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Qualitative assessment of bioethanol production sustainability applying the GBEP methodology: a comparative case between coconut husks and sugarcane bagasse

Avaliação qualitativa da sustentabilidade da produção de bioetanol aplicando a metodologia GBEP: um caso comparativo entre casca de coco e bagaço de cana-de-açúcar

Evaluación cualitativa de la sostenibilidad de la producción de bioetanol utilizando la metodología GBEP: un caso comparativo entre cáscara de coco y bagazo de caña de azúcar

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Abstract
The conventional production of bioethanol takes place through sugar cane processing. Given that Brazil generates abundant lignocellulosic residues, other bioethanol production routes from residual biomasses have been increasingly considered. In this context, this study aimed to assess the sustainability of two second-generation bioethanol (E2G) production routes, one from sugarcane bagasse and the other from coconut husks. To this end, nine indicators proposed by the GBEP (Global Bioenergy Partnership) methodology, namely GHG emissions, non-GHG emissions, water use and efficiency, income changes, bioenergy sector jobs, incidence of occupational injuries, illnesses and deaths, productivity, net energy balance and increased gross value from bioenergy production, were applied. Following the two bioethanol production route assessments through indicator application, a conclusive graphic outlook was constructed to identify the most sustainable route. The sugarcane bagasse production route derives from the Iogen technology and is employed at Raízen's Costa Pinto Plant, which produces this biofuel on an industrial scale, while the coconut husk production route is currently being improved on a bench scale. The indicator analysis demonstrates that, despite the coconut husk route exhibiting greater social sustainability, with better employee remuneration and less frequent injuries, illnesses and occupational deaths, the sugarcane bagasse route shows greater environmental and economic sustainability, due to lower GHG emissions and water extraction, besides higher productivity, and higher net production income. Therefore, the comparative analysis produced by applying the GBEP methodology demonstrates that the sugarcane bagasse route is the most sustainable regarding the production of second-generation bioethanol.
Keywords: Sustainability; GBEP; E2G; Biomasses.

Resumo
A produção convencional de bioetanol ocorre por meio do processamento da cana-de-açúcar. Dado que o Brasil gera resíduos lignocelulósicos em abundância, rotas de produção de bioetanol a partir de biomassas residuais têm sido consideradas. Nesse contexto, este estudo teve como objetivo avaliar a sustentabilidade de duas rotas de produção de bioetanol de segunda geração (E2G), uma a partir de bagaço de cana-de-açúcar e outra da casca de coco. Para tanto, nove indicadores propostos pela metodologia GBEP (Global Bioenergy Partnership), a saber, emissões de GEE, emissões não GEE, uso e eficiência da água, variações de renda, empregos no setor de bioenergia, incidência de acidentes de trabalho, doenças e mortes, produtividade, balanço energético e aumento do valor bruto da produção de bioenergia. Após a avaliação das rotas de produção de bioetanol, foi construído um panorama gráfico conclusivo para identificar a mais sustentável. A rota via bagaço de cana é derivada da tecnologia Iogen e é empregada na Usina Costa Pinto da Raízen, que produz esse biocombustível em escala industrial, enquanto a rota de produção via casca de coco está sendo aprimorada em escala de bancada. A análise dos indicadores demonstra que, apesar da rota da casca de coco apresentar maior sustentabilidade social, com melhor remuneração dos funcionários e menor frequência de

lesões, doenças e mortes ocupacionais, a rota do bagaço de cana apresenta maior sustentabilidade ambiental e econômica, devido à menor emissão de GEE e extração de água, além de maior produtividade e maior receita líquida de produção. Portanto, a análise comparativa produzida pela aplicação da metodologia GBEP demonstra que a rota do bagaço da cana-de-açúcar é a mais sustentável em relação à produção E2G.
Palavras-chave: Sustentabilidade; GBEP; E2G; Biomassas.

Resumen
La producción convencional de bioetanol se produce a través del procesamiento de la caña de azúcar. Dado que Brasil genera residuos lignocelulósicos en abundancia, se han considerado rutas de producción de bioetanol a partir de biomasa residual. En este contexto, este estudio tuvo como objetivo evaluar la sostenibilidad de dos rutas de producción de bioetanol de segunda generación (E2G), una a partir de bagazo de caña de azúcar y otra a partir de cáscara de coco. Para ello, nueve indicadores propuestos por la metodología GBEP (Global Bioenergy Partnership), a saber, emisiones de GEI, emisiones no GEI, uso y eficiencia del agua, variaciones de ingresos, empleos en el sector bioenergético, incidencia de accidentes de trabajo, enfermedades y muertes, productividad, balance energético y aumento del valor bruto de la producción de bioenergía. Después de evaluar las rutas de producción de bioetanol, se construyó un resumen gráfico concluyente para identificar la más sostenible. La ruta a través del bagazo de caña de azúcar se deriva de la tecnología Iogen y se utiliza en la planta de Costa Pinto da Raízen, que produce este biocombustible a escala industrial, mientras que la ruta de producción a través de la cáscara de coco se está mejorando a escala de banco. El análisis de los indicadores muestra que, si bien la ruta de la cascarilla de coco presenta mayor sustentabilidad social, con mejor remuneración de los empleados y menor frecuencia de lesiones, enfermedades y muertes ocupacionales, la ruta del bagazo de caña presenta mayor sustentabilidad ambiental y económica, debido a la menor emisión de GEI. emisiones y extracción de agua, además de una mayor productividad y mayores ingresos netos por producción. Por tanto, el análisis comparativo producido por la aplicación de la metodología GBEP demuestra que la ruta del bagazo de caña de azúcar es la más sostenible en relación a la producción de E2G.
Palabras clave: Sostenibilidad; GBEP; E2G; Biomasas.

1. Introduction

Brazil is one of the world's largest bioethanol producers, especially through sugarcane processing (ANP, 2016), although the production of second-generation bioethanol (E2G) is currently in development and gaining ground throughout the country. In this concern, Brazil possesses 11 plants that produce 2G bioethanol from sugarcane bagasse (ANP, 2020), indicating the insertion of E2G in the Brazilian energy matrix. Other countries have also invested in this segment, employing different plant biomasses (Nova Cana, 2015).

