Review Article

Circular Economy Integration in 1G+2G Sugarcane Bioethanol Production: Application of Carbon Capture, Utilization and Storage, Closed-Loop Systems, and Waste Valorization for Sustainability

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Abstract
Bioethanol production is a vital player in the renewable energy landscape. However, it faces pressing issues regarding carbon emissions and resource management. Traditional open-loop systems generate substantial waste and pollution, exacerbating environmental concerns. Various emerging technologies offer promising solutions. Carbon Capture, Utilization, and Storage (CCUS) presents avenues for tackling carbon emissions. Utilization transforms CO_2 emissions into valuable products, while Storage securely stores emissions to prevent atmospheric release. Closed-loop processes and waste valorization capitalize on material reuse, conserving natural resources, and minimizing waste. By promoting resource efficiency and waste minimization, circular economy principles align seamlessly with CCUS, closed-loop systems, and waste valorization. This study delves into utilizing Utilization technologies tailored to sugarcane 1G+2G bioethanol production, evaluates CO_2 capture options, and presents applications. Storage strategies suitable for bioethanol production facilities are scrutinized, and deployment options are explored, highlighting the closed-loop system and waste valorization's role in waste reduction and environmental preservation. Through synergistic integration, these technologies pave the way for sustainable sugarcane bioethanol production, addressing economic and technological challenges while fostering innovation and collaboration. This comprehensive study will serve as a guide for transitioning to a circular economy model in bioethanol production.

Keywords: Bioethanol, CCUS, Circular economy, Closed-loop systems, Sugarcane, Waste valorization

1 Introduction

Fossil fuels, due to their abundant supply, have been used in various industries for energy production [1]. However, with fossil fuel reserves depleting and contributing to greenhouse gas emissions, there is a growing global demand for eco-friendly energy sources [2]–[4]. The demand has highlighted the importance of bioethanol as a renewable alternative, particularly rich in carbohydrates. Leading countries such as the USA and Brazil have seen significant advances in bioethanol programs, driving global production growth [5], [6].

First generation (1G) dominates the industry for the production of bioethanol, which mainly uses food crops, sugary and starchy biomass, and by-products of the process itself to be fermented and produce bioethanol [7], [8]. Despite offering environmental benefits, 1G bioethanol production presents three particular challenges such as competition with food resources [9], carbon emission due to reliance on fossil fuels in the production itself [10], and the requirement of land for the sugary crops to grow [11].

Due to the problems faced by the current 1G bioethanol production, second generation (2G) bioethanol production emerges as an alternative for the use of food crops to reduce carbon emissions and reliance on food resources [12], [13]. The 2G bioethanol production primarily relies on lignocellulosic biomass, which comprises cellulose (30–50%), and hemicellulose (20–40%), that undergoes a hydrolysis process to produce monomeric sugars before proceeding to fermentation [7], [14].

Table 1: Comparison between literature reviews on the past years and current review about circular economy technologies.

1G Ethanol	2G Ethanol	Carbon Capture Technology	Closed-Loop Systems	Waste Valorization	Synergetic Approach	Circular Economy	Model	Ref.
X	X	√	X	X	X	√	X	[21]
X	X	√	X	√	√	√	X	[22]
X	√	X	X	√	X	√	X	[23]
X	√	X	X	√	X	√	X	[24]
X	X	√	X	X	X	√	X	[25]
X	X	X	√	√	√	√	X	[26]
√	X	X	X	√	X	√	X	[27]
√	√	√	√	√	√	√	√	This Study

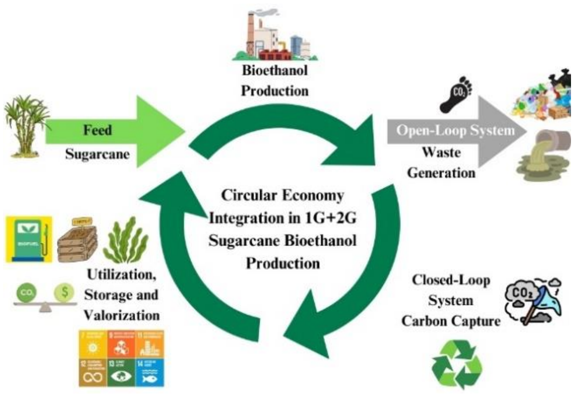

Figure 1: Circular economy integration in 1G+2G sugarcane bioethanol production.

Regardless of the effort to overcome challenges, such as carbon emissions and waste generation, integrating 1G+2G bioethanol production to maximize its potential and resolve the challenges, specifically in sugarcane, remains to be determined [15], [16]. However, potential solutions to these challenges exist, such as carbon capture technologies and waste valorization strategies [17], [18]. Implementing closed-loop systems can enhance sustainability and resource efficiency [19].

