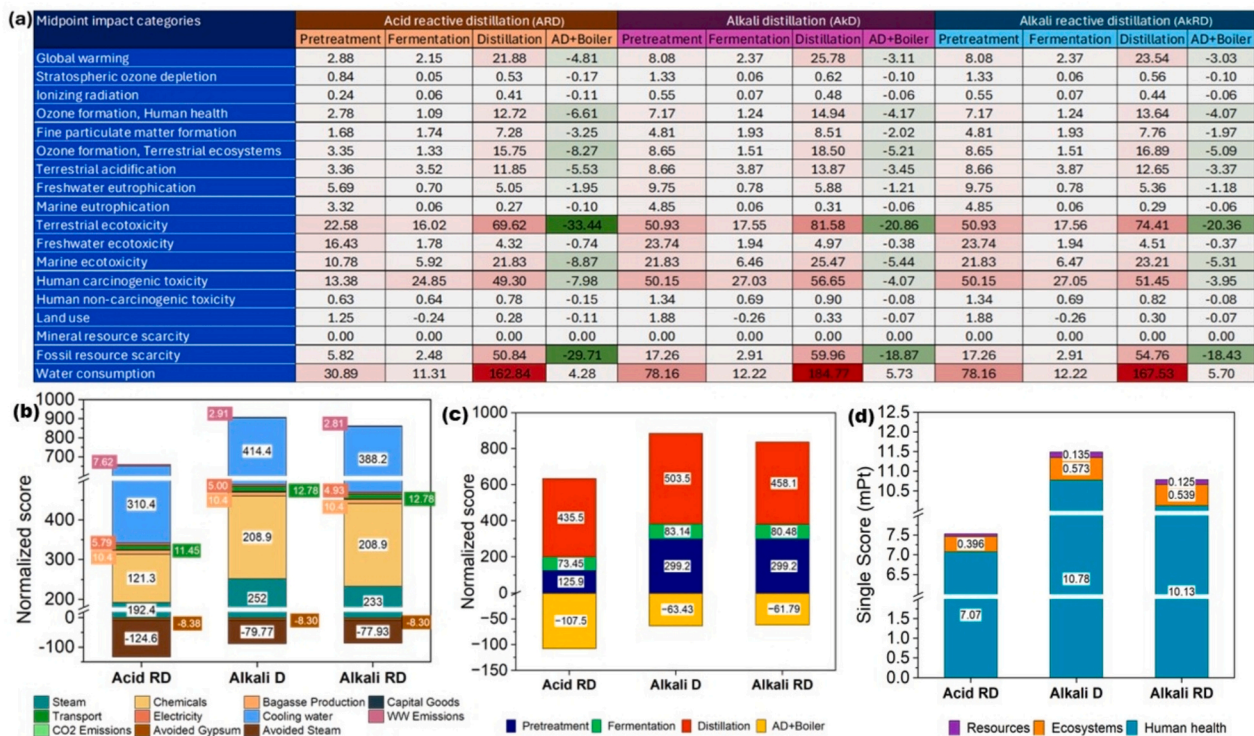


Fig. 2. Midpoint and endpoint environmental impacts among SCB valorization scenarios: (a) Relative midpoint impacts (normalized scores) of various processes across eighteen impact categories; (b) Categorical classification of midpoint impacts; (c) Contribution analysis of midpoint impacts among sub-processes; (d) Relative endpoint impacts (single score) of various processes across three endpoint impact categories.

the environmental impacts associated with these chemicals. The proportionate contribution of cooling water, steam, and chemicals to the overall midpoint impacts of these processes were 45–47 %, 27–29.1 %, and 18.4–24.2 %, respectively. These findings emphasize the need for optimizing water efficiency while minimizing chemical inputs to reduce environmental burdens in the current bioprocessing system.

The recycling of methanol (ARD, AkD, and AkRD) and ML (AkD) in the study significantly decreased the demand for these chemicals, reducing the overall resource impact on the processes. Additionally, steam generated as a by-product from the AD process integrated with boilers can be used to complement the steam demands of the overall process (by 31.7–64.8 %). It can reduce the need for external steam sources and cutting additional energy and resource requirements. Further, heat integration within the biorefinery can optimize energy efficiency, reducing reliance on external heating and cooling systems and enhancing overall environmental performance (Adom et al., 2014; Vanapalli et al., 2023). The complete midpoint characterisation data for all three process configurations is depicted in Table S6, in the SI. The detailed contribution analysis showing variations in the relative shares of materials, energy inputs, and avoided products across the three SCB valorization scenarios is presented in Figs. 2b and S2a (in the SI).

3.2. Consequential analysis

The cLCA accounted for both additional burdens and avoided products (byproducts) as long-term consequences of the technologies. This included diverting SCB from conventional incineration and substituting recovered CO₂ and LA into commercial products (see section 2.3 and Fig. S2, in the SI). The relative midpoint and endpoint environmental impacts of cLCA among the three processing scenarios are presented in Fig. 3. LA avoided alone represented the highest offsets in the environmental impacts by 34–44.2 % (midpoint) and 32–39.1 % (endpoint) of the total impacts. This highlights the long-term environmental benefits of replacing conventional production methods for

commercially available LA. Further, CO₂ recovered from microbial respiration during fermentation, considered an emission in aLCA model, could compensate for 0.17–0.25 % of the total impacts. However, it should be noted that the additional electricity requirement (by 5.3 %) for captured CO₂ compression was responsible for surplus environmental emissions.

The environmental impacts of SCB production increased by 12.1 % (midpoint) and 260 % (endpoint) compared to the aLCA models. This could be attributed to the additional burden of electricity to the grid (46,296.3 kWh) and cement as a substitute (250 kg) for incineration ash. Moreover, the avoided environmental emissions from the cogeneration plant negatively contributed to the impacts. Further, the recoverable nutrients from the filtered sludge in AkD and AkRD, considered commercial fertilizer substitutes, could negate up to 0.77–0.81 % and 0.8–0.85 % of the midpoint and endpoint impacts, respectively.