As sugarcane bagasse biomass is already included in Brazilian production (Raízen Annual Report 2018|2019, 2019) and coconut husks are an abundant lignocellulosic residue in the country (Marafon et al., 2019), exceeding 1.6 million tons per year and responsible for about 70% of the waste found on the beaches and wastelands, research is encouraged to support the use of these wastes, and bioethanol production is considered a promising option from a sustainability point of view.

As widely discussed in Melo et al. (2020) and Melo (2021), sustainability has been increasingly highlighted in the last decades. However, few studies have assessed product and process sustainability considering their three pillars, indicating the importance of developing studies in this context. Furthermore, the aforementioned authors report that sustainability assessment methodologies are usually adjusted to the goals of specific assessments. Thus, no official methodology is yet dedicated to this purpose.

In this context, having highlighted the importance of conducting studies that assess product and/or process sustainability based on their three pillars and recognizing the growing trend of 2G bioethanol production in Brazil, this study aimed to compare the sustainability of E2G production employing coconut (*Cocus nucifera* L) husks and sugarcane (*Saccharum officinarum*) bagasse, employing the methodology developed by the Global Bioenergy Partnership (GBEP) to assess bioenergy sector sustainability.

2. Methods

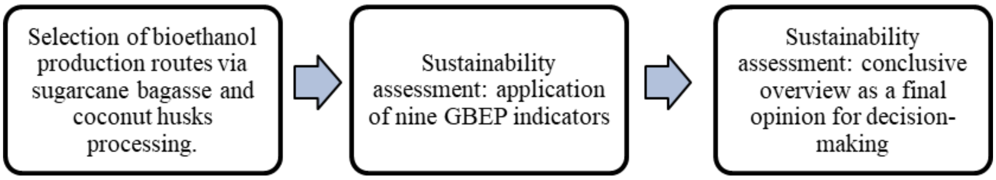
This study fits as an exploratory qualitative research, from a quali-quantitative methodology as explained in Pereira et al. (2018). Thus, in a complementary way, the collection of information from the literature was carried out, as well as the processing of data through GBEP indicators, for a comparative assessment of the sustainability of the production of 2G bioethanol. This type of approach is explained in detail in Yin (2015).

The GBEP methodology (2011) was selected considering the systematic literature research developed by Melo et al. (2020), as it applies indicators aimed specifically at bioenergy sector sustainability and does not require specialized computational resources. It also provides methodological support for its development through the provision of instructions that guide the application of each one of the 24 GBEP indicators.

Nine GBEP indicators, namely: Greenhouse gas emissions (GHG) emissions, non-GHG emissions, water use and efficiency, income changes, jobs in the bioenergy sector, incidence of occupational injuries, illnesses and deaths, productivity, net energy balance and increased gross value from bioenergy production, were selected according to Melo (2021), based on bioethanol sugarcane bagasse and coconut husk production process characteristics and the support of these indicators when considering the discussion presented by the aforementioned author.

The evaluation was limited to the productive (industrial) stage of sugarcane bagasse and coconut husk E2G production, so planting, harvesting and biomass transportation, as well as bioethanol use, were disregarded. The study followed the steps displayed in Figure 1.

Figure 1. Methodology flow.



Source: Produced by authors (2021).

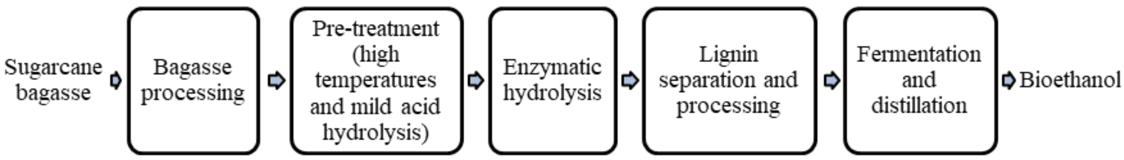
3. Results and Discussion

3.1 Bioethanol production routes

3.1.1 Sugarcane bagasse

Amid the 11 Brazilian plants that produce bioethanol from sugarcane bagasse, literature data concerning production processes are available only for Bioflex 1, GranBio (Alagoas), São Luiz (São Paulo) and Costa Pinto, Raízen (São Paulo). Considering that the DHR technology employed at the São Luiz plant is still under development (Montes, 2017), and not enough details are available regarding to the production through the PROESA technology applied at the GranBio Bioflex 1 plant, sugarcane bagasse bioethanol production employing Iogen technology, applied at the Costa Pinto Raízen plant, was selected (Figure 2).

Figure 2. Bioethanol sugarcane bagasse production scheme employing Iogen technology.



Source: Adapted from the Iogen Corporation (2021).

3.1.2 Coconut husks

As the global route for the production of lignocellulosic material bioethanol consists of three stages, namely pre-treatment, hydrolysis and fermentation (Cabral, 2015), some combinations and variants are possible. Thus, the production steps identified in the 14 studies presented in Table 1 were carefully analyzed concerning the routes that have been developed so far, and the most relevant was selected.

The three-stage bioethanol production route comprises the following:

i. Pre-treatment: the 14 studies evaluated herein employed physical pre-treatment as the initial procedure, indicating that the applied biomass must undergo drying and size reduction processes, sometimes accompanied by additional processes, such as substrate washing. Nine studies applied sodium hydroxide, alone or in combination with other treatments. Alkaline pretreatment was considered unanimously effective, either alone or combined with other compounds. Thus, the evaluated route displaying the following pre-treatment format was selected: Physical pre-treatment (drying, grinding, sieving) followed by alkaline pre-treatment employing NaOH.

ii. Hydrolysis: of the 14 studies evaluated herein, only one did not apply a hydrolysis procedure. Of the 13 that did, 12 opted for an enzymatic hydrolysis, inferring that this consists in the most advanced research stage. Of the 12 studies applying enzymatic hydrolysis, three did not specify the employed enzyme. Of the 9 that did, four employed the Novozymes-Cellic CTec enzyme and three, the *A. niger* enzyme. However, the efficiency of the hydrolysis step is directly associated to lignin removal achieved in the pre-treatment step, which is why the applied enzyme was not considered a determining factor for the hydrolysis selection.

Table 1. Studies concerning to the coconut husk bioethanol production.

