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Economic, environmental, and social impacts of different sugarcane production systems

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Abstract: Mechanization in the sugarcane agriculture has increased over the last few years, especially in harvesting and planting operations, in the Brazilian Center-South region. The consequences of such a technological shift, however, are not fully comprehended when multiple perspectives are considered such as economic aspects, environmental regulations, and social context. The main goal of this study is to generate comprehensive information to subsidize decision-making processes not only in Brazil but also in other countries where sugarcane production is still under development. Manual and mechanical technologies for planting and harvesting were evaluated (with and without pre-harvest burning), as well as straw recovery, seeking to identify their advantages and disadvantages, considering economic, environmental, and social aspects. Considering vertically integrated production systems (agricultural and industrial phases), sugarcane production scenarios were compared under the metrics from engineering economics, life cycle assessment (LCA), and social LCA. Manual technologies were related to the highest job creation levels; however, lower internal rates of return and higher ethanol production costs were also observed. In general, mechanized scenarios were associated with lower ethanol production costs and higher internal rates of return due to lower biomass production cost, higher ethanol yield, and higher electricity surplus. Considering the restrictions for sugarcane burning and practical difficulties of manual harvesting of green cane, environmental analysis showed that mechanical harvesting of green cane with straw recovery presents, in general, the best comparative balance of

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environmental impacts. A multi-criteria decision analysis was performed to generate an output rank, confirming that mechanized scenarios presented the best sustainability performances.

Keywords: harvesting technologies; sustainability assessment; sugarcane production; ethanol; social assessment; multi-criteria

Introduction

Sugarcane is largely cultivated in tropical countries, representing a main agricultural product and relevant feedstock for agroindustry. Its cost typically means around 50 to 60% of final cost of sugar or ethanol production.[1,2]

The Brazilian sugarcane sector has experienced several changes over the years. Historically, the technology of sugarcane production has been based on manpower and associated with the pre-harvesting burning of straw to reduce the risk of poisonous animals, decrease production cost, and improve field conditions for rural workers. Over the last decade, however, a variety of economic, social, and environmental issues have pushed the sugarcane sector to mechanical-based agricultural operations in Center-South region of Brazil, especially those of harvesting and planting. [3]

The mechanical harvesting participation in São Paulo state increased from about 31% of the total harvested area in 2005 to nearly 89% in 2013.[4] Although mechanical harvesting appears to consolidate its path in the sugarcane sector, many questions can still be raised regarding its sustainability. Several studies have separately evaluated environmental,[5-7] social,[8-10] and economic[1,11-14] aspects of sugarcane mechanization.

Some publications indicated that sugarcane mechanization is related to lower production costs when compared with the manual system.[15,16] Moreover, mechanical harvesting is associated with environmental benefits, such as reduction of greenhouse gas (GHG) and particulate material emissions due to the elimination of sugarcane burning.[17,18] Although mechanization in rural areas leads to lower job creation, this impact would be minimized by additional and better job opportunities in sectors such as machinery and inputs to the agricultural production.[19] Moreover, mechanization would promote better working conditions and higher income when compared with the manual sugarcane production system.[20]

To assess the broader impacts of different sugarcane technologies, a multi-criteria decision analysis (MCDA), based on PROMETHEE II,[21] was performed to generate a complete output ranking. The rank was generated according to three different biases perspectives focusing on each of the sustainability aspects. The aims were to analyze the economic, social, and environmental aspects of manual- and mechanical-based sugarcane production systems in Brazil, as well as their effects on the ethanol production system when a vertically integrated production model is considered.

This work identifies strengths and weaknesses of these technologies and enlightens decision making processes in other countries with substantial potential for sugarcane production expansion for bioenergy, such as South Africa, Mozambique, Colombia, Guatemala, among others.

Materials and methods

In this paper, the Virtual Sugarcane Biorefinery (VSB) was used to perform the simulations which give support to the technology assessments. The VSB has been developed by the Brazilian Bioethanol Science and Technology Laboratory (CTBE/CNPEM), which is an integrated computer simulation platform that evaluates technologies in use or under development, estimating the economic, environmental, and social impacts of the entire sugarcane production chain.[22]

The computational model for simulation and quantification of important parameters for technical, economic, environmental, and social assessment of the agricultural practices in the sugarcane production system are performed in CanaSoft. This model, which is one of the tools within VSB, is based on spreadsheets integrating diverse calculation modules.[1,14,22] From the main characteristics which describe the sugarcane production system – including scenarios description, involved operations, machinery, required labor force, and used inputs, the CanaSoft calculates the sugarcane production cost, life cycle inventory and provides information for the social assessment.

To assess the economic impact of sugarcane harvesting systems on the vertically integrated model, an economic spreadsheet was also used to calculate the overall effect of biomass production costs on the industrial stage. Therefore, the main parameters associated with the Engineering Economics[23] and cash flow analysis were determined for the different scenarios, focusing especially

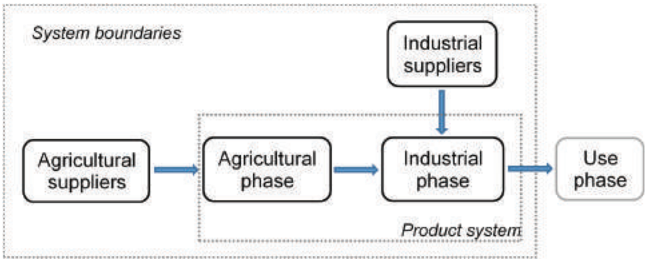

Figure 1. System boundaries of the methods used in the assessment.

on the internal rate of return (IRR), net present value (NPV), and ethanol production costs.

Figure 1 highlights the boundaries considered in the different categories of assessment. Economic and social assessments are focused on the modeling of processes involved from sugarcane cultivation to the industrial conversion of biomass into products. The environmental assessment, on the other hand, also includes a model which consider process inventories from both agricultural and industrial suppliers.