The midpoint and endpoint impact assessments (Fig. 2b, d) revealed notable reductions in environmental burdens while considering system expansion in cLCA. Across all impact categories, lower impacts were observed for both ARD and alkali-based processes. Considering the midpoint impact categories, the highest reductions were observed in freshwater eutrophication (111–162 %), fossil resource scarcity (82–161 %), ozone formation in terrestrial ecosystems (80–143 %), and marine eutrophication (89–122 %). Considering endpoint impact categories, impacts on human health decreased significantly, with ARD showing a 54 % reduction, while AkD and AkRD experienced declines of approximately 38 % and 40 %, respectively. Ecosystem impacts followed a similar trend, with ARD showing the greatest reduction (37 %), while AkD and AkRD saw declines of 26 % and 30 %, respectively. Resource depletion impacts shifted from a slight positive burden in aLCA to a net benefit in ARD under cLCA, while AkD and AkRD showed minimal resource impacts. Overall, the midpoint impacts through cLCA showed a reduction of 55.7 %, 38.6 %, and 40.7 % from aLCA across ARD, AkD, and AkRD processes, respectively. Similarly, endpoint impacts in cLCA showed reductions of 54.1 %, 38 %, and 40.4 % for these

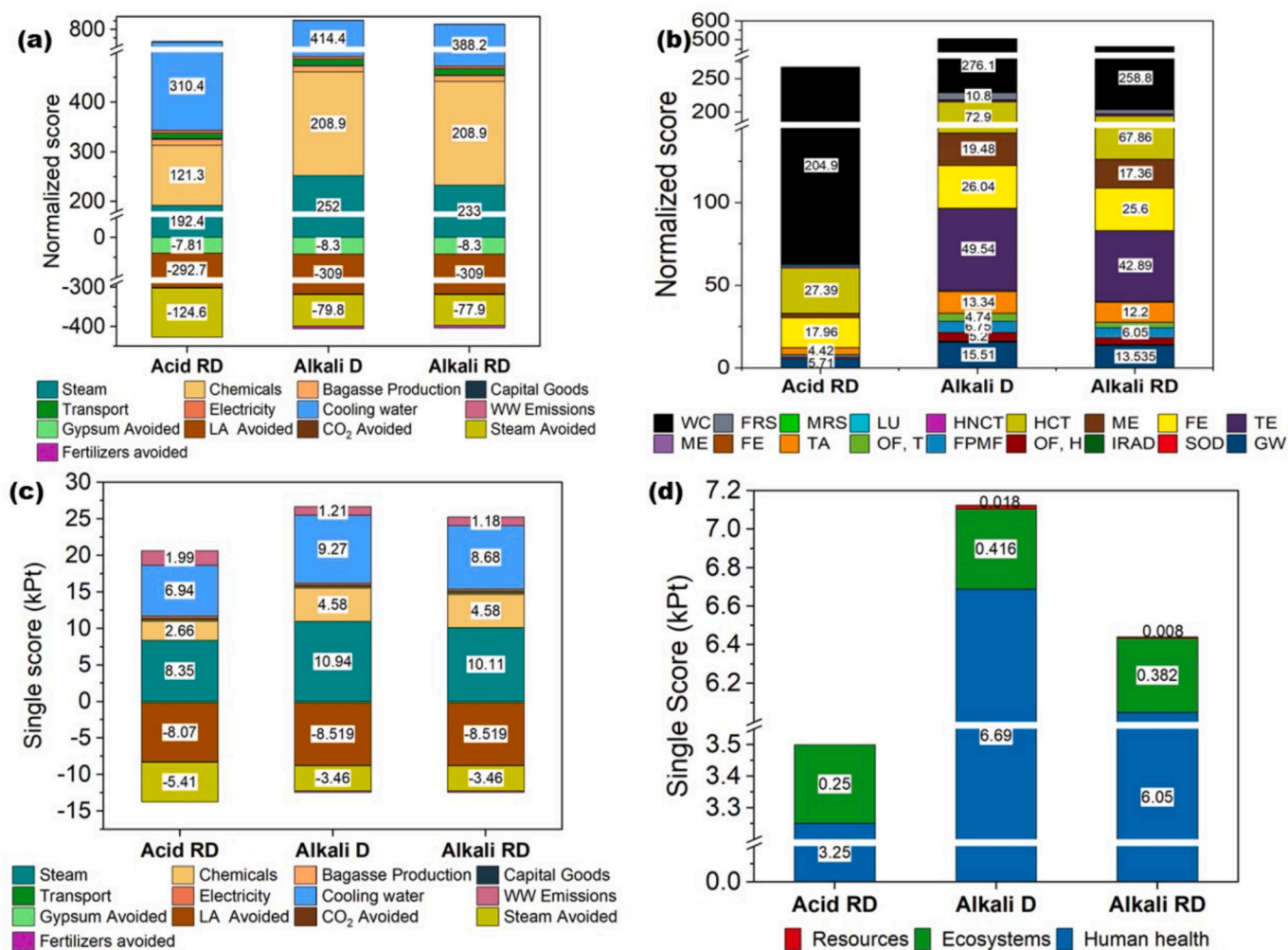


Fig. 3. Midpoint and endpoint environmental impacts of consequential LCA among SCB valorization routes: (a) Categorical classification of midpoint impacts; (b) Relative midpoint impacts (normalized scores) of various processes across eighteen impact categories (c) Categorical classification of endpoint impacts; (d) Relative endpoint impacts (single score) of various processes across three endpoint impact categories.

processes, respectively. Overall percentage reductions in the midpoint (normalized values) and endpoint (single score) impacts between attributional LCA and consequential LCA are given in Table S7, in the SI.