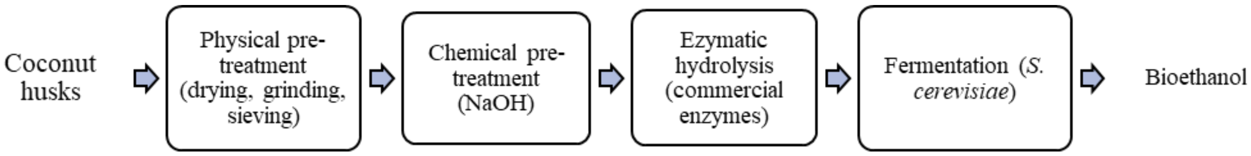
Reference	Pre-treatment	Hydrolysis	Fermentation
Janna and Asip, 2015.	PT-F + PT-Q with NaOH	Acid, employing sulfuric acid	*Saccharomyces cerevisiae*
Laghari et al., 2015.	PT-F + PT-Q com H_2SO_4, NaOH, H_2O_2, Na_2CaO_3 + PT-F by microwave radiation	-	Not performed
Sangian et al., 2015a	PT-F + NaoH; PT-F + NaoH + ionic liquid; PT-F + ionic liquid	-	Not performed
Sangian et al., 2015b	PT-F + PT-Q com água subcrítica	Enzymatic, employing pure *A. niger* enzyme cellulase substrate	Not performed
Bensah et al., 2015.	PT-F + PT-F hydrothermal	Not performed	Simultaneous Saccharification and Fermentation (SSF) using an unspecified fermentative microorganisms
Gonçalves et al., 2015.	PT-F + PT-Q with auto-hydrolysis	Enzymatic, employing pure *A. niger* enzyme cellulase substrate	Semi-simultaneous saccharification and fermentation (SSSF) or SSF, both employing *Zymomonas mobilis, Pichia stipitis* and *Saccharomyces cerevisiae*
Gonçalves et al., 2016.	PT-F + PT-F hydrothermal catalyzed by NaoH	Enzymatic, employing the *Cellic* CTec 2 and HTec 2 enzymatic kit	SSF or SSSF, both employing *Zymomonas mobilis, Pichia stipitis* and *Saccharomyces cerevisiae*
Cabral et al., 2016.	PT-F + PT-Q with NaOH	Enzymatic, employing the commercial enzyme Accellerase 1500	*Saccharomyces cerevisiae*
Soares et al., 2017	PT-F + PT-Q with NaOH + PT-Q with NaOH	Alkaline, with the addition of an unspecified commercial enzyme loads	*Saccharomyces cerevisiae*
Subhedar et al., 2018	PT-F + PT-Q with NaOH; e PT-F + PT-Q with NaOH assisted by ultrasound	Enzymatic, employing cellulase displaying carboxymethyl cellulase CMCase activity; ultrasound-assisted enzymatic	Not performed

Ebrahimi et al., 2018.	PT-F and PT-Q with $(NH_4)_2CO_3$	Enzymatic, employing an unspecified cellulase	SSF using *Saccharomyces cerevisiae*
Nogueira et al., 2019.	PP-F + PT-F hydrothermal with deionized water; PT-F + PT-Q alkaline diluted with NaOH; PT-F + PT-Q with acid diluted with H2SO4; PT-F + PT-Q with organosolv	Enzymatic, employing cellulase, β-glucosidase and xylanase	*Saccharomyces cerevisiae*
Sangkharak et al., 2020.	PT-F + PT-Q with NaOH	Enzymatic, employing two types of cellulase derived from *Trichoderma viride* and *Aspergillus niger*	*Saccharomyces cerevisiae*
Bronzato et al., 2020.	PT-F + PT-Q with four reagents (deionized water, C_3H_6O, H_2SO_4 and $NaClO_2$) + PT-Q and four mixtures (H_2O + $NaClO_2$; C_3H_6O + $NaClO_2$; H_2SO_4 + $NaClO_2$; $NaClO_2$).	Enzymatic, employing cellulase (Novozymes-Cellic CTec3, Bagsvaerd, Denmark)	Separate saccharification and fermentation and SSF with *Saccharomyces cerevisiae*

* PT-F: Physical pre-treatment; ** PT-Q: Chemical pre-treatment. Source: Produced by authors (2021).

iii. Fermentation: Of the 14 investigated studies, only four did not carried out a fermentation step. The ten studies encompassing all the steps employed *Saccharomyces cerevisiae*. Thus, this yeast was selected for our evaluation. Figure 3 presents the selected bioethanol coconut husk production sustainability evaluation route following a stepwise analysis.

Figure 3. Selected bioethanol coconut husk production sustainability evaluation route.



Source: Produced by authors (2021).

The selected route represented in Figure 3 was adopted in four of the analyzed studies. The selection of the reference study took in account the highest degree of detailing and clarity regarding the applied coconut husk bioethanol production procedures indicated in Cabral et al. (2016).

3.2 Sustainability assessment through indicator application

The nine indicators related to the sugarcane bagasse and coconut husk bioethanol production routes were applied individually, according to GBEP recommendations (2011).

3.2.1 Indicator 1: greenhouse gas emissions (GHG) during the bioenergy production life cycle and use

This indicator measured GHG emissions throughout the bioenergy production life cycle, expressed as $tCO_2.L^{-1}$ and $gCO_2.L^{-1}$.

Regarding sugarcane bagasse, Raízen's annual reports for the 2015|2016 and 2019|2020 harvests were consulted (previous harvests were not considered because commercial E2G production was implemented only from the 2015| 2016 harvest), which report total CO_2 emissions per ton of crushed sugarcane for each harvest. Raízen indicated that its 2G bioethanol production reduces CO_2 emissions by 35% compared to the production of 1G bioethanol. The data and performed calculations suggesting an average emission factor of $4.2x10^{-4}$ $tCO_2.L^{-1}$ of E2G, are presented in Table 2.

Regarding to coconut husks, Cabral et al. (2016) carried out a bench scale production following a novel route, supporting why no reports on GHG emissions as a result of the coconut husk bioethanol production process are available. As the process comprises several steps that vary according to the production route, each step must be analyzed separately. Table 3 indicates the coconut husk bioethanol production process steps displaying the potential for GHG emissions.

Table 2. Greenhouse gas emission estimates from sugarcane bagasse for E2G production.