The potential solutions, when integrated, create a circular economy, which maintains positive development cycles by conserving natural capital, optimizing resource use, and managing finite stocks and renewable flows to reduce system risks [20]. Therefore, a circular economy approach in bioethanol production can be achieved by integrating carbon capture, waste valorization, and closed-loop systems, as seen in Figure 1, fostering economic growth, job creation, and environmental sustainability, specifically on 1G+2G bioethanol production from sugarcane. This study delves into the technology and application of these strategies within various industries, examining their potential integration and synergistic approach to optimize and achieve sustainable bioethanol production. Furthermore, the study considers future directions and research priorities for future endeavors on achieving further advancements, cost-effective strategies, and future applications of technologies mentioned in various industrial sectors. In light of the recent advancements in these fields and the need to bridge the gap between the different technologies, a comprehensive overview of different literatures and the technologies discussed is provided in Table 1, along with the comparison and the novelty of this study.

2 Brief Overview of CCUS, Waste Valorization, and Closed-loop Systems on Different Industries

2.1 *Carbon Capture, Utilization and Storage (CCUS) in different industries*

CCUS has emerged as a potential solution to decarbonize challenging industrial sectors such as steelmaking and cement manufacturing. It includes various technical options, encompassing capture, transport, storage, and carbon utilization as seen in Figure 2, which address the economic development and decarbonization. Despite facing obstacles such as high costs and policy constraints, ongoing research, government support, and scale-up initiatives are working to overcome these barriers and pave the way or widespread CCUS deployment, which is crucial for achieving global climate and net-zero targets [17], [28], [29].

Various methods can capture carbon dioxide (CO_2), including pre-combustion, post-combustion, and oxy-fuel combustion processes [30]. Utilization options like synthetic fuel production, algae cultivation, and carbonation of concrete transform CO_2 into valuable resources, expanding sustainable alternatives

[31]–[33]. Storage methods include enhanced oil and gas recovery, where CO_2 injection aids extraction and secures underground storage and saline aquifer storage, ensuring long-term CO_2 sequestration [34]–[36]. These approaches collectively advance carbon management efforts and pave the way for a greener future. In Table 2, various carbon capture, utilization and storage techniques are presented. Descriptions of each method are also presented.

The global effort to achieve climate and net-zero targets requires industries to play a crucial role, but decarbonizing heavy industry poses significant challenges. Countries highly dependent on energy-intensive manufacturing rely on industrial activity for economic development [17], [54]. Table 3 displays various operating plants in different industries worldwide that utilize CCUS technologies according to Global CCS Institute [55]. Table 4 shows the top countries emitting greenhouse gases in 2022 according to European Commission Joint Research Centre [56].

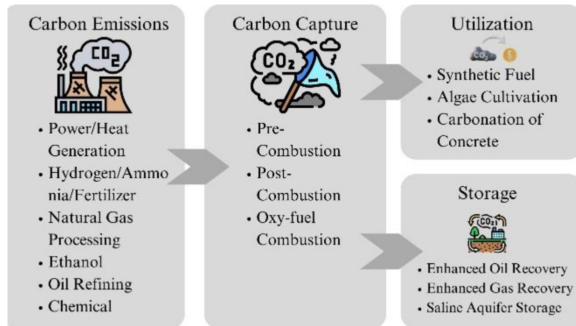

Figure 2: Overview of the flow process of CCUS.

Table 2: Carbon capture, utilization and storage applications on different industries.

Method	Techniques	Description	Ref.
Capture	Pre-combustion	Before fuel combustion, CO_2 is captured by converting it into a synthesis gas (syngas) composed of CO and H_2. This process separates relatively pure CO_2, which can be stored or used for other purposes.	[30], [37], [38]
	Post-combustion	Different methods, including chemical absorption and adsorption, are typically employed to extract CO_2 from flue gases produced following the combustion process in current power plants and industrial establishments.	[39]–[41]
	Oxy-fuel Combustion	During the combustion process, fuel mixes with oxygen and recycled flue gasses, which increases CO_2 concentration in the flue gas. This increase in concentration simplifies the capture of CO_2 after water vapor condensation.	[42]–[44]
Utilization	Synthetic Fuel	Liquid hydrocarbon fuels can be produced by utilizing CO_2 as a feedstock through processes like Fischer-Tropsch or methanol synthesis, converting CO_2 into synthetic fuels	[31], [45], [46]
	Algae Cultivation	The process enables the conversion of CO_2 into biomass, which can be harvested for various products such as biofuels, animal feed, food supplements, and bioplastics.	[32], [47], [48]
	Carbonation of Concrete	During the curing process of concrete, CO_2 is of Concrete injected and reacts with calcium ions to form calcium carbonate. This process not only sequesters CO_2 but also improves the strength and durability of the concrete.	[33], [49]
Storage	Enhanced Oil Recovery (EOR)	The injection of CO_2 into depleted oil reservoirs has been found to increase oil extraction rates by reducing oil viscosity and enhancing mobility. Additionally, this process stores CO_2 underground, boosting oil production and contributing to CO_2 storage efforts.	[34], [50], [51]
	Enhanced Gas Recovery (EGR)	Injecting CO_2 into depleted natural gas reservoirs increases gas production by elevating reservoir pressure and displacing gas towards production wells while simultaneously sequestering CO_2 underground.	[35], [52]
	Saline Aquifer Storage	CO_2 is commonly injected into deep saline aquifers, where it is stored in porous rock formations beneath impermeable caprocks, either as a supercritical fluid or dissolved in pore spaces. This process effectively sequesters CO_2 and reduces emissions.	[36], [53]