3.3. Scenario analysis

Considering cooling water and steam as critical process hotspots, a scenario analysis was conducted with heat integration by pinch technology for improving energy efficiencies through heat recovery and recirculation across processes. The relative environmental impacts of heat-integrated processes compared to the base scenarios are illustrated in Fig. 4. The heat integration by pinch technology reduced the overall steam and cooling water demands by 31.8 %, 27 % (ARD), 35.7 %, 29.8 % (AkD), and 38.2 %, 31.5 % (AkRD), respectively. While the steam demand of fermentation processes was completely met by heat recycling, significant reductions (by 29.3–31.9 %) were recorded in the distillation stage. In the case of cooling water consumption, the distillation stage alone depicted a reduction of 33.9–39.6 %. Additionally, steam from the AD process added as an avoided product was able to offset 94.4 % (ARD), 49.2 % (AkD), and 54.1 % (AkRD) of overall steam impacts of the pinch technologies. This corresponds to an overall reduction in the midpoint impacts by 26–27.5 %, and the endpoint impacts by 29.1–31 % following the order of ARD > AkRD > AkD (Fig. 4a, b). The relative midpoint and endpoint environmental impacts as per aLCA of different processes, along with their categorical

classification, are depicted in Fig. S4, in the SI. The complete midpoint characterisation data of these heat-integrated scenarios with pinch technology is depicted in Table S8, in the SI.

3.4. Sensitivity and uncertainty analyses

Sensitivity analysis was conducted to evaluate how variations in critical input parameters (cooling water, steam, and chemicals) affect the overall environmental impacts of the SCB-to-LA production processes. Fig. 5a,b illustrates the relative changes in midpoint and endpoint impacts, respectively, in response to ± 5 % and ± 10 % changes in these inputs. The ± 5 – 10 % ranges tested represent typical operational variability for utility streams in biorefinery settings, thereby ensuring real-world relevance of the results. The results reveal that cooling water consumption is the most influential parameter, with a ± 10 % variation causing approximately a ± 5.89 % change in midpoint impacts and a ± 4.61 % change in endpoint impacts. This strong sensitivity reflects the large contribution of cooling water to the overall environmental footprint, primarily through its role in the distillation stage. Consequently, the findings suggest that water management as the single most critical environmental bottleneck in the SCB-to-LA process.

Variations in steam consumption significantly affect the impacts, albeit to a slightly lesser degree than cooling water at the midpoint level (up to ± 3.64 %) but with notably higher variability at the endpoint level (up to ± 5.54 %). The greater endpoint sensitivity suggests that changes

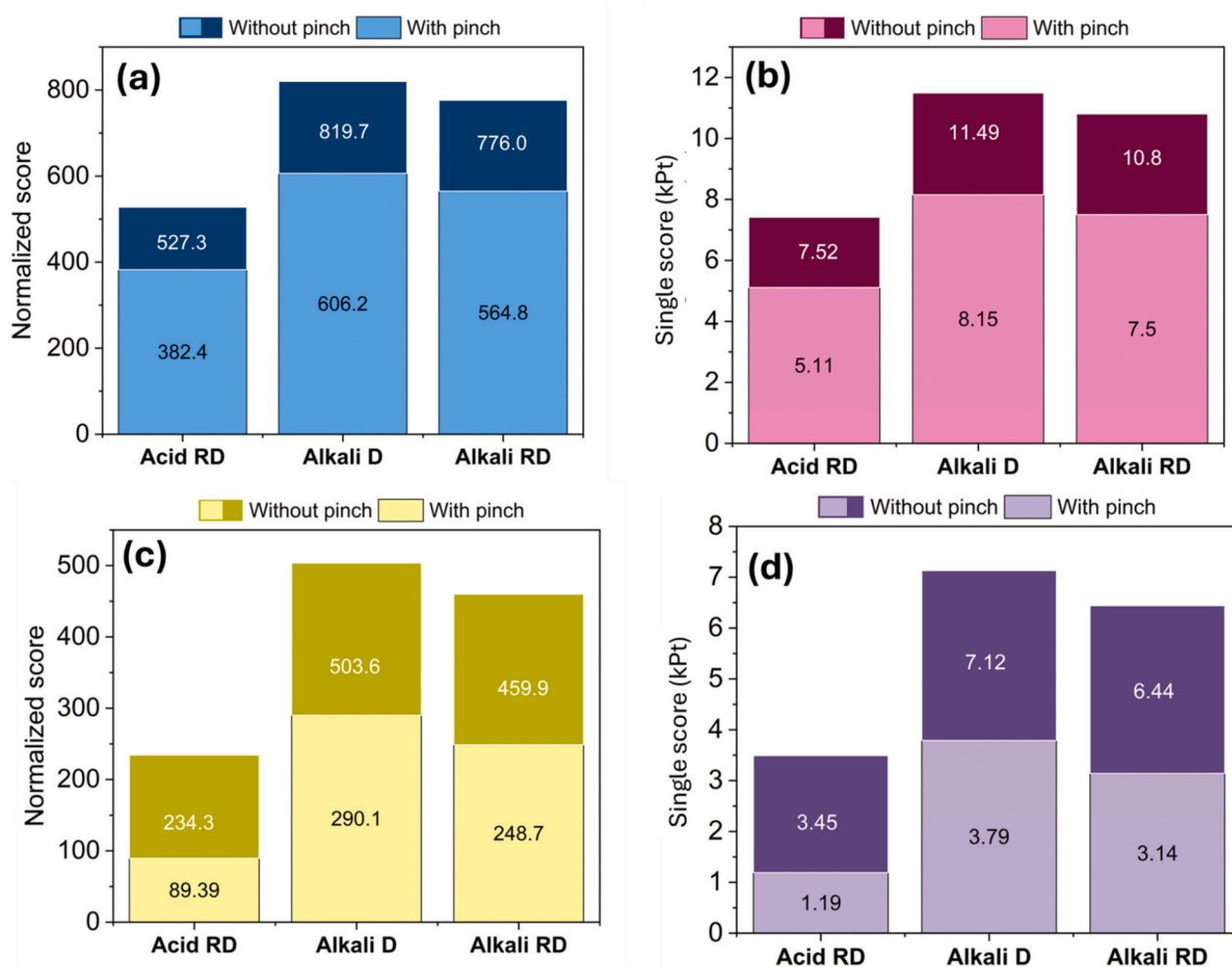


Fig. 4. Overall impact scores for scenario analysis of with and without pinch technology for (a) aLCA midpoint, (b) aLCA endpoint, (c) cLCA midpoint, and (d) cLCA endpoint impact categories.