	Harvest 2015|2016	**2016|2017**	**2017|2018**	**2018|2019**	**2019|2020**	**Means**
$tCO_2.t^{-1}$ of crushed sugarcane	No data for this harvest	No data for this harvest	0.0273	0.0239	0.0240	
t of crushed sugarcane			61,200,000	59,700,000	59,600,000	
tCO_2			1,670,760	1,426,830	1,448,273	
Total bioethanol Production (m^3)			2,112,000	2,516,500	2,500,000	
E2G production (m^3)			12,000	16,500	16.392	
% related to E2G production			0.57	0.66	0.66	
GHG emissions proportional to E2G production			9,523.33	9,417.08	9,558.60	
Reduction of GHG emissions from E2G (%)			35	35	35	
$tCO_2.L^{-1}$ E2G			$5.2x10^{-4}$	$3.7x10^{-4}$	$3.8x10^{-4}$	$4.2x10^{-4}$

Source: Based on the Raízen Annual Report 2017|2018 (2018) and Raízen Annual Report 2018|2019 (2019) and Raízen (2020).

Table 3. Greenhouse gas emission estimates from coconut husk for E2G production.

Stage	**Procedure**	**GHG emissions** Yes	No
Physical pre-treatment	Coconut husk cutting	X	
	Sanitization is conducted employing sodium hypochlorite (NaClO) at 100 ppm and drying at 50°C until constant weight	X	
	Crushing is performed in an electric forage and blender	X	
	Sieving	X	
Alkaline pretreatment	Dilution is performed using a 5% sodium hydroxide (NaOH) mixture in Erlenmeyer flask		X
	Autoclaving is ocnducted at 121 °C and 1 atm for 40 minutes	X	
	Filtering		X
Enzymatic hydrolysis	The resulting solid fraction is mixed with to the solution containing the enzyme		X
	The reaction is conducted in an orbital shaking incubator at 50°C and 150 rpm, for 72h	X	
	Filtering		X
Fermentation	The inoculum is cultivated for 18 h at 30°C in an incubator at 100 rpm shaking	Amount not informed	
	Instant yeast is dried in an orbital incubator shaker at 100 rpm	Process time not informed	
	An erlenmeyer is sterilized at 121ºC for 15 minutes	X	
	Fermentation is conducted in a sterilized Erlenmeyer flask	X	

Source: Produced by authors (2021).

The potential for GHG emissions is based on procedures that employ electricity and on the gases generated by the fermentation process. Seven procedures comprise possible GHG emission sources among which six employ electrical energy. To estimate the electricity-dependent emissions for each procedure, the data provided by the equipment manufacturers were consulted and the SOS Mata Atlântica Project CO_2 emissions calculator (Projeto SOS Mata Atlântica, 2021) pointed out an average emission rate of $6.55x10^{-4}$ $gCO_2.L^{-1}$ of bioethanol, about 56% higher than the average of $4.2x10^{-4}$ $tCO_2.L^{-1}$ estimated for sugarcane bagasse. Further details concerning the applied calculations and estimates are available in Melo (2021).

3.2.2 Indicator 2: non-GHG emissions, including toxic substances

For this indicator, non-GHG pollutant emissions were considered, including toxic substances, arising from biomass burning for energy cogeneration and from vehicles circulating within the plant yard, expressed in mg (PM, NO_x and SO_2).m^{-3}.

According to Violante (2018), emissions consisting of gases that do not cause the greenhouse effect are mostly associated to transportation, especially vehicles that employ diesel as fuel, and the size and age of the vehicle fleet, in addition to the type of fuel, should be considered. The author also mentions that these emissions may also be associated to biomass burning on plant assumptions, with emphasis on burning using boilers for energy cogeneration.

Regarding sugarcane bagasse, none of the harvest data presented in Raízen's annual reports from 2012 to 2020 reports non-greenhouse gases. For coconut husks, Cabral et al. (2016) carried out only e bench scale production with no mention to non-GHG emissions concerning coconut husk bioethanol production. Thus, due to the lack of information on non-greenhouse gas emissions for investigated routes and considering that non-GHG emissions are mainly associated to the production specificities of each plant, we considered this indicator as still under improvement, suggesting that plants include the necessary information for such calculations in their control routines and annual reports.

3.2.3 Indicator 3: water use and efficiency

This indicator, expressed as $m^3.H_2O.L^{-1}$ of bioethanol, measures extracted water and water used for bioethanol production and biomass processing per unit of produced energy (reports indicate that the water extraction comprises the amount obtained from the environment for the production, while water sed includes water inflows from reuse and recycling processes in addition to the income flow).

The Raízen Annual Report 2018|2019 (2019) was consulted concerning 2G sugarcane bagasse bioethanol production, indicating 0.0163 m^3.H2O.L^{-1} for E2G extraction. However, no data on water use is available in connection with coconut husk bioethanol production. Thus, each step of this route was analyzed individually, as shown in Table 4.

Three procedures use water in the coconut husk bioethanol production process, while two do not mention this issue. Hence, only those three indicated procedures were considered. To estimate the volume of water for each step, the concentrations and amount of solutions used in each procedure were considered, as reported by Cabral et al. (2016), in addition to the potential for water recycling/reuse in industrial processes, identified as 96% at the São Manoel sugarcane plant (São Manoel Sustainability Report 2018, 2018). Thus, a water extraction ratio of 0.037 m^3.H2O.L^{-1} of bioethanol was estimated. Calculation details are found in Melo (2021).

Table 4. Water use in each coconut husk E2G production step.

Stage	**Procedure**	**Water use**	
		Yes	No
Physical pre-treatment	The coconut husks are cut		X
	Sanitization is performed using 100 ppm NaClO and drying at 50°C	X	
	Crushing is performed using an electric forage and blender		X
	Sieving		X
Alkaline pretreatment	Dilution in a 5% NaOH mixture	X	
	Autoclaving		X
	Filtering		X
Enzymatic hydrolysis	The resulting solid fraction is mixed with the enzyme solution	X	
	The reaction is conducted in an orbital shaking incubator		X
	Filtering		X
Fermentation	Inoculum cultivation	Not informed	
	Fermentation	Not informed	

Source: Produced by authors (2021).

3.2.4 Indicator 4: income changes

This indicator measured income changes due to the bioenergy production, based on sector salaries, expressed as BRL/employee. In relation to sugarcane bagasse, Raízen's reports for the 2015|2016 and 2019|2020 harvests were consulted. Commercial production of 2G bioethanol from bagasse was included in Raízen's Plant from the 2015|2016, discarding previous crops data. Values were corrected for 2021, as compiled in Table 5.