Scenario descriptions

Agricultural phase

Sugarcane is a semi-perennial crop whose average yield of cane stalks is 60–100 tons per hectare per year. This yield, however, can vary depending on a variety of factors such as climate, soil type, sugarcane variety, crop management practices, fertilizers use, local pests and diseases, harvest period, and others. Sugarcane production cycle is normally about 5 or 6 years long. It is replanted when sugarcane yield is considered low, according to the criteria of the producer.[24]

Seven sugarcane production scenarios were defined in this study. Annual yield of 80 tons of sugarcane stalks per hectare was assumed for all scenarios considering the average of five harvests per cycle and the average transport distance from the field to the sugarcane industry was assumed to be 25 km.[26] In the green cane systems, i.e., management without pre-harvesting burning, the amount of straw (green leaves, dry leaves, and tops) corresponds to about 140 kg of dry matter per ton of stalk.[24,26,27]

The main differences among the scenarios are highlighted in Table 1. These conditions were based on different assumptions for sugarcane planting operations, sugarcane pre-harvesting burning, harvesting and straw recovery technologies.

In the semi-mechanized planting, the operations associated with sugarcane seedling planting, distribution in the furrow, cutting of stalks, and harvest are done manually, whereas furrow opening and closing are mechanical-based. In the mechanized planting, however, all operations are performed mechanically, from seedling harvesting to furrow closing. The planters currently available on the market, however, cause mechanical damage on the sugarcane seedlings and, therefore, require a larger number of seedlings per hectare.[28] In this study, 12 tons per hectare of seedlings for semi-mechanized planting and 20 ton per hectare for mechanized planting were considered.

The straw recovery systems considered were the integral harvesting and the baling system. In the integral harvesting, the straw is harvested, chopped, and transported along with the sugarcane stalks. In the baling system, the straw is left on the field for about 15 days to decrease its water content before being recovered for the industrial processing; the straw is windrowed when moisture is about 13% and then collected and compacted in bales which, in turn, are subsequently loaded and transported to the mill separately from the stalks.[22,29] In this study, it was assumed that 50% of the total straw available on the field is transported to the sugarcane mill.

A 10% loss of sugarcane stalks due to harvesting process inefficiencies was assumed in all scenarios, except Scenario 7 where straw recovery technology (integral harvesting) is based on the reduction of harvester's primary extractor speed which, in turn, reduces stalk losses to 6%.[26,30]

After harvesting, sugarcane stalks are assumed to be transported in trucks of nearly 60 m^3 volumetric loading capacity for manual harvesting, and 184 m^3 in the case of

Table 1. Description of scenarios based on main agricultural operations.

	Scenario						
	1	2	3	4	5	6	7
Planting	Semi-mechanized	Semi-mechanized	Semi-mechanized	Mechanized	Mechanized	Mechanized	Mechanized
Pre-harvesting	Burned	Green cane	Green cane	Burned	Green cane	Green cane	Green cane
Harvesting	Manual	Manual	Manual	Mechanized	Mechanized	Mechanized	Mechanized
Straw recovery	No	No	Baling system	No	No	Baling system	Integral harvesting system

Table 2. Main agricultural parameters considered in the scenarios assessment.

Parameter	Scenario						
	1	2	3	4	5	6	7
Mineral fertilizers application (in ratoon, kg per ha)							
N	100	120	153	100	120	153	154
P_2O_5	—	—	5	—	—	5	5
K_2O	120	150	184	120	150	184	190
Harvesting efficiency (tons per day)							
Manual (per worker)	8.6	4.0	4.0	—	—	—	—
Mechanized (per harvester)	—	—	—	697	581	581	604

Source: Based on Cardoso *et al.*,[1] CGEE,[24] and CONAB.[25]

mechanical harvesting. Scenarios with manual harvesting make use of trucks with lower loading capacity because stalks entanglement does not allow the sugarcane trans-loading equipment to be used. Therefore, trucks entering the plantation must be lighter to avoid damage on both sugarcane ratoons and soil structure.

Table 2 highlights the main agricultural parameters associated with the fertilization operations and harvesting efficiencies. Compared to the burned sugarcane (i.e., sugarcane harvested after pre harvesting burning), green cane requires a slightly higher fertilizer input due to the remaining aboveground straw which decreases the capacity of fertilizer absorption by the soil.[31,32] In the scenarios with straw recovery, nutrients removed along with straw were assumed to be replaced by synthetic fertilizers.[1] Regarding harvesting efficiencies, burned sugarcane (Scenarios 1 and 4) are related to better yields both in the manual and mechanized scenarios because the absence of straw facilitates the harvesting operations.

Industrial phase

To assess the broader impacts of different harvesting technologies, sugarcane production scenarios are assumed to be vertically integrated to the industrial processing. The sugarcane production scenario affects the investment on industrial equipment. For instance, straw recovered using green sugarcane harvesting technology must be separated from stalks using a dry-cleaning station at the industrial facility. Moreover, ethanol and electricity yields may vary according to the biomass inputs associated with the different agricultural production scenarios.

In the Virtual Sugarcane Biorefinery, the industrial conversion scenarios were simulated using AspenPlus® to establish complete mass and energy balances of sugarcane processing operations. Despite variations in industrial equipment and adjustments related to different ethanol and electricity yields, all industrial scenarios are represented by an autonomous distillery processing 2 million tons of sugarcane stalks per year, assuming 200 working days per season. The main products are anhydrous ethanol and surplus electricity – whose yearly production will vary depending on the scenario. Other main characteristics of the industrial scenarios are: the use of electric drivers for sugarcane milling, molecular sieves for the dehydration process, 65-bar boilers for the combined heat and power (CHP) unit and a 20% reduction of steam consumption in the process due to energy integration.[14,22,33]

Techno-economic analysis

A discounted cash flow analysis was performed to assess the economic viability of the different sugarcane harvesting technologies. Considering the assumption by which every scenario is a vertically integrated production model, sugarcane and straw production costs were calculated (using CanaSoft – model of VSB) considering the technological specificities of each agricultural scenario. These biomass production costs were further used to calculate the operating expenses with biomass of the industrial phase. Other operating costs – such as labor, utilities, chemical inputs, maintenance, etc. – for the industrial phase were calculated according to the database available in the VSB.[22] The revenues from anhydrous ethanol and electricity were calculated according to market prices of US$ 0.58 per liter[34] and US$ 57.40 per MWh,[35] respectively. The exchange rate considered in this study was 2.30 BRL (Brazilian Real) per US$. All values used in the techno-economic assessment considered July 2014 as the reference date.