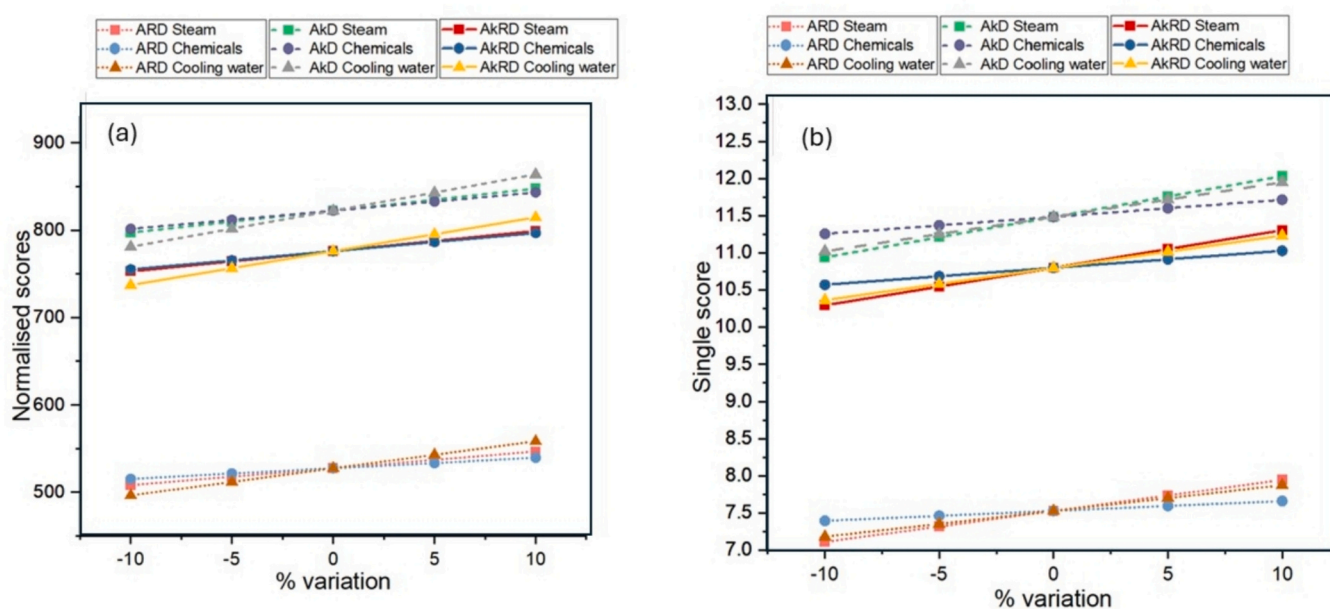


Fig. 5. Sensitivity analysis showing variations in the respective (a) midpoint and (b) endpoint impacts with variations in the hotspot input parameters.

in steam demand can disproportionately influence long-term human health and ecosystem impacts, likely due to the fossil resource use and emissions associated with steam generation. These outcomes reinforce the critical importance of thermal efficiency enhancements for lowering burdens associated with endpoint impact categories.

In contrast, chemical consumption exhibits the least sensitivity, with ± 10 % variation resulting in less than ± 2.69 % change in midpoint impacts and under ± 2.12 % at the endpoint. While still non-negligible, the lower sensitivity highlights that process optimization in chemical input use yields only incremental environmental benefits compared with water and energy management priorities. These sensitivity trends are consistent across all three process routes and are further supported by sensitivity results for pinch-integrated processes (Fig. S5 in the SI). This demonstrates that heat integration not only improves energy efficiency but mitigates the variability in environmental impact related to steam consumption. Collectively, these results underscore that utility flows, particularly cooling water and steam, are leverage points for process improvement, both from a technical design and sustainability perspective. While single-parameter sensitivity analysis robustly identifies these drivers, future research could incorporate global sensitivity methods to account for parameter interactions, thereby offering deeper insight for comprehensive optimization (Baaqel et al., 2023).

The effects of logistical variability (± 50 km, ± 100 km) and volatility in the market prices of SCB resulted in changes of less than ± 1.5 % and ± 0.2 %, respectively, in the overall midpoint impact results. Furthermore, when the baseline electricity scenario (southern grid) was replaced with energy mixes from the northern, eastern, or western grids, the variation observed in the total midpoint impacts remained below 0.22 % (Fig. S6 in the SI). These results collectively demonstrate that the LCA findings are highly robust to geographical and market fluctuations, and that the environmental profile is overwhelmingly dominated by the core on-site process utility consumption (cooling water and steam).

Complementing the sensitivity analysis, uncertainty analysis via Monte Carlo simulation (10,000 iterations) assessed the robustness of the environmental impact estimates for processing 86,333 kg of SCB (Table S9, in the SI). The low coefficients of variation (Cv) were observed across key impact categories, ranging from approximately 2.7 % to 7.9 % (e.g., water consumption, terrestrial ecotoxicity, fossil resource scarcity, human carcinogenic toxicity). This proves high confidence and reliability in the LCA results. A $Cv < 10$ % indicates that the mean impact value is a stable and highly representative estimate (Lloyd and Ries, 2007). It confirms that the inherent variability and uncertainty in the underlying inventory data do not significantly alter the magnitude or ranking of the identified environmental burdens.

4. Discussion

4.1. Process hotspots

Across all the processes, cooling water and steam were identified as the critical process hotspots. Cooling water and steam impacts are primarily linked to raw water sourcing, treatment, and energy requirements for heating and cooling. Implementing closed-loop recirculation systems with near-zero liquid discharge could substantially reduce raw water demand and wastewater generation, enhancing overall sustainability (Alnouri et al., 2018; Lamolinara et al., 2022; Vanapalli et al., 2024). In the current study, water recycling from distillation was already integrated to partially offset water needs for enzyme hydrolysis, washing, and fermentation in ARD, and pretreatment across all three scenarios. However, a techno-economic feasibility assessment of such integrated systems remains essential to ensure the desired quality of steam and cooling water.