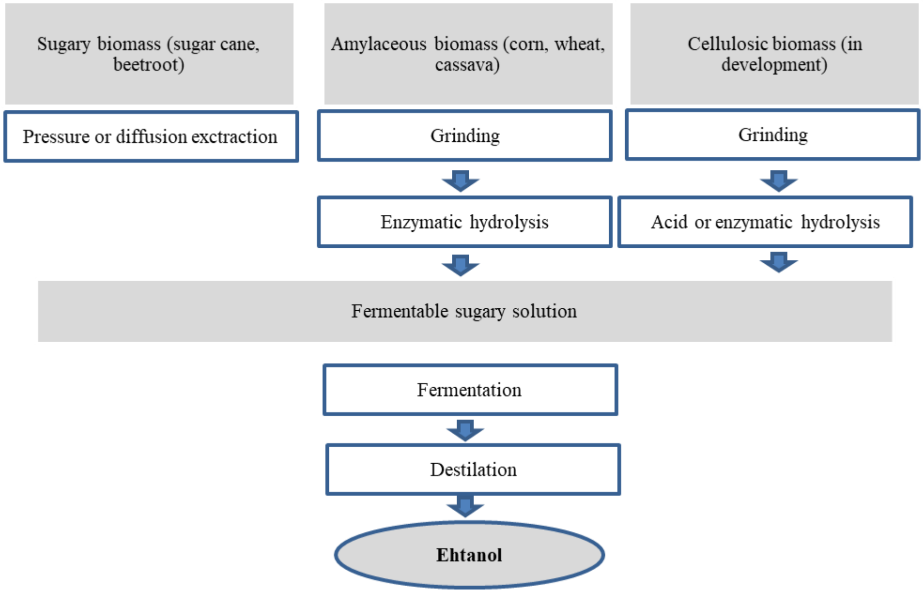
Table 5. Average monthly salary per employee for the sugarcane bagasse E2G production.

	Harvest				
	2015|2016	**2016|2017**	**2017|2018**	**2018|2019**	**2019|2020**
Employees	No data are available for this harvest	29,557	29,514	28,983	28,333
(1) % ethanol equivalent to E2G production		0.34	0.57	0.66	0.66 *
Employees proportional to 2G production		100	168	191	187
Salary (BRL)		272,357,000 (D) 344,473,000 (T)	301,200,000 (D) 376,987,000 (T)	374,641,000 (D) 459,866,000 (T)	483,664,000 (D) 566,530,000 (T)
Salary proportional to E2G production (BRL)		926,013.80(D) 1,171,208.20(T)	1,716,840.00(D) 2,148,825.90(T)	2,472,630.60(D) 3,035,115.60(T)	3,192,182.40(D) 3,739,098.60(T)
Average monthly Salary proportional to E2G production (BRL/employee)		771.68(D) 976.01(T)	851.61(D) 1,065.89(T)	1,078.81(D) 1,324.22(T)	1,422.54(D) 1,666.26(T)
Minimum salary for the period (BRL)		880.00	937.00	954.00	998.00
Average monthly salary corrected for the year 2021, in (BRL/employee)		964.60(D) 1,220.01(T)	999.75(D) 1,251.31(T)	1,243.91(D) 1,526.88(T)	out1,567.93(D) out1,836.56(T)

[D]Average direct compensation = 1,332.73 BRL. [T]Average total compensation (direct + benefits) = 1,069.42 BRL. Source: Produced by authors (2021).

Regarding to coconut husks, as Cabral et al. (2016) carried out only a bench scale production, we deduced that there are no plants dedicated to bioethanol production using this biomass. Thus, the average salary could not be calculated for this route. However, as presented in Figure 4, bioethanol production steps employing both corn (starch biomass) and coconut husks (cellulosic biomass) are similar. Thus, the authors considered a similar income to corn biofuel production, allowing for a parallel comparative scenario development.

Figure 4. Bioethanol production routes employing fermentation. Adapted from BNDES and CGEE (2008).



Source: Produced by authors (2021).

Therefore, reports from plants using corn for bioethanol production was sought out and found for only one plant (FS Bioenergia). Table 6 was arranged using these data, resulting in an average monthly per capita income of 1,403.00 BRL.

Table 6. Average monthly salary per employee in the corn bioethanol production route at the FS Bioenergia plant.

Harvest	(B) Minimum salary for the period, in BRL	(B) % paid above the current minimum wage	(P) Lowest salary paid, in BRL	(P) Lowest monthly salary of the crop, corrected for the year 2021, in BRL
2018|2019	954.00	20	1,144.80	1,332.00
2019|2020	998.00	34	1,337.32	1,474.00
	Average of the lowest monthly salary paid by the plant:		1,403.00	

Source: According to the FS Bioenergia 2018|2019 and 2019|2020 Annual Sustainability Report (2019, 2020).

Thus, considering the similarity between corn and coconut husk bioethanol production stages, an average salary of 1,403.00 BRL was adopted for coconut husk bioethanol, higher than the direct income of 1,069.42 BRL and total income of 1,332.73 BRL for sugarcane bioethanol production (Table 5).

3.2.5 Indicator 5: jobs in the bioenergy sector

This indicator measures the net job creation resulting from bioenergy production, comprising total job creation and non-specified/temporary job creation, expressed as number of employees.m^{-3}. Regarding sugarcane bagasse, Raízen's annual reports were consulted from the 2011|2012 to 2019|2020 harvests (Table 7), but they do not discriminate the number of employees for 1G and 2G production. Therefore, this indicator is based on the estimate of the number of employees per liter of bioethanol, assuming the same average for both productions (1G and 2G).

Table 7. Jobs associated to the integrated production of 1G and 2G bioethanol at the Raízen plant.

Harvest	Employees	Total bioethanol volume, in m^3	Employees.m^{-3}
2011|2012	40,000	1,921,000	20.82 x10^{-3}
2012|2013	40,170	1,900,000	21.14 x10^{-3}
2013|2014	41,751	2,000,000	20.88 x10^{-3}
2014|2015	38,572	2,100,000	18.37 x10^{-3}
2015|2016		No data were obtained for this harvest.	
2016|2017	29,557	2006.800	14.73 x10^{-3}
2017|2018	29,514	2,112,000	14.00 x10^{-3}
2018|2019	28,983	2,516,500	11.52 x10^{-3}
2019|2020	28,333	2,500,000	11.33 x10^{-3}
		Mean	16.60x10^{-3}
		Mean after insertion of 2G production*	12.90 x10^{-3}

*Commercial 2G sugarcane bagasse bioethanol started in the 2015|2016 harvest, so this average considers the 2016|2017-2019|2020 periods. Source: According to the Raízen Sustainability Reports for the 2011|2012, 2012|2013, 2013|2014, 2014|2015 harvests (2012-2015); Raízen Annual Reports for the 2016|2017, 2017|2018, 2018|2019 harvests (2017-2019); and Raízen Annual Report 2019|2020: Indicators Book (GRI) (2020).