For the ethanol production cost, operating and capital expenses were taken into consideration to compute the total production costs. The operating expenses are calculated by summing variable costs (such as sugarcane stalks and straw, chemical inputs, utilities, etc.) and fixed costs (mainly maintenance and labor) of a distillery, in yearly basis. The total production cost, however, depends also on the investment associated with buildings, equipment, and infrastructure. These expenses will depend on the project lifetime and company's financial leverage (which indicates the proportion of equity and debt the firm is using to finance its assets). Most of the VSB studies assume a 25-year project lifetime and no financial leverage, i.e., the firm is totally financed by equity. Therefore, the yearly capital cost of a biorefinery was estimated by considering the annual payment that would be necessary to remunerate the total investment as if it was a loan (12%-per-year interest rate over a 25-year period).

The total production costs are obtained by summing up operating and capital expenses, this value is equivalent to the minimum selling price. All operating and capital expenses were allocated according to the ethanol and electricity participations on the total revenues. In the case of ethanol production, the cost per liter would be the total allocated cost divided by the number of liters of ethanol produced over the year.

Environmental assessment

Environmental analysis was performed using the environmental life cycle assessment (LCA) methodology. It is a method for determining the environmental impact of a product (good or service) during its entire life cycle. The software package SimaPro® (PRé Consultants B.V.) and selected categories from ReCiPe Midpoint (H) V1.05 life cycle impact assessment have been used as tools for the environmental impact assessment in the VSB. The evaluated environmental impact categories were: Terrestrial Acidification (AP) measured in kg of SO_2 eq.; Particulate Matter Formation (PMF) measured in kg of PM_{10} eq.; Climate Change (CC) measured in kg of CO_2 eq.; Ozone Depletion (ODP) measured in kg of CFC-11eq.; and Fossil Depletion (FD) measured in kg of oil eq. Identification of significant issues, conclusions and recommendations are made in the interpretation step. The approach applied is compliant with the ISO 14040-14044 standards and follows the current state of the art of LCA methodology documents.[36,37]

According to LCA methodology, allocation is required for multi-output processes. In this study, economic allocation based on the market value of the process output was applied in each scenario, as specified in the ISO 14040-14044 documents.[36,37]

Social assessment

The social assessment in this study was performed using the Social Life Cycle Assessment (S-LCA) methodology. S-LCA aims at assessing social and socio-economic aspects of products, including their potential positive and negative impacts along their life cycle.[38] According to Macombe and Loillet,[39] S-LCA has also been able to estimate important social effects on the mostly affected actors (e.g. workers) by considering changes in organizations' behavior.

One of the features of the S-LCA is the estimation of social effects of changes considering base and future scenarios.[40] This method allows for anticipating social consequences of a given change, for example, the adoption of a new technology. In this study, three social effects were assessed in the sugarcane production systems: the total number of jobs created, number of occupational accidents and average wage of workers. This assessment relies on detailed sugarcane production models for calculating the total working hours and sugarcane production costs based on the characteristics of each scenario. These outputs were then used to estimate the number of jobs and the average wage of workers.

The data on occupational accidents in the sugarcane sector was estimated in a two-step procedure. First, a linear correlation between the incidence of accidents (number of accidents per worker) in the sugarcane production sector[41] and the level of mechanization[4] was established. This correlation reveals that the higher the mechanization level, the lower the probability of occupational accidents. This assumption makes sense since in manual cutting there is a higher probability of accidents because workers are in direct contact with cutting tools and the sugarcane. In the other hand, the probability of accidents is lower in mechanized operations since the workers are protect by the interface of the machinery. Assuming this correlation as reasonable, the second step was to estimate the number of accidents in each agricultural scenario. In the case of industrial stage, the number of occupational accidents, from MPS (2015)[41] was maintained constant for all scenarios because the same industrial plant configuration is considered.

Risk assessment

Uncertainties related to agricultural parameters associated with both mechanized and manual operations in sugarcane production scenarios were considered. The Latin Hypercube method embedded in @Risk 6.2® software was employed to assess the impact of uncertainties on both sugarcane stalks and straw production costs. As shown in Table 3, seven parameters relate to triangular distributions based on the literature and experts' consultancy.[25,42,43] The main uncertainties considered in this study are those related to harvesting operations which, in turn, affect the sugarcane production costs, i.e., sugarcane yield, harvester speed (which is directly related to the harvester yield in CanaSoft), manual cutting yield, diesel price, harvest operator salary, and the capital cost related to the investment on machinery.

A total of 5000 simulations were performed to estimate the uncertainties related to the sugarcane production costs – sugarcane stalks and straw – in scenarios using both manual and mechanical operations. It is important to point out that the results in the analysis of the vertically integrated production models (agricultural and industrial

Table 3. Ranges considered for parameters in the risk assessment of agricultural scenarios.

Parameter	Unit	Min	Avg.	Max	Reference
Salary of harvester operator	US$/hour	1.81	3.10	6.99	IEA, 2014[42]
Manual cutting yield (burned sugarcane)	tons/day	6.5	8.56	12	This study
Manual cutting yield (green sugarcane)	tons/day	1	3.5	5	This study
Harvester speed	m/s	0.9	1.25	1.5	This study
Sugarcane yield	TC/ha/year	70	80	100	This study
Diesel price	US$/L	0.740	0.863	1.095	ANP, 2014[43]
Discount rate (cash flow analysis)	% per year	10%	12%	14%	This study