Among the 47 operational plants utilizing CCUS, 25 have been operational within the past decade [56]. China, which is the leading emitter of CO_2 according to the European Commission Joint Research Centre's 2022 report, which is 29.16% of the global CO_2 emissions for that year, has operated nine of these plants. Together, these nine facilities have a carbon capture capacity of 3.25 megatons per annum, which is only a 0.02% reduction of China's total emissions, at 15684.63 megatons in 2022.

Within the last decade, four plants have begun operating in the United States, the world's second-largest emitter of CO_2, accounting for 11.19% of total global emissions. Together, these facilities can remove 2.761 megatons of CO_2 annually, representing 0.046% of the nation's total emissions in 2022.

Additionally, they are one of the top producers of bioethanol in the world and all three of the CCUS applications on bioethanol that were operated in the last decade can be found [57]. It indicates that bioethanol production is one of the primary sources of CO_2; therefore, CCUS application is needed, and the USA is the leading innovator for CCUS application on bioethanol production.

Interestingly, Canada, contributing 1.41% of the world's total emissions in 2022, hosts seven CCUS plants, removing 16.752 megatons of CO_2 annually, which represents approximately 2.2% of Canada's total emissions. The recent growth of CCUS plants, particularly in China, the United States, and Canada underscores a significant step towards mitigating global carbon emissions.

Table 3: Operating CCUS integrated plants since 2014 according to Global CCS Institute.

Industry	Name	Country	Year	Capacity (MT)
Power/Heat Generation	SaskPower Boundary Dam	Canada	2014	1
Chemical	Xinjiang Dunhua Karamay	China	2015	0.1
Hydrogen/Ammonia/Fertilizer	Shell Quest	Canada	2015	1
Natural Gas Processing	Saudi Aramco Uthmaniyah	Saudi Arabia	2015	0.8
Iron and Steel	ADNOC Al-Reyadah	United Arab Emirates	2016	3.2
Power/Heat Generation	Petra Nova Carbon Capture	USA	2017	1.4
Ethanol	ADM Illinois Industrial	USA	2017	1
Natural Gas Processing	CNPC Jilin Oil Field	China	2018	0.6
Natural Gas Processing	Qatargas Qatar LNG	Qatar	2019	n/a[a]
Natural Gas Processing	Chevron Gorgon	Australia	2019	n/a[a]
CO_2 Transport/Storage	Wolf Alberta Carbon Trunk Line	Canada	2020	14.6[b]
Hydrogen/Ammonia/Fertilizer	WCS Redwater	Canada	2020	14.6[b]
Oil Refining	NWR Sturgeon Refinery	Canada	2020	14.6[b]
CO_2 Transport/Storage	Enhance Clive Oil Field	Canada	2020	14.6[b]
Chemical	Yangchang Yan'an CO_2-EOR	China	2021	0.1
Chemical	Sinopec Nanjing Chemical	China	2021	0.2
Direct Air Capture	Climeworks Orca	Iceland	2021	0.004
Power/Heat Generation	China National Energy Guohua Jinjie	China	2021	0.15
Chemical	Yangchang Yulin CO_2-EOR	China	2022	0.3
Chemical	Sinopec Qilu-Shengli	China	2022	1
Ethanol	Red Trail Energy Richardton Ethanol	USA	2022	0.181
Natural Gas Processing	Entropy Glacier Gas Plant	Canada	2022	0.152
Ethanol	Harvestone Blue Flint Ethanol	USA	2023	0.18
Natural Gas Processing	CNOOC Enping	China	2023	0.3
Power/Heat Generation	China National Energy Taizhou	China	2023	0.5

2.2 *Waste valorization and closed-loop systems in different industries*

Closed-loop systems are widely acknowledged to reduce waste and promote sustainability, particularly in process industries. However, most scholarly research has focused on discrete industries, leaving a gap in knowledge regarding waste disposal and reuse practices specific to process industries [19]. More comprehensive exploration is needed to fully address sustainable practices within these diverse sectors, particularly in the bioethanol industry.