Beyond water management, process integration offers significant environmental benefits. Steam generation in ARD proved critical in offsetting the impacts associated with emissions from boiler-based CHP systems used for sludge management and biogas combustion, which

were previously identified as environmental hotspots (Khoshnevisan et al., 2020). Supplementary analysis of industrial steam generation (1 kg of steam) (Fig. S7, SI) confirmed that steam as a byproduct provided tangible environmental benefits across all three scenarios. Similarly, gypsum recovered from the fermentation stage yielded comparable benefits, reducing total impacts by 0.9–1.3 %. In contrast, Gezae Daful and Görgens (2017) treated gypsum as a waste product, leading to higher emissions. This highlights the importance of co-product recovery as a strategy to enhance bioprocessing efficiency.

Consistent with previous findings on SCB valorization (Munagala et al., 2021) and industrial candy waste fermentation (Vance et al., 2024), NaOH consumption during alkali pretreatment emerged as a major contributor to environmental impacts in the current study. The utility and energy hotspots identified in the current study align with the findings of other studies, which depicted water consumption (Daful et al., 2016), chemical inputs (Farzad et al., 2017; Mandegari et al., 2018; Munagala et al., 2021), and energy-intensive utilities such as steam, cooling water, and ancillary chemicals (Albizzati et al., 2021; Vanapalli et al., 2023a; Vance et al., 2024) as dominant hotspots in LA production (Table 2). The relative contribution of chemicals versus utilities is largely determined by feedstock characteristics and process design. Lignocellulosic feedstocks such as SCB require chemical- or energy-intensive pretreatments, making inputs like NaOH or enzymes as key contributors to energy consumption. In contrast, waste-based feedstocks with readily available sugars (e.g., bread or food waste) shift the burden toward utilities such as steam, cooling water, and wastewater treatment. Purification routes also differ widely: conventional lime neutralization produces gypsum waste, membrane-based systems transfer impacts to electricity and digestion processes, and reactive distillation demands high steam and cooling water use. Overall, differences in feedstock properties, pretreatment strategies (acid, alkali, enzymatic), purification routes (e.g., distillation, electrodialysis), along with methodological considerations such as system boundaries, and the choice of impact assessment methods largely explain the variations among various LCA studies (Table 2).

In contrast to the current study, previous studies have frequently identified sugarcane cultivation and its processing as major environmental hotspots (Daful et al., 2016; Farzad et al., 2017; Gezae Daful and Görgens, 2017; Mandegari et al., 2018). Similarly, the study on cane sugar fermentation to LA (Morão and de Bie, 2019) reported feedstock cultivation as a significant environmental concern. Conventional sugar- and starch-based LA production from sugarcane juice and corn is typically associated with high greenhouse gas emissions, freshwater use, and land occupation due to intensive agricultural inputs, fertilizer use, irrigation, and land use changes (Adom et al., 2014; Li et al., 2021; Morão and de Bie, 2019). The use of agrochemicals such as fertilizers and herbicides during sugarcane cultivation also contributes to fossil fuel depletion, as well as water and land occupation impacts. In contrast to other studies, the current study reported approximately 30 % lower greenhouse gas emissions and up to 50 % lower water footprint compared to traditional feedstock-based production (Table S10, in the SI). This could be partly attributed to sugarcane cultivation and processing contributing only 1.2–1.6 % of total midpoint impacts. This finding is consistent with other studies in regions like India (Munagala et al., 2021), likely due to differences in input parameters (e.g., fertilizer, water, and energy use) and output parameters such as yield considered across studies (Pachón et al., 2018). System boundaries further affect the results, with cradle-to-gate studies dominated by cultivation impacts, while waste valorization studies emphasize conversion-stage utilities and chemicals. Table S10 in the SI summarizes the typical environmental impact indicators per kg of LA for conventional production, alongside the midpoint impacts of the best-performing SCB valorization route (ARD) from the current study.

Variations in environmental impact distribution can also arise from the allocation approach used between SCB and co-products (Gezae Daful and Görgens, 2017; Munagala et al., 2021). The current study applied

Table 2

Comparison of previous life cycle assessment (LCA) studies on conversion of SCB and other edible and non-edible feedstocks to lactic acid.