An important remark the number of employees/m³ decreased throughout the sugarcane harvests, probably due to mechanization, which has taken place since the mid-2000s (Nova Cana, 2018), and the beginning of commercial 2G bioethanol production in the 2015 | 2016 harvest. A decrease of about 20% in the ratio of number of employees to volume of bioethanol was noted comparing the 2014|2015 harvest (prior to E2G production) to the 2016|2017 harvest (with cellulosic bioethanol production already in place), increasing to about 45% when comparing the 2011|2012 and 2019|2020 harvests.

According to Raízen (2020), 2G bioethanol production increased plant productivity by 50% and does not require agricultural labor, according to Nova Cana (2017), who states that "The results of the analyzes indicate that harvesting mechanization and 2G ethanol production causes a drop in the number of workers due to a decreased need for people to carry out manual operations, such as planting and harvesting, and for sugarcane to produce 2G ethanol". Therefore, considering the eight harvests included in Table 7, a total rate of 16.60x10^{-3} employees.m^{-3} of bioethanol is estimated. On the other hand, by considering only the harvests after 2G bioethanol production implementation (2016|2017 to 2019|2020), estimates indicate 12.90x10^{-3} employees.m^{-3} of bioethanol. This value was considered for the comparisons carried out herein.

Regarding the coconut husk route, as production is still at a bench scale, the number of jobs associated to this biomass could not be estimated. However, in view of the aforementioned similarity of corn and coconut husk bioethanol production steps, the estimated corn employee/m³ was applied for comparative purposes. Thus, corn bioethanol production plant data were obtained for two facilities, presented in Table 8. The Cochran test was then applied, at a 95% confidence level, and no outliers were identified, indicating employee/m³ rate homogeneity and an average of 1.0x10^{-3} employees.m^{-3} of bioethanol.

When comparing the employees/m³ values presented in Tables 7 and 8, Indicator 5 receives an average of 12.9x10^{-3} employees.m^{-3} for the sugarcane bagasse bioethanol production route and 1x10^{-3} employees.m^{-3} for coconut husk bioethanol production route.

Table 8. Number of employees per m³ of bioethanol in the corn bioethanol production process.

Plant	Biomass	Harvest	Bioethanol production, in m³	Employees	Employees.m⁻³
FS Bioenergy	Corn	2017|2018	137,800	179	$1.3x10^{-3}$
		2018|2019	258,900	271	$1.0x10^{-3}$
		2019|2090	516,600	571	$1.1x10^{-3}$
			Mean		$1.1x10^{-3}$
Inpasa	Corn	2019|2020	528,000	375	$0.7 x10^{-3}$

Source: Adapted from the FS Bioenergia Annual Sustainability Report Crop 2019|2020 (2020) and Inpasa Agroindustrial S.A. (2021).

3.2.6 Indicator 6: incidence of occupational injuries, illnesses and deaths

This indicator measures the incidence of occupational accidents, illnesses and deaths in the production of bioenergy, expressed as number.m^{-3}.

Regarding the sugarcane bagasse bioethanol production route, data from Raízen's reports for the last four crops are presented in Table 9 (crops prior to 2015|2016 were not considered, as commercial 2G bioethanol production began in this harvest year). No data concerning accidents, illnesses and occupational deaths are available for the coconut husk bagasse bioethanol production route, because it is still at a bench scale production stage. Thus, these data were adopted from corn bioethanol production plants and obtained only for one plant (FS Bioenergia). This low number is justified by the lack of plant data access. Table 10 presents data on injuries, accidents and fatalities for different FS Bioenergia harvests. Thus, important differences were noticed in relation to this Indicator, suggesting a higher occurrence of cases for the sugarcane bagasse bioethanol production route.

Table 9. Incidence of deaths, injuries and occupational diseases associated to the E2G bioethanol sugarcane bagasse production route.

Harvest	Issue	Incidence	Total bioethanol production, in m^3	2G production, in m^3	% regarding E2G production	Incidence proportional to E2G production	Number.m^{-3} E2G
2016|2017	Deaths resulting from work-related injuries	1	2,006,800	6,800	0.34	0.0034	$0.5x10^{-6}$
	High-consequence work-related injuries (excluding deaths)	16				0.0544	$8.0x10^{-6}$
	Reportable work-related injuries	122				0.4148	$61.0\ x10^{-6}$
	Deaths resulting from work-related health problems	-				-	-
	Cases of reportable occupational diseases	-				-	-
2017|2018	Deaths resulting from work-related injuries	0	2,112,000	12,000	0.57	0	0
	High-consequence work-related injuries (excluding deaths)	11				0.0627	$5.2\ x10^{-6}$
	Reportable work-related injuries	75				0.4275	$35.6\ x10^{-6}$
	Deaths resulting from work-related health problems	0				0	0
	Cases of reportable occupational diseases	17				0.0969	$8.1\ x10^{-6}$
2018|2019	Deaths resulting from work-related injuries	1	2,516,500	16,500	0.66	0.0066	$0.4\ x10^{-6}$
	High-consequence work-related injuries (excluding deaths)	*13				0.0858	$0.5\ x10^{-6}$
	Reportable work-related injuries	*101				0.6666	$40\ x10^{-6}$
	Deaths resulting from work-related health problems	0				0	0
	Cases of reportable occupational diseases	-				-	-
2019|2020	Deaths resulting from work-related injuries	4	2,500,000	Not informed. **Adopted: 16,392	**0.66	0.0264	$1.6x10^{-6}$
	High-consequence work-related injuries (excluding deaths)	14				0.0924	$5.6x10^{-6}$
	Reportable work-related injuries	82				0.5412	$33.0x10^{-6}$
	Deaths resulting from work-related health problems	0				0	0
	Cases of reportable occupational diseases	3				0.0198	$1.2x10^{-6}$
Means	Deaths resulting from work-related injuries						$0.5x10^{-6}$
	High-consequence work-related injuries (excluding deaths)						$5.4x10^{-6}$
	Reportable work-related injuries						$42.4x10^{-6}$
	Deaths resulting from work-related health problems						0
	Cases of reportable occupational diseases						$4.7x10^{-6}$

* 107 million hours worked were considered, based on the 2019|2020 harvest; ** Due to the lack of data, the volume was calculated adopting the proportion of the previous season. Outliers identified by the Cochran Test at 95% confidence were disregarded for the means calculations. Source: Adapted from the Raízen Annual Reports for the 2016|2017, 2017|2018, 2018|2019 harvests (2017-2019) and Raízen Annual Report 2019|2020: Indicators Book (GRI) (2020).