Transforming by-products, such as organic residues, into valuable resources through waste valorization effectively reduces waste. These wastes present challenges due to their high moisture content and organic loading due to their origin, such as processing drinks, dairy, and fruits/vegetables. Nevertheless, improper disposal can lead to environmental issues, prompting stricter regulations worldwide. Therefore, waste valorization aligns with the principles of the waste management hierarchy: reduce, reuse, and recycle [58]–[60].

Table 4: Top 12 CO_2 emitting countries according to the European Commission Joint Research Centre in 2022.

Country	**CO_2 Emissions** (Mt)	Percent
China	15684.63	29.16
USA	6017.44	11.19
India	3943.26	7.33
Russia	2579.80	4.80
Brazil	1310.50	2.44
Indonesia	1240.83	2.31
Japan	1182.77	2.20
Iran	951.98	1.77
Mexico	819.87	1.52
Saudi Arabia	810.51	1.51
Germany	784.00	1.46
Canada	756.81	1.41
Others	17696.31	32.9

Closed-loop systems integrate the utilization of wastes, and waste valorization upscales wastes into more valuable products; therefore, both utilize wastes, offering a possible synergetic application on bioethanol production, as illustrated in Figure 3. Different methods and examples of closed-loop and valorization systems used in various industries are shown in Table 5.

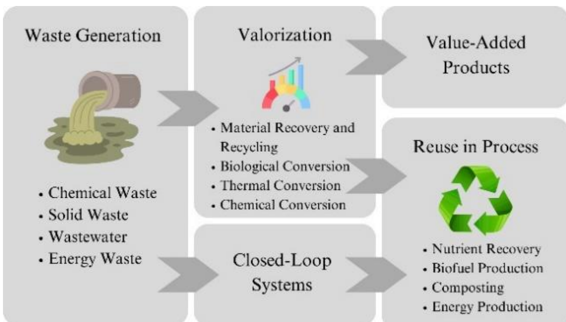

Figure 3: Synergetic flow of waste valorization and closed-loop systems.

Figure 4 shows the categories of different applications of valorization and closed-loop systems by the concept of reduce, reuse, and recycle. Carbon emission, material, and energy waste reduction was done by capture and recovery. Closed-loop systems reuse material and energy; solid and water wastes, for example, can be used for composting and irrigation. Recycling was done by utilization of waste valorization through upcycling and conversion.

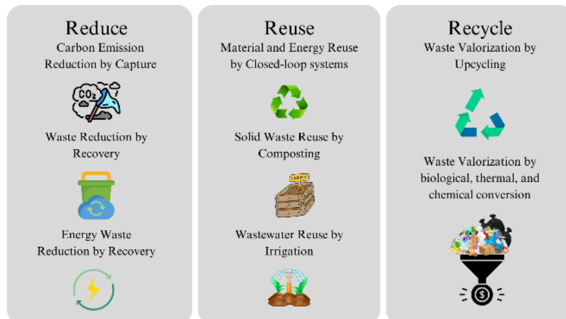

Figure 4: Valorization and closed-loop application on reduce, reuse, and recycle.

Table 5: Waste valorization and closed-loop systems in different industries.

Method	Techniques	Examples	Ref.
Valorization	Material Recovery and Recycling	The transformation of end-of-life tires into valuable resources such as rubberized asphalt.	[61]–[63]
	Biological Conversion	The biological conversion of digestate offers opportunities for energy production.	[64], [65]
	Thermal Conversion	The thermal conversion of waste heat, maximizing hydrogen production.	[66]
	Chemical Conversion	The chemical conversion of biomass into a valuable resource such as vanillin, muconate, and other value-added products.	[67]–[69]
Closed-Loop Systems	Material	Closed-loop fibers utilization, mitigating raw material costs.	[70]
	Energy	Closed-loop geothermal systems, ensuring stable energy production and efficient reservoir utilization for long-term operation.	[71]–[73]
	Water	Closed-loop water treatment system for aquaculture, enhancing water quality and reducing environmental impact.	[74], [75]
	Nutrient	Closed-loop nutrient system for aquaculture in a soilless environment.	[76], [77]

3 Circular Economy Integration on 1G+2G Bioethanol Production from Sugarcane

3.1 *Process flow of 1G+2G bioethanol production from sugarcane*

Sugarcane is harvested from the farm and then milled to separate sugarcane juice from the bagasse. The extracted sugarcane juice is then purified and clarified before entering fermentation. Meanwhile, the sugarcane bagasse undergoes pre-treatment and hydrolysis, followed by separating solids and liquids, and the liquid fraction is fermented into ethanol. Sugarcane juice is also fermented in an ethanol-water mixture, then distilled with 2G ethanol to concentrate the ethanol content. Following this, ethanol undergoes a dehydration process to purify it further. The solids resulting from separating solids and liquids are dried and utilized as fuel for energy generation. This process is illustrated in Figure 5, which shows the 1G+2G ethanol production from sugarcane [78]–[80].