S. No	Reference	Feedstock	Process description	System Boundary	LCA method	Environmental hotspots ^a	Key impact categories identified ^a
1.	(Daful et al., 2016)	Sugarcane bagasse	1. Steam explosion pretreatment 2. Enzymatic hydrolysis 3. Neutral pH fermentation 4. Reactive distillation 5. Separation and purification	Cradle-to-gate	Recipe Midpoint (H)	<ul style="list-style-type: none"> Agricultural land use for sugarcane cultivation Process water utilized in LA production Sugar mill Sugarcane cultivation 	<ul style="list-style-type: none"> Agricultural land occupation water depletion particulate matter formation.
2.	(Farzad et al., 2017)	Sugarcane bagasse	1. Pretreatment 2. Enzymatic hydrolysis 3. Neutral pH fermentation 4. Neutralization 5. Reactive extraction 6. Thermal decomposition 7. Esterification-hydrolysis purification	Cradle-to-gate	CML-IA baseline 3.02 and water scarcity	<ul style="list-style-type: none"> Agrochemical production (<i>herbicides, N/P fertilizers, diesel consumption</i>) Combustion stages (<i>emissions and ash released</i>) Furfural production stage (<i>tetrahydrofuran, NaCl and HCl consumption</i>) 	<ul style="list-style-type: none"> Abiotic depletion fossil fuel depletion ozone depletion.
3.	(Gezae Daful and Görgens, 2017)	Sugarcane bagasse	1. Steam explosion pretreatment 2. Filtration 3. Simple fermentation/simultaneous saccharification and fermentation 4. Lactic acid production using acid-tolerant bacterial strains 5. Reactive distillation 6. Separation and purification.	Cradle-to-gate	Recipe Midpoint (H)	<ul style="list-style-type: none"> Production of gypsum as solid waste Nutrients used for the strains Sugarcane cultivation 	<ul style="list-style-type: none"> Human toxicity Global warming potential Abiotic depletion.
4.	(Mandegari et al., 2018)	Sugarcane bagasse	1. Pretreatment 2. Enzymatic hydrolysis 3. Neutral pH fermentation 4. Neutralization 5. Exchange reaction 6. Thermal decomposition 7. Esterification-hydrolysis purification	Cradle-to-gate	The CML-IA baseline 3.02	<ul style="list-style-type: none"> Chemical consumption Consumption of phosphate fertilizer and magnesium sulphate Coal burning 	<ul style="list-style-type: none"> Abiotic and fossil fuel depletion Ozone depletion potential Global warming potential
5.	(Pachón et al., 2018) ^b	Sugarcane bagasse	1. Dilute sulfuric acid pretreatment 2. Saccharification 3. Fermentation 4. Purification.	Cradle-to-gate	ReCiPe Midpoint (H)	–	<ul style="list-style-type: none"> Climate change Fossil fuel depletion impacts^c
6.	(Munagala et al., 2021)	Sugarcane bagasse	1. Alkali pretreatment 2. Hydrolysis 3. Fermentation 4. Reactive distillation purification.	Cradle-to-gate	Recipe Midpoint (H) and Recipe Endpoint (H)	<ul style="list-style-type: none"> Pretreatment (<i>NaOH utilized in alkali pretreatment</i>) Hydrolysis stage (<i>Enzyme production</i>) 	<ul style="list-style-type: none"> Water depletion Climate change impacts Fossil depletion
7.	Current study	Sugarcane bagasse	1. Acid/alkali pretreatment 2. Enzymatic hydrolysis 3. Fermentation 4. (Reactive) distillation 5. Anaerobic digestion integrated with boiler	Cradle-to-gate	Recipe Midpoint (H) and Recipe Endpoint (H)	<ul style="list-style-type: none"> Cooling water and steam in distillation Sulfuric acid and enzyme use in pretreatment and fermentation processes. 	<ul style="list-style-type: none"> Water consumption Terrestrial ecotoxicity Fossil resource scarcity Human carcinogenic toxicity. Global warming potential
8.	(Morão and de Bie, 2019)	Sugarcane (cane sugar)	1. Fermentation with lime 2. Calcium lactate acidulated with H ₂ SO ₄ 3. Crude lactic acid 4. Purification	Cradle-to-gate	International Reference Life Cycle Data System (ILCD) 2011 Midpoint +	<ul style="list-style-type: none"> Agricultural feedstock production Manufacturing process of LA from sugar. 	<ul style="list-style-type: none"> Water, eutrophication Acidification Particulate matter Land use.
9.	(Ögmundarson et al., 2020)	Corn, corn stover, <i>Laminaria</i> sp.	1. Biomass harvesting 2. Pretreatment (if needed) 3. Hydrolysis	Cradle-to-gate	Recipe Midpoint (H), and Recipe Endpoint (H)	<ul style="list-style-type: none"> Energy consumption Triethanolamine in LA purification 	<ul style="list-style-type: none"> Fine particulate matter impacts Fossil resources scarcity

(continued on next page)

Table 2 (continued)

S. No	Reference	Feedstock	Process description	System Boundary	LCA method	Environmental hotspots ^a	Key impact categories identified ^a
			4. Fermentation 5. purification			• Treatment of refinery sludge.	<ul style="list-style-type: none"> • Freshwater eutrophication • Global warming • Marine water eutrophication • Mineral resource scarcity • Ozone formation • Terrestrial acidification • Terrestrial ecotoxicity
10	(Khoshnevisan et al., 2020)	Municipal solid waste	1. Fermentation 2. Anaerobic digestion 3. Electrodialysis ion-exchange membranes	Cradle-to-gate	Impact 2002+	<ul style="list-style-type: none"> • Anaerobic digestion process • Combined heat and power generation 	<ul style="list-style-type: none"> • Climate change • Human health damage
11	(Fei et al., 2020)	Natural gas	1. Methane Sourcing 2. Bioconversion by methanotrophic bacteria 3. Fermentation 4. Separation 5. Purification	Cradle-to-gate	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) – midpoint oriented LCA	<ul style="list-style-type: none"> • Natural gas production and distribution • Direct CO₂ emission from the plant 	<ul style="list-style-type: none"> • Global warming potential • Eutrophication • Carcinogenics • Ecotoxicity.
12	(Li et al., 2021)	Lignocellulosic biomass	1. Dilute sulfuric acid pretreatment 2. Saccharification (enzymatic hydrolysis) 3. Fermentation (batch or continuous, neutral or low-ph) 4. Separation (esterification to ethyl lactate, hydrolysis back to lactic acid, distillation).	Cradle-to-gate	Using Python for LCA with simulated stream data (input chemicals and emissions) and utility inventories from BioSTEAM.	<ul style="list-style-type: none"> • Natural gas and electricity demand in boiler • Lime consumption in fermentation process 	<ul style="list-style-type: none"> • 100-year global warming potential • Fossil energy consumption.
13	(Albizzati et al., 2021)	Mixed food waste	4. De-packaged clean food waste grinding 5. Food waste powder 6. Processing plant	Cradle-to-gate	International Reference Life Cycle Data System (ILCD) Midpoint	<ul style="list-style-type: none"> • Steam consumption • Feedstock-to-product yields • Usage of other ancillary materials. 	<ul style="list-style-type: none"> • Global warming potential
14	(Vanapalli et al., 2023)	Bread waste	1. Shredding and slurry formation 2. Sterilization 3. Enzymatic hydrolysis (Dextrozyme) 4. Sugar solution 5. Fermentation (Neutral pH/ Low pH) 6. Downstream separation 7. Esterification 8. Methyl lactate hydrolysis	Cradle-to-gate	Recipe Midpoint(H), and Recipe Endpoint (H)	<ul style="list-style-type: none"> • Wastewater generation from anaerobic digestion • Cooling water in eutrophication 	<ul style="list-style-type: none"> • Freshwater eutrophication • Human carcinogenic toxicity • Marine water eutrophication • Ozone formation • Water consumption.
15	(Vance et al., 2024)	Industrial candy waste and liquid digestate	1. Lactic acid fermentation 2. Centrifugation 3. Microfiltration 4. Nanofiltration 5. Bipolar electrodialysis	Cradle-to-gate	Intergovernmental Panel on Climate Change (IPCC) 2013	<ul style="list-style-type: none"> • Steam • Electricity • NaOH 	<ul style="list-style-type: none"> • Global warming potential

^a Empty cell indicates no analysis was carried out in the respective study.