Table 10. Incidence of deaths, injuries and occupational diseases at the FS Bioenergia plant (E1G plant via the corn bioethanol production route) for different crops.

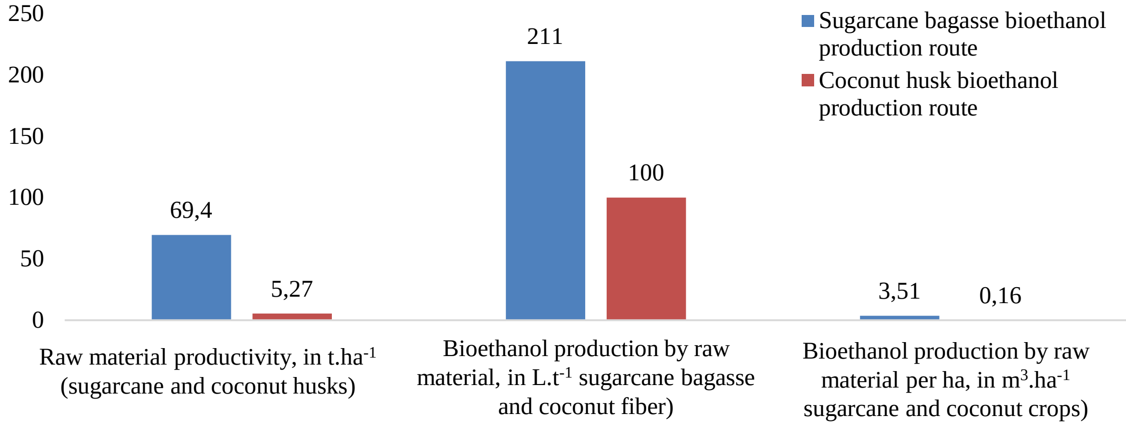
Issue	Number by harverst			Bioethanol volume produced in the harvest, in m^3			Number.m^{-3} of bioethanol			
	2017|2018	**2018|2019**	**2019|2020**	**2017|2018**	**2018|2019**	**2019|2020**	**2017|2018**	**2018|2019**	**2019|2020**	**Means***
Deaths as a result of work-related injuries or occupational diseases	0	0	0				0	0	0	0
High-consequence work-related injuries (excluding deaths)	0	0	0	137,800	256,200	516,600	0	0	0	0
Reportable work-related injuries	3	3	2				22 x10^{-6}	12 x10^{-6}	4 x10^{-6}	13 x10^{-6}
Occupational disease cases	0	0	0				0	0	0	0

*For the means calculations, outliers identified by the Cochran Test at 95% confidence were disregarded. Source: Produced by FS Bioenergia Annual Sustainability Report Crop 2019|2020, 2020.

3.2.7 Indicator 7: productivity

This indicator measures raw material productivity, biomass processing efficiency and the amount of final product generated per hectare, as follows: i) Raw material productivity per plantation: $t.ha^{-1}$; ii) Processing efficiency by raw material: $L.t^{-1}$; iii) Quantity of final bioenergy product per hectare: $m^3.ha^{-1}$. Figure 5 displays productivity comparisons between the sugarcane and coconut husk bioethanol production routes evaluated herein.

Figure 5. Productivity comparisons between sugarcane bagasse and coconut husk bioethanol production routes.



Source: Adapted from Cabral et al. (2016), Nova Cana (2021), Nunes, Santos and Santos (2007), AGEITEC (2021) and Raízen Annual Report 2018|2019 (2019).

From the Figure 5, it is clear that the productivity was considerably higher when sugarcane bagasse is used as biomass, producing approximately 152% more biofuel than coconut fiber.

3.2.8 Indicator 8: net energy balance

This indicator assesses the net energy balance of bioethanol production routes, expressed as $GJ.L^{-1}$. However, the difference between energy output and input during production, comprising the energy balance itself could not be calculated. For this reason, this indicator was evaluated in terms of the net energy consumption presented by each assessed production plants. However, we suggest that plants include information allowing for net energy balance calculations in their annual reports.

For the sugarcane bagasse bioethanol production route, data available in Raízen's reports between the 2015-2016 and 2019|2020 harvests were obtained (Table 11) and the average ratio of energy per volume of biofuel was calculated as 0.054 $GJ.L^{-1}$ of 2G bioethanol. For the coconut husk bioethanol production route, bioethanol corn production data from the FS Bioenergia plant was used, presented in Table 12.

Table 11. Energy consumption for different harvests of E2G bioethanol obtained from sugarcane bagasse.

Harvest	Energy intensity rate, in $GJ.t^{-1}$ of crushed cane	[1] 2G bioethanol production per ton of crushed cane, in $L.t^{-1}$	GJ of $energy.L^{-1}$ of bioethanol 2G
2015|2016	2.63	50.64	0.052
2016|2017	2.83	50.64	[out]0.056
2017|2018	2.77	50.64	0.055
2018|2019	2.75	50.64	0.054
2019|2020	2.66	50.64	0.053
	Mean		0.054

[1]: Estimated data reported in Melo (2021). out: Outlier identified through the Cochran test at a 95% confidence level. The identified outlier was excluded for the mean calculation. Source: Based on the Raízen Annual Report 2019|2020: Indicators Book (GRI) (2020).

Table 12. Energy consumption data for corn bioethanol generation for the FS Bioenergia Plant.

Harvest	[B] Total energy consumption, in GJ	[B] Volume of bioethanol produced, in L	[P] GJ of $energy.L^{-1}$ of bioethanol
2017|2018	1,627,400	137,800,000	0,012
2018|2019	2,626,700	258,900,000	0,010
	Mean		0,011

Source: Based on the FS Bioenergia Annual Sustainability Report Crop 2018|2019 (2019).