3.2 *Pollution, waste, and resource management challenges on 1G+2G bioethanol production from sugarcane*

Bioethanol production from sugarcane poses various pollution, waste management, and resource utilization challenges. Different challenges and issues in sugarcane bioethanol production are summarized in

Table 6. Before sugarcane is processed to produce bioethanol, it is grown on land that requires a significant area to meet the current demand for bioethanol, as sugarcane is one of its primary sources [81]. After sugarcane is harvested, it is crushed to extract the juice. However, this extraction process generates wastewater with organic matter, suspended solids, and chemicals used in milling, posing environmental concerns [82]. Production has an intensive requirement for water resources; therefore, wastewater must be treated for reuse [82]. It also produces significant particle pollution that causes healing effects [83]. Additionally, the fibrous residue known as bagasse, left after juice extraction, can worsen air and soil pollution if improperly disposed of or burnt [84].

Purifying crushed sugarcane juice is necessary to remove impurities such as dirt and fibers, yet this purification process generates wastewater containing organic matter and purification chemicals, necessitating proper treatment before discharge [82]. Solid waste in the form of residual fibers and filter cake may also result [103]. Fermentation, where purified sugarcane juice and yeast interact, converts sugars into ethanol and carbon dioxide. However, this process generates fermentation by-products, such as wasted yeast and residual biomass, which add to the waste streams [82]. Significant energy input is required during distillation and dehydration, which is essential for the purification of ethanol, and that can lead to greenhouse gas emissions if it comes from non-renewable sources [85], [109]. Stillage, a residue from distillation, and wastewater from dehydration containing residual ethanol and agents are produced [84].

In the pre-treatment and hydrolysis process of the 2G sugarcane bagasse ethanol production, chemical and energy-intensive processes are used, which potentially cause pollution and emissions [89]. Hydrolysis, which breaks down cellulose and hemicellulose into fermentable sugars, generates wastewater and solid residues such as lignin [95]. Solid-liquid separation techniques separate lignin from the liquid phase containing ethanol and water, although this process may generate solid waste and wastewater [82]. Energy production involves combusting dried solids in boilers to produce steam for electricity or process heat [101]. However, this process emits air pollutants and greenhouse gases, and combustion residues require proper management [85].

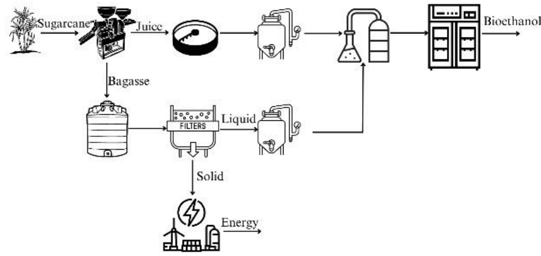

Figure 5: Traditional process flow of 1G+2G bioethanol production from sugarcane.

Table 6: Pollution, wastes, and resource management issues of 1G+2G bioethanol production from sugarcane.

Category	Example	Produced and Requirement (per kilotonnes processed sugarcane)	Ref.
Pollution and Waste	CO_2	~90 t	[85], [86]
	Volatile organic compounds (VOCs)	~215 kg	[87], [88]
	Chemical	~27 kg	[82], [89], [90]
	Stillage/ Vinasse	~1.7 t	[91], [92], [93]
	Wastewater	~1 kt	[82], [94]
	Lignin	~35 t	[95], [96]
	Particulates	~22 PM10 mg/m^3 air	[83]
	Bagasse	~130 t	[84], [97]
	Ash	~5.5 kg	[98]–[100]
	Filter Cake	~40 t	[101]–[103]
	Spent Yeast	~12 t	[104]
	Nutrients	~38 t	[105], [106]
Resource Manage ment	Land	~177 ha	[107]
	Water	~244 t	[82], [108]
	Energy	~1606 GJ	[109]
	Feedstock	1 kt	[32], [81]

3.3 *Applications of CCUS, closed-loop systems, and waste valorization on 1G+2G bioethanol production from sugarcane*

Following the major challenges and concerns faced by the 1G+2G sugarcane bioethanol production, which includes significant land use, yield efficiency, seasonality, competing use of food resources, and carbon emissions [9]–[11], the integration of CCUS, closed-loop systems, and waste valorization have emerged as promising strategies for sustainable mitigation.

Table 7: Physicochemical properties and metal constituents of wastewater produced on bioethanol production according to Fito *et al*. [111].