^b environmental benefits, instead of impacts, are determined in this study.

^c in comparison with their reference systems.

economic allocation between unprocessed sugarcane juice and SCB, while other studies included juice processing to sugar and molasses separation, assigning higher impacts to SCB (Daful et al., 2016; Farzad et al., 2017; Mandegari et al., 2018). Differences in market prices across countries may further influence the allocated burdens. Consequently, studies with lower cultivation-related contributions identify process-related stages, such as enzymatic hydrolysis, pretreatment, and distillation, as dominant hotspots. These energy- and chemical-intensive

stages drive fossil fuel use, ozone depletion, and global warming potential. Waste-based LA production studies (Albizzati et al., 2021; Khoshnevisan et al., 2020; Vanapalli et al., 2023; Vance et al., 2024) generally neglected upstream processes leading to waste generation, highlighting how system boundary definitions strongly influence whether agricultural or industrial stages emerge as key environmental hotspots in LCA results.

4.2. Longterm impacts

The findings from cLCA highlight that maximizing lactic acid production, CO₂ recovery, and nutrient recovery while minimizing reliance on grid electricity and supplemental cement are critical to enhancing the long-term environmental performance of biorefineries, supporting broader decarbonization goals. The loss of cogeneration benefits and increased external resource demands represent key trade-offs that must be carefully managed to achieve optimal sustainability outcomes.

Although not significant in reducing the impact of the processes, fermentation-based CO₂ is one of the purest forms and it does not require complex processing techniques (Alonso-Moreno and García-Yuste, 2016; Bommarreddy et al., 2020). This makes it a suitable feedstock for various applications, including use as a carbonating agent, preservative, packaging gas, and several other uses in the food and pharmaceutical industries (Cuéllar-Franca and Azapagic, 2015). Utilizing it can help reduce the greenhouse gas emissions of biorefineries, aiding the industry in meeting decarbonisation goals through carbon sequestration. This will be a very significant factor for biorefinery processes such as natural gas fermentation to LA, where direct CO₂ emissions from the plant were reported as an environmental hotspot (Fei et al., 2020). Additionally, advanced integrated techniques like gas fermentation (Lee et al., 2021), mineral carbonation (Huijgen, 2007), and algae growth for biofuels (Passell et al., 2013) can be incorporated into the industry under the concept of industrial symbiosis to further mitigate environmental impacts. For instance, Bommarreddy et al. (2020) demonstrated an integrated technology of carbon-efficient biocatalysis from fermentative CO₂ and renewable H₂ produced from supercritical gasification as co-feeds for the production of commodity chemicals. Policymakers should support incentives and regulations that promote efficient resource use, product substitution, and CO₂ utilisation to drive sustainable biorefinery adoption.

Previous cLCA studies have considered the effects of biogenic carbon uptake from biomass cultivation as a potential means of carbon sequestration, thereby reducing environmental emissions (Alvarenga et al., 2013; Munagala et al., 2021). In the present cradle-to-gate cLCA study, we have excluded sugarcane cultivation as a means of biogenic carbon uptake. This decision is based on the primary product—LA—being a platform chemical for numerous products with variable end-of-life scenarios, leading to significant variations in the duration of carbon sequestration. Moreover, additional variability in the system's carbon sequestration potential can also be introduced by the various valorisation routes of sugarcane-derived co-products (other than SCB) and their multiple end-of-life scenarios. Therefore, for the sake of simplicity and uniformity, we have excluded this consideration.

Further, cLCA studies have considered the impact of indirect land-use change as a critical factor in evaluating the long-term effects of sugarcane cultivation (Alvarenga et al., 2013; Kami Delivand and Gnansounou, 2013). Most of these assessments have focussed on bioethanol and the by-products from the sugar industry (Bergtold et al., 2017). In India, SCB is a low-value byproduct of the sugar industry, where the primary value derives from sugar production and molasses-based bioethanol and alcohol production (Agrawal and Kumar, 2023). Therefore, it has been assumed that the valorization of abundant low-value resource of SCB in a biorefinery does not significantly drive land-use change. Moreover, sugarcane farming in India predominantly confined to existing agricultural lands generally in rotation with crops such as wheat, rice, and pulses, and no evidence of sugarcane expansion causing major land-use change or deforestation was reported (FAO, 2011; GoI, 2021; SBI-ICAR, 2015). Consequently, the effects of land-use change have been omitted from the scope of this study.

It is important to acknowledge that this cLCA was modelled using currently dominant commercial production methods for LA and its by-products, thereby reflecting the long-term environmental performance within the present market context. However, given the dynamic nature of markets and technological advancement, the long-term impacts

projected in this cLCA may alter as cleaner and more sustainable alternative technologies become more widespread.

4.3. Thermal efficiency using heat integration

The observed differences in energy savings (steam and cooling water) among the ARD, AkD, and AkRD scenarios following pinch-based thermal integration primarily reflect the thermodynamic characteristics and energy profiles of each process route. Specifically, the number, temperature, and enthalpy of hot/cold streams, as well as the baseline energy demand for pretreatment and separation, determine the extent of feasible heat recovery. In this study, a consistent pinch analysis approach, with an identical ΔT min setting and comparable heat exchanger network criteria, was applied across all scenarios to ensure methodological uniformity and comparability. Thus, the variation in energy savings is attributable to intrinsic process differences rather than the pinch analysis implementation.

While the percentage contributions of steam and cooling water remained consistent in cLCA as well, the integration of a heat exchange network resulted in significantly higher percentage reductions in overall midpoint (42–61.8 %) and endpoint (46–65.5 %) environmental burdens. The higher reductions depicted by processes in cLCA were due to the proportional positive contributions of the avoided products and associated burdens to the relevant scenarios (Fig. 4c, d). The trend across all processes reinforces the role of pinch technology in optimizing energy use, with the extent of impact reduction depending on the specific process characteristics and integration potential. Moreover, steam recycling from AD integrated with the boiler can reduce the need for external steam sources and cut additional energy and resource requirements.