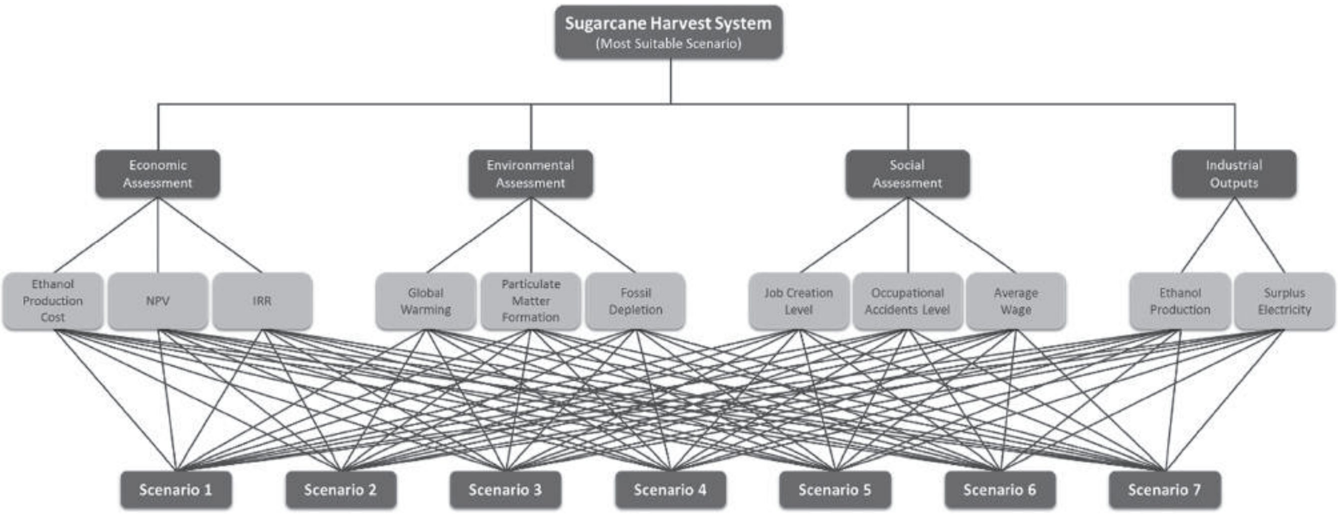

Figure 2. Hierarchical structure of multi-criteria decision (MCDA).

stages) will embody the uncertainty related to the biomass production costs.

Multi-criteria decision analysis

To generate an output ranking of the evaluated scenarios a multi-criteria decision analysis (MCDA) was made. The selected MCDA methodology was the PROMETHEE II – for a complete ranking generation – from the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) outranking family.[21]

The MCDA was performed considering a hierarchical structure, composed by two weight levels (Fig. 2). The first one is related to the assessment category (i.e., technical, economic, environmental, and social) and the other to the criteria (e.g. net present value, internal rate of return, climate change). The performance of each scenario was based on the values presented on results section. These values were normalized to the interval [0, 1] according to the criterion target – i.e., the criterion must be maximized or minimized. This normalization expresses the degree to which the scenario is close to the ideal value (1.0), which is the best performance in criterion, and far from anti-ideal value (0.0), which is the worst performance in criterion. Both performances, are achieved by at least one of the scenarios under consideration.[44] The weights for the second level were defined according to the criteria importance through inter-criteria correlation (CRITIC).[44-46] Pair-wise comparison of the scenarios was performed using the PROMETHEE-II methodology. Since all criteria were quantitative, the selected PROMETHEE preference function was the type V (criterion with linear preference and indifference area). [47]

To carry out a sensitivity analysis, the weights assumed in the first level were subjectively chosen creating three different biased perspectives: economic, environmental, and social. To emphasize the focused sustainability category a weight of 50% was attributed; other sustainability categories received a weight of 20%. The exception was the weight of the technical category, which was maintained as constant in 10 %. Additional information about the

PROMETHEE II methodology can be found at Brans and Vincke[47] and Parajuli *et al.*[48]

Results

Production costs of sugarcane biomass

The results shown in Table 4 are the sugarcane biomass production costs for the seven scenarios according to the simulations using the CanaSoft model. The sugarcane production cost breakdown highlights the main sugarcane production operations such as planting, fertilization, harvesting and transportation. It is possible to observe that manual harvest (Scenario 1) leads to higher sugarcane production costs when compared with mechanical harvesting (Scenario 5). These results are in accordance with findings from other publications.[15,16]

Regarding straw production costs presented in Table 4, it is possible to observe that both Scenarios 3 and 6 (baling systems) lead to very similar straw recovery costs – roughly US$ 36 per metric ton, dry basis. Scenario 7, on the other hand, presented the lowest straw recovery cost (roughly US$ 26/t_{db}) mainly due to lower stalk losses in the harvest operation and because additional costs are proportionally divided between straw and extra stalks, according to their mass (wet basis).

It is possible to observe that the different agricultural technologies lead to different costs for sugarcane production as well as straw recovery costs. Scenario 4 presented the lowest sugarcane production cost (US$ 25.50 per ton) mainly because of harvester efficiency which is higher in burned cane fields when compared to the green cane harvesting scenarios. The second lowest production cost is associated with Scenario 7 (US$ 26.95 per ton) because straw recovery under the integral harvesting system decreases sugarcane stalk losses. Considering that the higher the stalk yield of a given scenario the smaller the area required to produce sugarcane – considering a constant industrial processing capacity – production costs will decrease. Moreover, smaller areas imply on additional cost reduction because of shorter transportation distances.

Figure 3 shows the results according to the risk assessment involving uncertainties on sugarcane yield (TC/ha), harvester speed (m/s), manual cutting yield (TC/worker/

Table 4. Main components of sugarcane stalks and straw production costs according to CanaSoft.

	Scenarios						
Production costs (US$/ha)	1	2	3	4	5	6	7
Planting	281.80	290.08	290.08	256.38	259.16	259.16	257.42
Fertilizers (NPK)	237.41	299.78	353.58	239.91	302.15	356.53	355.20
Harvesting	846.06	1,116.75	1,257.44	671.82	735.97	876.65	877.92
Transport (included inputs)	360.05	361.28	387.39	247.83	249.07	275.19	342.30
Total	2,139.21	2,497.21	2,689.32	1,937.93	2,083.50	2,276.19	2,283.47
Stalks (US$/t)	27.57	32.18	32.18	25.50	27.41	27.41	26.95
Straw (US$/$t_{db}$)			36.54			36.66	26.07