Parameters	Concentration (mg/L)
Physicochemical Properties	
pH	3.9 ± 0.1
Total Solids (TS)	300 ± 9200
5 Day Biochemical Oxygen Demand (BOD_5)	40271 ± 3014
Chemical Oxygen Demand (COD)	132445 ± 6655
Nitrate (NO_3^- N)	3.2 ± 1.0
Phosphate (PO_4^{-3})	21.2 ± 2.7
Sulphate (SO_4^{-2})	4502 ± 69
Cl^-	6722 ± 873
Metal Constituents	
Sodium (Na)	207.6 – 263.0
Potassium (K)	1143.9 – 2987.0
Magnesium (Mg)	816.3 – 927.6
Calcium (Ca)	1787.4 – 3389.8
Chromium (Cr)	0.8 – 2.3
Copper (Cu)	1.1 – 1.5
Zinc (Zn)	1.4 – 2.8
Iron (Fe)	13.8 – 19.6
Nickel (Ni)	0.13 – 2.7
Manganese (Mn)	1.5 – 6.6

A significant amount of sugarcane bagasse burning is employed to reduce reliance on fossil fuels, which results in substantial carbon dioxide emissions added by the emission of the fermentation process. However, an effective mitigation of carbon emissions from sugarcane-derived ethanol production can be achieved by adopting carbon capture technologies [30]. This approach reduces the greenhouse gas emissions associated with ethanol production and facilitates the utilization of sugarcane bagasse without aggravating climate change.

Post-combustion technology is one option that can be used in the energy production process to capture carbon dioxide [30]. Moreover, post-combustion technologies, such as chemical absorption, physical adsorption, membrane separation, and cryogenics, can capture high-purity carbon dioxide from fermentation by-products, achieving up to 95% capture efficiency rates [110]. Captured carbon can be utilized in various ways depending on the technologies examined earlier. It can be converted to synthetic fuel to increase the energy availability for energy-intensive processes [31], such as the distillation process of sugarcane bioethanol. Another option is to employ it in algae cultivation, which can integrate third-generation ethanol production to enhance bioethanol yield and reduce dependence on sugarcane feedstock [32]. Additionally, captured carbon dioxide can be used in concrete production facilities for concrete carbonation [33], [98].

A potential use of captured carbon that has yet to be discussed is its use as a fertilizer for sugarcane farms, as it does not negatively affect soil quality [85]. Although storing captured carbon can also be part of this process, its impact on production is less significant than its utilization on sugarcane bioethanol production. However, this presents a valuable opportunity to reduce carbon emissions.

As previously discussed, VOCs, a by-product of fermentation, and spent yeast can be subjected to biological conversion techniques. Biofiltration effectively converts VOCs into biofuels, which can power energy-intensive processes [87], as discussed before. Moreover, spent yeast from sugarcane ethanol production can be subjected to bioconversion processes to produce biofuels [104].

Production requires a significant amount of water, around 244 tonnes per kt of sugarcane processed, making daily wastewater treatment crucial for resource management [82], [108]. Table 7 shows the different physicochemical properties and of wastewater produced by sugarcane bioethanol production [111]. Sugarcane farms can benefit from the wastewater from the grinding process for irrigation purposes [94]. Furthermore, the treatment of wastewater from fermentation, pretreatment, and hydrolysis of bagasse fiber can recover nutrients such as nitrogen and phosphorus, which can be used as fertilizer for sugarcane cultivation [105]. Furthermore, the anaerobic digestion of all wastewater generated in production, including distillation and dehydration, can produce biofuels for energy-intensive processes [91], [92].

During the production process, solid waste is created. Compost material can be produced using residual fibers from filter cakes, which help to improve soil fertility and structure [101]. Filter cakes can also be used as a fuel for energy production combined with bagasse burning [102]. Lignin, derived from second-generation ethanol production, can be used as fuel for energy production. In addition, it can be used to create valuable products such as biopolymers, and bioactive compounds [95]. Smoke-produced ash can be incorporated into the soil as an amendment [98] and used as a construction material [99].

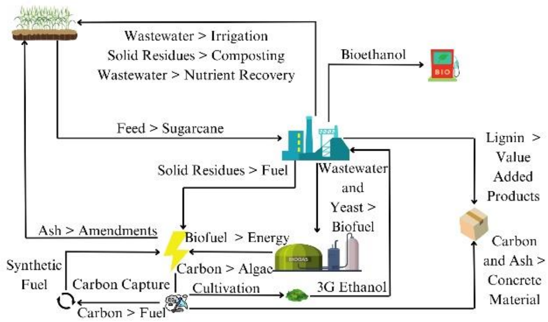

Figure 6: Proposed circular economy model for 1G+2G bioethanol production from sugarcane.

Table 8: Major technological barriers of integration of CCUS, closed-loop systems, and waste valorization on 1G+2G sugarcane bioethanol production.