The energy consumption of 2G bioethanol production from sugarcane bagasse (0.054 $GJ.L^{-1}$) is about 491% higher than from corn (0.011 $GJ.L^{-1}$) and, as coconut and corn husk bioethanol production stages are similar, their energy consumptions are approximately equal.

3.2.9 Indicator 9: increase in gross bioenergy production value

This indicator aims to provide the gross added value per unit of bioenergy produced. The coconut husk route information was obtained referring only to the net equivalent revenue, which is why the comparison was performed based on the net revenue of the plants, expressed as $BRL.L^{-1}$.

The Raízen's report data for the sugarcane bagasse bioethanol production route between the 2015-2016 and 2019|2020 harvests were employed, and the average net equivalent revenue was calculated at 2.63 $BRL.L^{-1}$., presented in Table 13.

Data for the coconut husk bioethanol production route is not available. Thus, reports from the FS Bioenergia plant that produces corn bioethanol, presented in Table 14, were employed, resulting in an average of 2.25 $BRL.L^{-1}$, close to the sugarcane bagasse bioethanol production value.

Table 13. Net equivalent revenue from the generation of E2G bioethanol from sugarcane bagasse for different harvests.

Harvest	Net Revenue (BRL)	(1) % referring to 2G production	Net revenue equivalent to 2G production (BRL)	2G production (m3)	$BRL.L^{-1}$.of bioethanol 2G
2015|2016	3,798,448,000	0.31	11,775,188,90	6,500,000	1.81
2016|2017	4,564,404,000	0.34	15,518,973,60	6,800,000	2.28
2017|2018	5,546,010,000	0.57	31,612,257,00	12,000,000	2.63
2018|2019	9,515,421,000	0.66	62,801,778,60	16,500,000	3.81
2019|2020	17,827,716,000	*0.66	117,662,925,60	*Adopted: 16,500,000	[out]7.13
			Average		2.63

1: Data calculated from the total production volume and the production volume of 2G bioethanol, presented in the reports of their respective harvests. out: Outlier identified through the Cochran test at a 95% confidence level. The identified outlier was excluded for the mean calculation. * due to lack of data, the same value as in the previous season was adopted. Source: Based on the Raízen Annual Report 2015|2016 – Innovation (2016); Raízen 5 Years (2016); Raízen Annual Report 2016|2017 – GRI Indicators (2017); Raízen Annual Report 2017|2018 (2018); Raízen Annual Report 2018|2019 (2019); and Raízen Annual Report 2019|2020: Indicators Book (GRI) (2020).

Table 14. Net equivalent revenue from bioethanol generation at the FS Bioenergia plant.

Harvest	(B) Net revenue, in BRL	(B) Bioethanol volume (L)	(P) $BRL.L^{-1}$.of bioethanol
2018|2019	565,300,000	258,900,000	2.18
2018|2019	1,200,000,000	516,600,000	2.32
	Mean	2.25	

Source: Based on the FS Bioenergia Annual Sustainability Report Crops 2018|2019 and 2019|2020 (2019, 2020).

3.3 Sustainability assessment: concluding overview

Once the indicators were applied, a conclusive sustainability overview of the two evaluated bioethanol production routes was obtained. A lack of data on both routes was perceived, limiting the intended assessment. This is probably due to the fact that 2G bioethanol production is still in the development and expansion phases. Table 15 presents the conclusive graphic overview concerning the sustainability of the evaluated production processes considering the nine indicators presented herein, in conjunction with the discussion carried out by Melo (2021).

Table 15. Summary graph of the sustainability assessment of the two bioethanol production routes assessed herein.

Indicators	Sugarcane bagasse	Coconut husks
Indicator 1: GHG emissions during the life cycle of bioenergy production and use	+ sustainable	- sustainable
Indicator 2: Non-GHG emissions, including toxic substances	Inconclusive	
Indicator 3: Water use and efficiency	+ sustainable	- sustainable
Indicator 4: Income changes	- sustainable	+ sustainable
Indicator 5: Jobs in the bioenergy sector	+ sustainable	- sustainable
Indicator 6: Incidence of occupational injuries, illnesses and deaths	- sustainable	+ sustainable
Indicator 7: Productivity	+ sustainable	- sustainable
Indicator 8: Net energy balance	- sustainable	+ sustainable
Indicator 9: Increase in gross value from bioenergy production	+ sustainable	- sustainable

Source: Authors.

In this fashion, considering the methodology applied herein, the sugarcane bagasse 2G bioethanol production route was the most sustainable, presenting higher environmental and economic sustainability. In turn, the coconut husk 2G bioethanol production route presented better results concerning the social point of view.

4. Conclusion

The commercial production of bioethanol from sugarcane bagasse is currently expanding, and this biofuel is produced on a large scale, employing consolidated routed in 11 Brazilian bioethanol production plants. On the other hand, the use of coconut husks is still in the research phase and is currently being produced in bench scale-up processes. Three productive steps (pre-treatment, hydrolysis and fermentation) are required for bioethanol production, with sodium hydroxide and enzymatic hydrolysis remaining as the most frequent in the pre-treatment and hydrolysis stages, respectively.

Concerning the sustainability of the evaluated sugarcane bagasse and coconut husk bioethanol production routes, few plants have made their annual reports available and a lack of data on the industrial production of bioethanol from sugarcane bagasse is noted. Furthermore, greater difficulty in obtaining and processing coconut husk route data was also verified, requiring estimates, once this production still takes place on a bench scale.

From the abovementioned reasons, indicator 2 (non-GHG emissions) was inconclusive, as the survey revealed that emissions of non-greenhouse gases mostly depend on the specificities of each bioethanol production plant, regardless of the employed biomass. Regarding the other indicators, the discussion pointed out that the coconut husk route was the most sustainable (concerning income changes incidence of occupational injuries, illnesses and deaths and net energy balance), while the sugarcane bagasse route was identified as the most sustainable for the other five indicators (GHG emissions, water use and efficiency, jobs in the sector, productivity and increase in gross value through production). Thus, the sugarcane bagasse bioethanol production route was the most sustainable for 2G bioethanol production.

Finally, considering the lack of information some data were estimated, especially with regard to the coconut husk bioethanol production route, which is still in its beginnings. The development of theoretical studies that promote scenario simulations is strongly suggested, in order to produce data for assessments concerning this productive route, or even aiming to develop partnerships with entrepreneurs in the bioethanol production segment to provide feasible data.

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