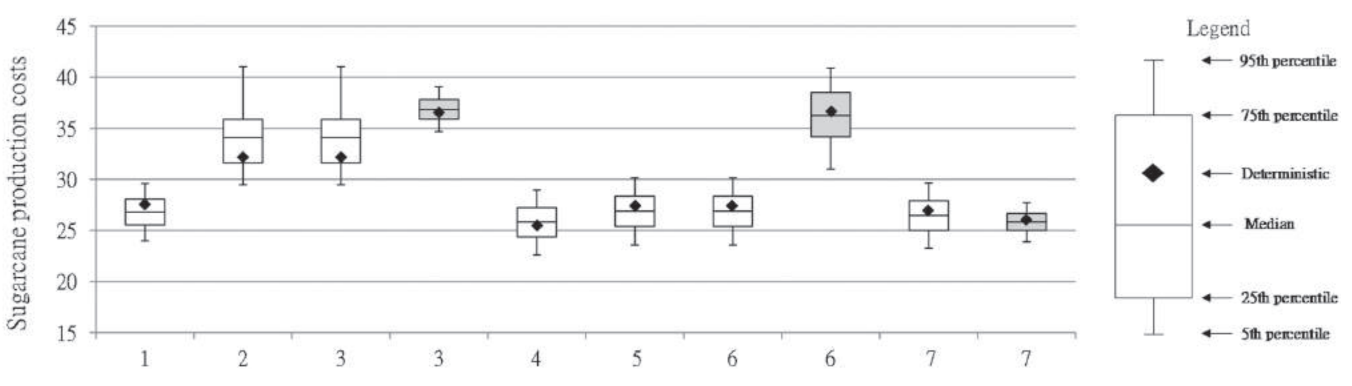

Figure 3. Sugarcane biomass production costs US$ per ton (stalks, in white bars, and straw$_{db}$, in gray bars) considering the risk assessment.

day), diesel prices (US$/L), harvest operator wages (US$/hour) and the discount rate (% per year) as previously described in Table 3. The highest uncertainties on sugarcane production costs are clearly associated with Scenarios 2 and 3. These scenarios are highly reliant on manual operations whose uncertainties on parameters are relatively high, especially the manual sugarcane harvesting yield which varies from 6.5 to 12 tons per worker per day. Considering that manual operations importantly contribute to the overall green sugarcane production costs, such uncertainties were expected to be higher in Scenarios 2 and 3.

On the other hand, scenarios with more intensive employment of mechanical operations (4, 5, 6, and 7) are related to relatively lower levels of uncertainties because the parameters associated with mechanical operations are either related to a lower range of uncertainties or cause comparatively lower impact on the total production costs.

Regarding the straw recovery costs, uncertainties were higher in Scenario 6. This result is related to the approach used to calculate straw recovery costs. They are obtained by the difference between the scenarios with straw recovery and without straw recovery. In both scenarios, stalk production cost is the same. The difference between these scenarios will be the cost of straw which, in turn, is allocated entirely to the amount of straw transported from the field to the industry. For this reason, the greater the difference between stalk and straw production costs the greater the uncertainty associated with the straw production cost.

Considering that Scenario 6 has the highest difference between those costs, the uncertainties associated with straw recovery cost will be higher. In other scenarios, such as Scenario 3, for example, the difference between straw and stalk costs is lower; consequently, the opposite situation is observed.

Techno-economic assessment

Technical results

The technical results related to the industrial phase (Table 5) were obtained from process simulations that highlight the electricity surplus and anhydrous ethanol production for the industrial plants associated to the different agricultural scenarios. It is clear that the agricultural stage affects mostly the electricity surplus, mainly because the straw recovered from the field to the sugarcane industry will be burned to generate bioelectricity. It is clear that the scenarios with straw recovery – 3, 6, and 7 – are related to the highest electricity production levels. The ethanol yields, on the other hand, resulted in roughly 85 liters per ton of sugarcane stalk, with slightly reduction – Scenario 7 – due to higher amount fiber, caused by the low efficiency of dry cleaning station, with sugar losses in the extraction operation.

Economic results

The economic assessment was performed to understand the impact of different agricultural production technologies on the industrial phase. In order to perform the cash flow analysis – whose results are presented in Table 6 – it

Table 5. Industrial yields of considered scenarios.

		Scenario						
		1	2	3	4	5	6	7
Electricity surplus	kWh/TC	91.76	91.76	192.36	92.03	92.03	194.69	179.34
Anhydrous ethanol	L/TC	84.82	84.82	84.82	84.91	84.91	84.91	84.19

Table 6. Results of economic analysis of the vertically integrated scenarios.

		Scenario						
Economic results		1	2	3	4	5	6	7
CAPEX[a]	US$ million	188.90	188.90	200.61	188.89	188.89	200.82	203.84
IRR	% per year	13.25	10.51	11.73	14.43	13.37	14.33	14.12
NPV[b]	US$ million	17.8	–20.3	–4.0	35.5	19.6	36.2	33.2
Ethanol cost[c]	US$/L	0.50	0.55	0.53	0.47	0.49	0.48	0.48

[a] Total investment in the industrial plant.
[b] Considering a 12% minimum acceptable rate of return per year.
[c] Ethanol production cost considering both the operating and capital costs.

was necessary to estimate the total investment required on the industrial plants. It is clear that the capital expenditures (CAPEX) associated with Scenarios 3, 6, and 7 were slightly higher because they accounted for the additional investment in straw reception in the industry and also in the power and heating unit (CHP) generating additional surplus electricity.

When uncertainties of biomass production costs are considered, the highest internal rate of return (IRR) is observed in Scenario 6 (Table 6 and Fig. 4). Although Scenario 4 achieved a higher deterministic IRR, Scenario 6 is the most likely to achieve higher IRRs when all parameters' ranges are considered in the risk assessment. According to the results in Table 6 and Fig. 4, it is possible to observe that Scenarios 2 and 3 presented the lowest IRRs. Assuming a minimum acceptable rate of return of 12% per year, these scenarios would be the most likely to be unsustainable from an economic point of view due to their negative net present value (NPV) and internal rate of return (IRR) lower than 12%.

The ethanol production costs presented in Fig. 5 are related to a similar trend when compared to the IRR. As expected, ethanol production costs were higher in Scenarios 2 and 3, mostly because of the higher operating costs associated with the biomass inputs. The other scenarios – 1, 4, 5, 6, and 7 – are associated with the lowest ethanol production costs mainly because of the lower biomass production costs. The uncertainties related to the ethanol production costs were clearly higher in Scenarios 2 and 3 mainly because of the uncertainties embodied in the biomass production costs.