Technology	Measured Parameter	Percent/ Remark	Ref.
Distillation	Energy Requirement	>80% of total energy requirement	[117], [118]
CCUS	Energy	30–60% Efficiency	[119]–[121]
	Removal	<95% Efficiency	[110], [122]
2G Sugarcane Bioethanol	Efficiency	12–64%	[123], [124]
Closed-loop systems and valorization	Efficiency	Low	[125]–[127]

Integration of the technologies, as mentioned earlier, in 1G+2G bioethanol production is modeled in Figure 6. In addition, the proposed model also shows a potential application of third generation (3G) bioethanol from algae to increase the yield and optimize the process. This circular economy model minimizes resource usage and waste production and enhances production yield, illustrating a sustainable approach to bioethanol production.

3.4 *Economic challenges, technological challenges and social impact of integration of CCUS, closed-loop systems, and waste valorization on 1G+2G bioethanol production from sugarcane*

Integration of CCUS, closed-loop systems, and waste valorization faces different technological and economic challenges and social impacts. Technological challenges cover process and resource efficiency, resource intensiveness, technological advancement, and application in existing bioethanol production plants. Economic challenges highlight problems with the cost-effectiveness of the integration of these technologies. Social impact covers the impact on the communities that significantly hinders the widespread adoption of the mentioned technologies.

3.4.1 Technological challenges

The manufacturing process of green technology faces challenges, particularly in terms of efficiency and resource effectiveness [112], as shown in Table 8. Various factors influence bioethanol production, and although post-combustion capture is highly efficient, it has low effectiveness. Carbon capture efficiency depends on specific requirements to achieve workable efficiency, which results in decreased efficiency when requirements are not met [113]. Ethanol production is already an energy-intensive process [109], and the addition of CCUS, which is also an energy-intensive process, increases the energy demand. The integration of 2G ethanol, while increasing the bioethanol yield, suffers from efficiency due to the additional processes needed for production [114]. Closed-loop systems and technological advances in waste valorization are also barriers to integrating these technologies into the process [58], [115]. These technologies have impeded the application of technological advancements in existing production plants [116].

3.4.2 Economic challenges

The technologies mentioned above also face the same challenge: economic effectiveness. Carbon capture, the main technology of CCUS, costs an estimated 70–80% of the total cost of CCUS integration, but carbon capture has not yet been considered cost effective [113], [128]. Although closed-loop systems and waste valorization help produce higher yield and value-added products, they suffer from economic effectiveness due to yet efficient technological advancement and government support [115], [19]. These economic and technological challenges have impeded the application of these technologies in existing production plants [116].

Aside from the capital cost needed to integrate the aforementioned technologies, other economic indicators such as the energy prices due to the intensive energy processes of the process, return on investment (ROI), and government incentives for the project to be economically attractive to investors are needed to be examined. Energy prices have recently increased, especially for non-renewable sources like coal and natural gas [129]–[131]. Bioethanol production requires a lot of energy, especially when using 2G sugarcane bioethanol and CCUS technology [109]. With the recent inflation in energy prices, integrating these methods may seem less economically attractive. However, the inflation in non-renewable energy prices may make renewable energy options, such as bioethanol production, a better investment [129], [132]. CCUS is a technology that can reduce carbon emissions in production [133], [134]. However, it needs to be optimized, meaning the return on investment may take longer [135]. To make CCUS more economically viable, government interventions such as subsidies and policies can help increase carbon profit [133], [134].

3.4.3 Social impact

An approach to renewable energy, including CCUS, closed-loop systems, and waste valorization, can offer both environmental and economic opportunities that cause a social impact. Integrating CCUS, closed-loop systems, and waste valorization can create jobs in renewable energy production, particularly in the construction and installation sectors, due to a shift favoring renewable energy production [136]. Bioethanol production also reveals effects on local communities, which indicates a potential driver of economic development and social good. Still, it also necessitates careful planning and government intervention [137]. Public perception of sugarcane bioethanol production is likely influenced by sustainability concerns, government policies, and competition with food resources [79]. However, by addressing these concerns and implementing sustainable practices, bioethanol production can become a tool for social progress alongside environmental responsibility.

3.5 *Life cycle assessment*

Sugarcane bioethanol production faces significant environmental challenges, including land use, yield efficiency, seasonality, and carbon emissions [9]–[11]. However, these challenges can be mitigated by integrating CCUS technologies, closed-loop systems, and waste valorization, making the production process more environmentally sustainable.

Resource efficiency is crucial in sugarcane bioethanol production. Carbon capture from fermentation by-products improves energy efficiency and reduces reliance on fossil fuels. Wastewater treatment is also essential for resource management [108]. It provides opportunities to recycle water for irrigation and recover nutrients for fertilizer in sugarcane cultivation [94]. Additionally, converting solid waste into compost material and biofuels enhances resource efficiency by effectively minimizing waste and utilizing by-products [98], [101].