4.4. Context and future outlook

The current study aligns with previous LCA studies that emphasize the dominance of energy and water utilities as key environmental hotspots in lignocellulosic bioprocesses. Further, the sensitivity and uncertainty patterns highlight that technological improvements in enzymatic or chemical processes remain important. It further reduces utility consumption, and enhancing heat and water recycling, representing the most impactful levers for sustainable SCB valorization to LA.

Despite the comprehensive scope of this analysis, it is essential to contextualize the findings within the inherent methodological and data constraints. Specifically, the cradle-to-gate boundary excludes the highly variable gate-to-grave phase of LA derivatives, potentially underestimating the total life cycle burden due to end-of-life complexities. The consequential LCA relies on existing market substitution data. This means that the projected long-term environmental benefits are sensitive to future technological shifts and market dynamics, which could alter the baseline for avoided products. Further, while the reliance on India-specific electricity and regional inventory data enhances relevance, the use of Ecoinvent 3.10 global or rest of the world averages for certain ancillary inputs and the conservative capital goods estimation (excluding maintenance, land, and decommissioning) introduce minor levels of uncertainty. Similarly, the decision to exclude indirect land-use change and biogenic carbon uptake from the system boundary, while justified for simplification, prevents a full assessment of the LA process's carbon sequestration potential over varied end-of-life scenarios.

To significantly improve the overall sustainability of SCB valorization to LA, an immediate implementation of practical solutions targeting the identified hotspots is essential. Closed-loop water recycling and thermal integration must be implemented across all process routes, supported by a necessary techno-economic feasibility assessment to ensure the maintenance of adequate water and steam quality for core unit operations. Further, future process designs should prioritize the adoption of innovative or less intensive pretreatment methods to reduce the reliance on high volumes of sulfuric acid and enzymes, thereby

lowering the associated environmental burden from chemical inputs.

To realize the long-term environmental benefits projected by the LCA, robust policy and market frameworks must be established. While India's National Biofuel Policy (Ministry of New and Renewable Energy, 2018) and the SATAT initiative (IOCL, 2018) identify agricultural residues as sustainable bio-feedstocks, they predominantly prioritize high-volume, low-value energy recovery via biofuels. Although these policies frequently cite 'integrated biorefinery' concepts for co-product valorisation alongside bioethanol, the potential of biochemical pathways to generate high-value products, such as lactic acid, remains underrepresented. Realizing the full potential of a circular bioeconomy necessitates a strategic pivot toward high-value biochemical production; however, the current policy framework lacks targeted incentives for these emerging technologies, creating gaps in practical implementation (Mahendrasinh Kosamia et al., 2022). In this regard, the introduction of viability-gap funding and fiscal mechanisms tailored to offset the high capital and operational expenditures of advanced bioprocessing is critical. For instance, the United States' Renewable Identification Number (RIN) system acts as a compliance currency and a financial incentive mechanism for biorefinery operators and feedstock producers, effectively accelerating market adoption and innovation across the bioeconomy (Whistance et al., 2016). Furthermore, regulatory guidelines should mandate resource efficiency measures, specifically closed-loop water recycling and thermal integration, as identified in this study. Simultaneously, new circular economy programs are needed to incentivize the valorisation of co-products (Duan et al., 2022), such as fermentation-derived CO₂ and nutrient-rich sludge, as substitutes for fertilizers. Furthermore, effective supply-chain models for SCB aggregation are crucial, necessitating enforceable sustainability standards and traceability frameworks to ensure reliable feedstock management and promote inclusive rural value chains in India (Yadav and Yadav, 2025). Such policy interventions can accelerate the commercialisation of SCB valorisation pathways, better aligning bio-based industrialisation with India's broader Panchamrit decarbonization targets (MoEFCC, 2022).

Future research should focus on the following key areas: (i) developing and incorporating India-specific primary datasets for feedstock cultivation, processing, and energy generation to improve the regional accuracy of environmental assessments; (ii) expanding the cLCA model to include comprehensive gate-to-grave scenarios for LA, providing insights into managing biogenic carbon associated with SCB and supporting broader decarbonization goals; (iii) evaluating the techno-economic feasibility of closed-loop water recycling and energy integration systems to optimize resource use; (iv) exploring advanced valorization routes for co-products such as CO₂, gypsum, sludge, and steam to maximize resource recovery and minimize environmental impacts; (v) assessing the integration of industrial symbiosis concepts and emerging technologies, including gas fermentation and mineral carbonation, to enhance circularity and decarbonization; (vi) comparing the environmental benefits of alternative and more efficient separation technologies, such as membrane separation and extraction, as they become viable for large-scale production; and (vii) investigating policy and market frameworks that can incentivize scaling and commercialization of these sustainable processes, fostering a circular bioeconomy.

5. Conclusion

This study evaluated the environmental performance of three fermentative SCB-to-LA valorization routes using aLCA and cLCA. Alkaline pretreatment-based processes (AkD and AkRD) showed higher impacts than the acid pretreatment-based route (ARD), while reactive distillation outperformed conventional distillation in all categories. Key hotspots included cooling water and steam utilities, along with H₂SO₄ and enzymes used in pretreatment and hydrolysis. The cLCA demonstrated considerable environmental advantages when LA from these processes substitutes conventional LA production. Moreover, recovering by-products such as CO₂, gypsum, sludge, and steam, along with heat

integration through pinch technology, can enhance overall process efficiency. Integrating energy and material recovery within these systems can therefore substantially improve the sustainability of SCB valorization to LA.

CRedit authorship contribution statement

Kumar Raja Vanapalli: Writing – review & editing, Writing – original draft, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Naseeba Parveen:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Sunil K. Maity:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Roberto Parra Saldivar:** Writing – review & editing, Writing – original draft. **Samuel Jacob:** Writing – review & editing, Conceptualization. **Gopalakrishnan Kumar:** Writing – review & editing. **Vinod Kumar:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known conflicting financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.spc.2025.11.008>.

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Vanapalli, Kumar Raja; Parveen, Naseeba; Maity, Sunil K.; Parra-Saldívar, Roberto; Jacob, Samuel ...

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