In Figs 3, 4, and 5, the results obtained from the deterministic approach are very close to the median in all scenarios, except in Scenarios 2 and 3. In these scenarios,

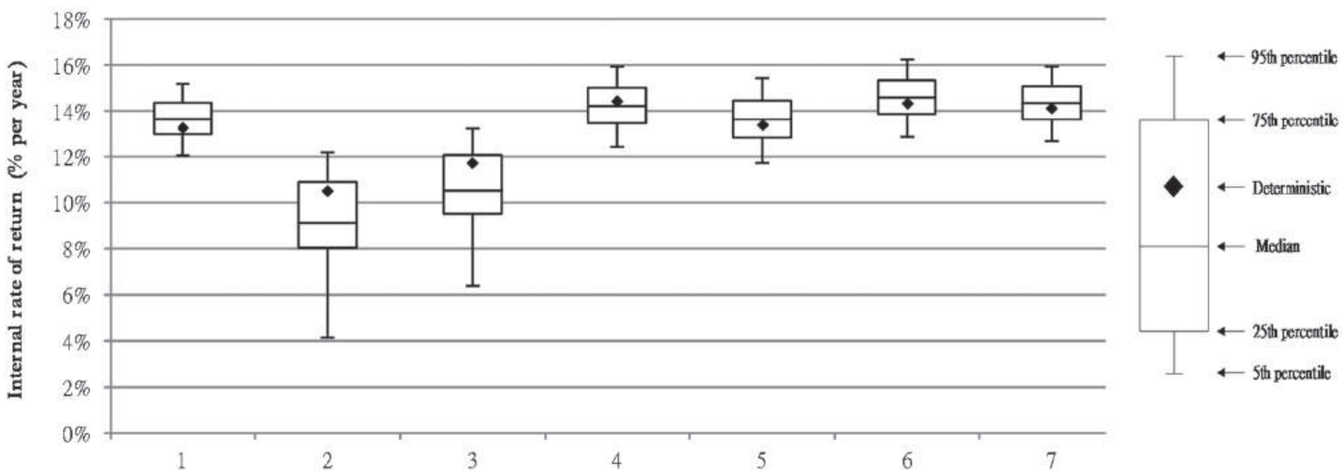

Figure 4. Internal rates of return considering the uncertainties of biomass production costs.

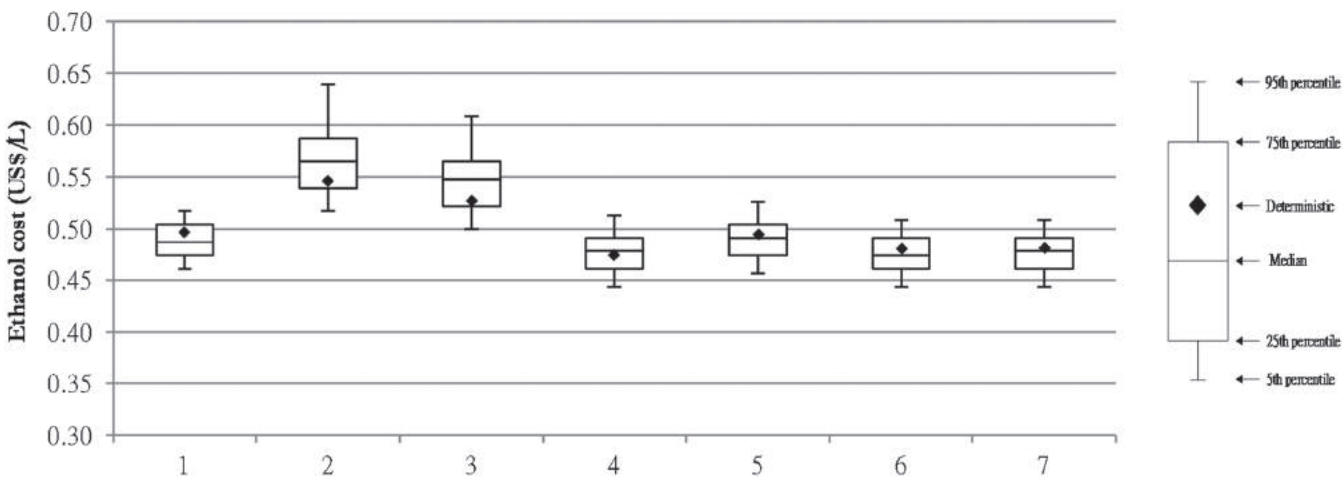

Figure 5. Ethanol production costs considering the uncertainties of biomass production costs.

deterministic calculations of biomass and ethanol production costs were underestimated and, as a consequence, the deterministic internal rates of return were overestimated when compared to their medians. It occurs mostly because of the deterministic value associated with the manual harvesting yield which was closer to the maximum value considered the range. Bearing in mind that the manual harvesting yield has a high impact in the total biomass production costs, this assumption significantly affects the calculations based on the deterministic approach.

Environmental assessment

Comparative environmental impact scores per unit of ethanol produced in each of the seven evaluated scenarios calculated using the LCA methodology are presented in Fig. 6. In general, scenarios with straw burning have higher impacts in the Climate Change (CC) category, due to uncontrolled GHG emissions in field burning (e.g. CH_4 and N_2O), as presented in Fig. 7(a). Even using higher amounts of fertilizers, green cane scenarios presented environmental advantages in the CC category. Integrating the industrial impacts, in Fig. 7(b), the lower impacts were observed in scenarios with straw recovery (3, 6, and 7), due to higher electricity production in these scenarios and consequentially lower impacts allocation to ethanol. These results are in accordance with other publications [17,18] that indicate mechanical harvesting as being associated with environmental benefits, such as reduction of GHG emissions and particulate material due to the elimination of sugarcane pre-harvesting burning.