Various by-products are generated during production, including VOCs, spent yeast, and solid waste. These by-products can be managed through biological conversion techniques such as biofiltration and bioconversion, which convert them into valuable biofuels and compost materials [82], [104]. By managing by-products effectively, the production process becomes more sustainable, reducing waste and environmental impact.

Sustainable technologies in sugarcane bioethanol production involve trade-offs between different factors such as cost, energy efficiency, and environmental impact. For example, while carbon capture technologies can reduce greenhouse gas emissions, they may require significant investment and energy for implementation [85], [109]. Similarly, utilizing captured carbon for different purposes, such as synthetic fuel production or algae cultivation, involves trade-offs regarding resource allocation and technology compatibility [119], [120]. Balancing these trade-offs is crucial to optimize the sustainability of bioethanol production processes.

Adopting sustainable strategies such as CCUS integration, by-product valorization, and resource recycling is crucial to mitigating environmental impact, improving resource efficiency, and optimizing bioethanol production processes. These approaches contribute to developing a circular economy model that minimizes waste, maximizes resource utilization, and enhances overall sustainability.

3.6 *Attainable Sustainable Development Goals (SDGs) of the proposed circular economy model*

The UN Member States adopted the SDG in 2015 as part of the 2030 Agenda for Sustainable Development [138]. The SDGs aim to address many social, economic and environmental challenges facing today’s world and build on the Millennium Development Goals (MDGs). Each goal has specific targets to be achieved by 2030, covering areas such as poverty eradication, education, health, gender equality, clean water and sanitation, sustainable energy, economic growth, climate action and environmental conservation. The SDGs provide a framework for international cooperation and action to promote a more sustainable and equitable future for everyone and the planet. The proposed circular economy model for the production of 1G+2G sugarcane bioethanol aligns with six of the 17 Sustainable Development Goals (SDGs). These SDGs include SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water), as shown in Figure 7.

Reducing carbon emissions associated with bioethanol production facilitates the transition to cleaner energy sources through CCUS, addressing SDG 7. Closed-loop systems and waste valorization strategies promote innovative approaches to by-product utilization and resource optimization, enhancing sustainable industrial practices in line with SDG 9. Waste valorization and closed-loop systems mitigate waste generation, promote sustainable waste management, and contribute to mitigating urban air pollution, promoting healthier living environments, which aligns with SDG 11. Waste stream valorization promotes resource efficiency and responsible consumption, while closed-loop systems minimize waste generation, bolstering sustainable production practices supporting SDG 12. CCUS combats greenhouse gas emissions and addresses climate change, directly addressing SDG 13. Finally, sustainable agricultural practices reduce pollution runoff into water bodies, minimize waste generation, and implement closed-loop systems that preserve marine ecosystems and mitigate ocean acidification, which is critical for marine biodiversity and aligns with SDG 14.

4 Future Directions and Research Priorities

Research on sugarcane bioethanol production is set to focus on integrating emerging technologies with the circular economy to improve efficiency and scalability. One area of focus will be the development of advanced CCUS methods specifically for bioethanol facilities. The aim is to increase recovery rates and reduce energy consumption [139], [140]. An essential aspect of this research will be optimizing closed-loop systems to minimize waste generation and reuse by-products in innovative ways [141]. There will also be a continued emphasis on waste valorization, with efforts to extract maximum value from waste streams and develop novel applications for recovered materials [142]. Additionally, research into algae-based 3G bioethanol production is expected to increase, driven by advances in cultivation techniques, genetic engineering, and biorefinery processes [143]. As sustainability becomes increasingly important in bioethanol production, interdisciplinary collaborations and holistic approaches will likely characterize future research endeavors. These efforts will pave the way for more efficient, environmentally friendly, and economically viable bioethanol production systems.

Figure 7: Attainable SDGs from a proposed circular economy model.

5 Conclusions

The study provides a comprehensive framework for enhancing sustainable bioethanol production, focusing on sugarcane-derived 1G+2G bioethanol. While it may not be cost-effective to implement the model studied in this industry, the research can be further developed to make it more beneficial to the sector. It also offers valuable information for transitioning the bioethanol industry toward a more sustainable future by examining technological integration, economic challenges, and SDG alignment. Moreover, it provides a roadmap for stakeholders to navigate towards greener and more efficient bioethanol production systems. This approach promotes environmental preservation, innovation, economic growth, and collaboration to achieve a sustainable energy landscape. In the current era, where pollution turns into waste if not utilized properly, it is essential to integrate these pollutants into the production process. In this way, they can become useful and serve a better purpose.

Author Contributions

R.J.P.L.: conceptualization, data gathering, data analysis and writing an original draft; R.V.R.: conceptualization, investigation, reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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