Compared to the scenarios where bagasse and straw are controlled burnt in industrial boilers, emissions from pre-harvesting burning of sugarcane lead to very high impact

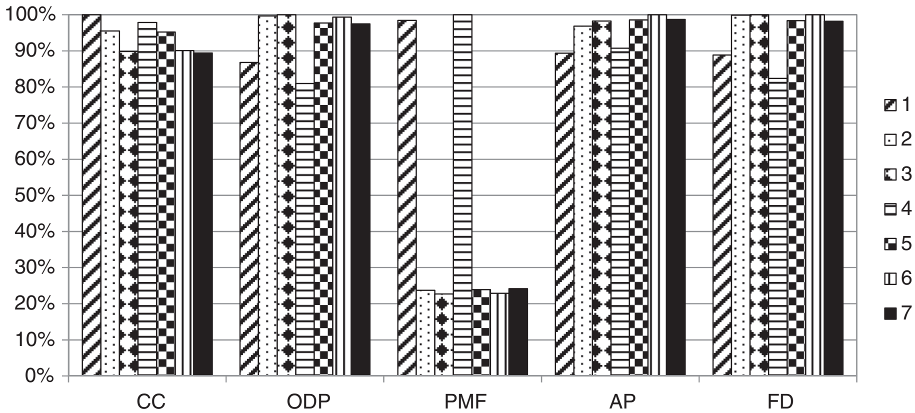

Figure 6. Environmental impacts per unit on mass of ethanol produced in the evaluated scenarios.

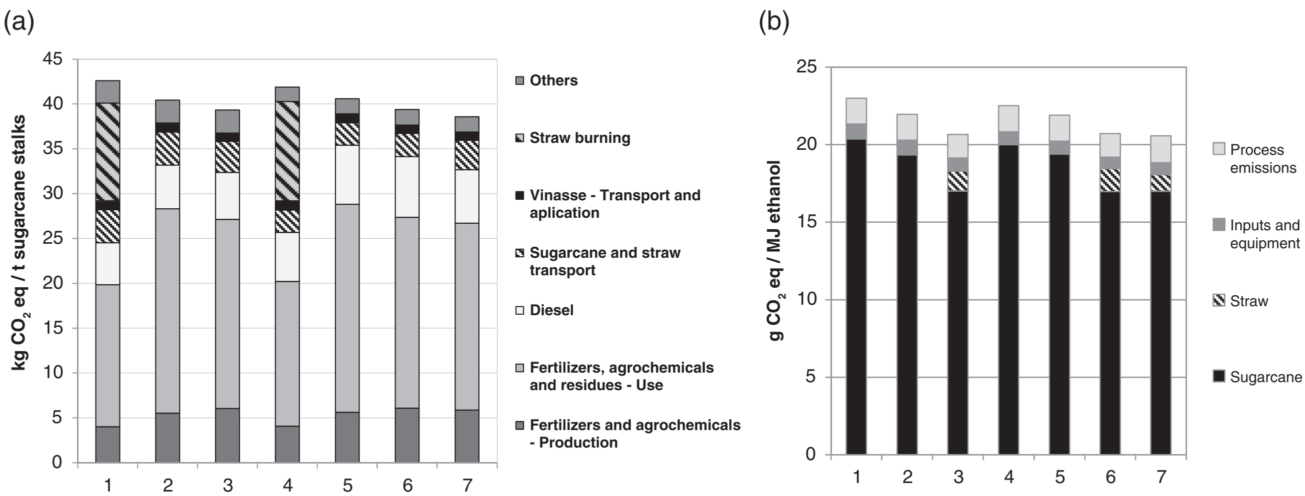

Figure 7. Climate change impacts of the evaluated scenarios: (a) agricultural phase only and (b) at factory gate.

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on the PMF category for Scenarios 1 and 4, as shown in Fig. 6. Categories ODP, AP, and FD presented similar results for all scenarios. For ODP and FD categories, lower impacts are observed in Scenarios 1 and 4, with burned sugarcane practices, due to lower amounts of fertilizer used in burned sugarcane cultivation. In the AP category, scenarios with pre-harvesting burning of sugarcane presented lower impacts since lower amounts of straw remain in the field.

Taking into consideration the evaluated environmental impact categories, it is not possible to identify the best scenario. However, bearing in mind the restrictions for sugarcane burning and practical difficulties of manual harvesting of green cane, Scenario 7 with mechanical harvesting of green cane and integral straw recovery system present, in general, the best comparative balance of environmental impacts.

Social assessment

The results of social assessment are presented below, per million liters of ethanol. In Fig. 8(a), it is clear that job creation levels of the industrial phase in the scenarios are only slightly different. This result was expected because they have similar industrial processing areas and differences in ethanol and electricity production do not necessarily implies on a different number of jobs. On the other hand, agricultural scenarios lead to different results. The highest level of job creation was associated with manual sugarcane harvesting operations of Scenarios 1 to 3. Scenarios of manual green cane harvesting (2 and 3) present low efficiency as an intrinsic characteristic of such agricultural operation. Consequently, more jobs are created. Compared with these two scenarios, Scenario 1 has a lower level of job creation mainly because manual harvesting is more efficient in a burned sugarcane field. The other scenarios (4 to 7), associated with mechanical harvesting, are related to a much lower level of job creation mainly due to their higher reliance on mechanical operations.

The occupational accidents are presented in Fig. 8(b). Similar to the results of job creation, the total occupational accidents in the industrial phase are only slightly different because of their similar industrial configuration. The agricultural scenarios, however, are quite different. Scenarios 1, 2, and 3 are related to a higher level of occupational accidents due to two main reasons: first, more workers are hired in the agricultural phase, increasing the sample space. The second reason is that the lower the level of mechanization – which is the case in manual harvesting scenarios – the higher the probability of occupational accidents per worker. These two effects combined explain the higher level of occupational accidents in Scenarios 1, 2 and 3. The opposite effect is observed in Scenarios 4, 5, 6 and 7: low levels of job creation and high levels of mechanization reduce the total number of accidents.

The average wage in the mechanized harvesting scenarios (4, 5, 6, and 7) is slightly higher than those related to manual harvesting (Fig. 9). As expected, manual operations are mostly associated with low-qualified employees. Consequently, lower wages are observed in manual harvesting. This contributes to a lower average wage in Scenarios 1, 2, and 3 when compared with 4, 5, 6, and 7. Once again, the average wages in the industrial phase are exactly the same due to similar industrial configuration in all scenarios.

The results related to the social assessment are also in accordance with other publications [19,20] which indicate that, although mechanized sugarcane systems create less

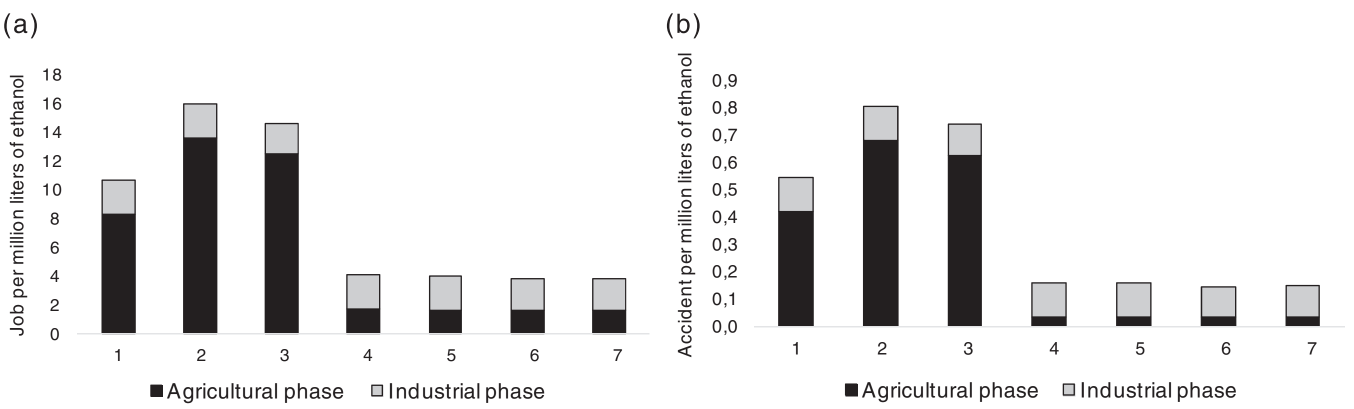

Figure 8. Job creation (a) and occupational accidents (b) per million liters of ethanol in both agricultural (dark bars) and industrial phases (light bars).

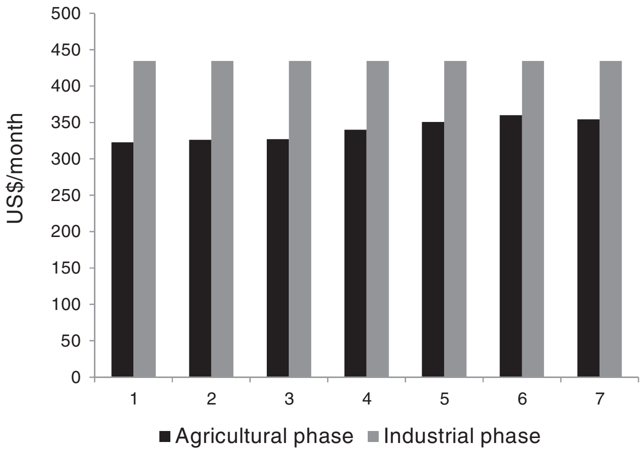

Figure 9. Average wage of workers in the different scenarios.

Table 7. Sensitivity analysis in multi-criteria decision (MCDA).

Alternatives	Output Ranking		
	Economic Bias	Environmental Bias	Social Bias
Scenario 1	5	6	5
Scenario 2	7	7	7
Scenario 3	6	5	6
Scenario 4	2	4	4
Scenario 5	4	3	3
Scenario 6	1	2	1
Scenario 7	3	1	2
Level 1 weights[a]	(**50%** / 20% / 20%/ 10%)	(20% / **50%** / 20%/ 10%)	(20% / 20%/ **50%** /10%)

[a]Percentages in parenthesis reflect weights given to economic, environmental, social, and technical impacts, respectively.

jobs, better working conditions and workers with higher income are also observed, especially in the agricultural phase.

Sensitivity analysis based on multi-criteria decision

As expected, none of the scenarios reached the best relative score in all sustainability impact categories. For this reason, a sensitivity analysis was performed using the proposed MCDA methodology. As described in methodology section, the aim was to rank the scenarios according to three different biased perspectives, changing the weights of the sustainability assessment categories (level 1), i.e., economic, environmental, and social, as shown in Table 7.

According to the presented results, the best options were Scenarios 6 and 7. These scenarios present the best scores for the assessed perspectives, showing the advantages of mechanical harvesting with straw recovery. The exception was for the economic perspective, where the Scenario 4 was the second best scored alternative. This occurs due to its highest IRR and lowest ethanol production cost (Table 6). It is also important to highlight that, for the environmental perspective, the best scored alternative was the scenario with integral harvesting (Scenario 7), due to the lower number of mechanized operations, while Scenario 6 was the best alternative for social perspective, mainly due to the lowest occurrence of occupational accidents. The worst options for all perspectives were the scenarios with manual harvesting (Scenarios 1, 2 and 3).

It is important to highlight that the selection of the best scenario(s) will depend on the decision maker's options on which sustainability aspects will be prioritized.

Conclusions

Manual harvesting scenarios were related to a higher risk on biomass and ethanol production costs due to the uncertainties associated with manual operations especially those employed in green sugarcane harvesting. Considering the vertically integrated production systems, manual technologies were related to the highest job creation levels, however, lower internal rates of return and higher ethanol production costs were also observed. In general, mechanized scenarios were associated with lower ethanol production costs and higher internal rates of return due to low biomass production cost, high ethanol yield and high electricity surplus.

In the environmental analysis, bearing in mind the restrictions for sugarcane burning and practical difficulties of manual harvesting of green cane, Scenario 7 with mechanical harvesting of green cane and integral straw recovery system present, in general, the best comparative balance of environmental impacts.

The methods applied in this study, highlight both strengths and weaknesses of different harvesting technological configurations considering the effects on the working conditions. This study shows that manual cutting technology is associated with positive effects on employment rates. On the other hand, harvesting mechanization scenarios were related to better working conditions, since less occupational accidents and higher average wages are observed.

When all the sustainability impact categories were taken into account, the definition of the best scenario was not possible. For this reason, an MCDA and sensitivity analysis were performed, confirming that mechanized scenarios presented the best sustainability performances, based on the output ranks for all biased perspectives.

The results presented in this study can provide the decision maker with an overview on the economic, environmental, and social aspects of sugarcane production technologies considering a broader perspective of vertically integrated production models. Bearing in mind that the main purpose of the study was to provide quantitative subsidies for specific decision-making processes, further interpretation on the meaning of results presented in this paper may vary according to the local economic situation, environmental conditions, and social context of sugarcane industry.

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