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ORIGINAL PAPER

Optimal reconfiguration of a sugar cane industry to yield an integrated biorefinery

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Abstract The sugar cane production is one of the main economic activities of the agriculture sector in several places around the world. Nowadays, the sugarcane production zones face different technologic, economic, and social problems that impact negatively their profitability. The low price of sugar in the market demands the search of alternatives; being the bioethanol production from resides of the sugar cane industry an attractive option. This way, this paper presents a new approach for using the residues from the sugar cane industry to yield a sustainable biorefinery. In this approach, process integration techniques have been implemented to optimize the overall process. A case study from the State of Michoacán in Mexico is presented, where the proposed approach shows significant economic, environmental, and social benefits.

Keywords Supply chain · Sugar cane · Bioethanol · Optimization · Biorefineries

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Introduction

The climate change has yield significant environmental problems, which mainly have been caused by the high energy consumption from fossil fuels (MäKinen and Leppälahti 2009). This way, sustainable energies have been proposed to mitigate the effects of climate change (Sun et al. 2013), and energy from biomass (i.e., biofuels; see Brondani et al. 2014) appears as an attractive option (Cucek et al. 2012); therefore, there has been increased the interest in the identification of cost-effective, clean, and renewable sources of energy (González-Delgado et al. 2015). Bioethanol (used instead of gasoline) has proved to be an attractive option technically (Najafi et al. 2009) and environmentally (Goldemberg et al. 2008). One of the major issues for the biofuels is the biomass availability and the resources used for their production, including water, land, and nutrients (Balat et al. 2008). Therefore, the concept of integrated biorefinery has gain a lot of attention (Chouinard-Dessault et al. 2011), where the main feedstock corresponds to residues (Ponce-Ortega et al. 2012); this is biomass that has been previously processed in other processes and that can be used as raw material to yield biofuels. In this context, Murillo-Alvarado et al. (2014) presented an optimization framework for designing a bioethanol supply chain using the residues of *Agave* as feedstock. Santibañez-Aguilar et al. (2013) proposed a mathematical programming formulation for synthesizing distributed biorefinery networks using water hyacinth as feedstock. In the same way, various investigations have focused on the evaluation of the biotechnological potential of sugarcane bagasse (Pandey et al. 2000; Sarkar et al. 2012), and the search of improved opportunities for bioethanol production (Hahn-Hägerdal et al. 2006; Cardona and Sánchez 2007; Vaccari et al. 2009; Ojeda et al. 2011; Kravanja et al. 2012; Tang et al. 2013). Other works have focused on evaluating the life cycle assessment and life cycle costing of the bioethanol production (Quintero et al. 2008, 2011, 2013; Goldemberg et al. 2008; Luo et al. 2009; Dias et al. 2009, 2012; Cavalett et al. 2012).

Furthermore, in several countries such as Mexico, the sugar cane industry is totally dedicated to produce sugar to satisfy food demands. However, in recent years, this industry has experimented serious economic problems because of the low price for the sugar in markets, which is the only product. In addition, the sugar cane industry has a lot of residues that can be converted to bioethanol (i.e., sugar cane bagasse, see Poonam and Ashok 2009). This way, in this paper is presented a study to identify the potential transformation of the sugar cane industry into an integrated biorefinery, where several options such as the use of residues and new sugar cane can be used to produce biofuels and electricity while satisfying the sugar demands. To solve this problem, in this paper is implemented an optimization formulation based on process integration techniques involving technical, economic, environmental, and social issues. The addressed problem is described in next section.

Problem statement

The problem addressed in this paper can be stated as follows: Given a traditional sugar cane industry, where only sugar is produced, and for which there are fixed the location, used infrastructure, cultivation activities, available land for cultivating new areas with sugar cane in the region, transportation options as well as the weather conditions. Also, there is available information regarding the markets and distribution of products. Furthermore, all the socio-economic information required to determine the current and new social impact is available. The problem then consists in determining the optimal reconfigured industry that can satisfy the sugar demands as well as the production of biofuels. This retrofitted biorefinery can use as feedstock residues from the sugar cane industry and new cultivated sugar cane. This way, the optimal reconfigured biorefinery must determine the opportunity to use the current infrastructure as well as to install new infrastructure to produce additional sugar cane and bioethanol. Also, the reconfigured biorefinery includes the option to cultivate additional area. In the optimal reconfigured biorefinery, it is considered the opportunity to satisfy the current and future sugar and bioethanol demands. For determining the optimal reconfigured biorefinery, the entire life cycle for the supply chain has been evaluated since the economic, environmental, and social points of view. This way, several scenarios are determined based on process integration techniques to compare the analyzed scenarios and evaluate the best reconfigured biorefinery from a mill. The implemented methodology is described in the next section.

Methodology

In this paper, it is considered a sugar cane industry currently focused only on the sugar production with different refinement levels (like the case of several places around the world such as in Mexico). It is noteworthy that currently this activity is not profitable for several farmers around the world. The idea for retrofitting a sugar cane industry includes using the existing infrastructure and to install new infrastructure for simultaneously producing bioethanol from the yielded residues. Furthermore, cultivating new area is considered as an option for yielding additional bioethanol satisfying the sugar and bioethanol demands. In the analysis, all the stages for the supply chain involved are considered to determine the best reconfigured sugar cane industry, and several scenarios are proposed which are analyzed from the economic, environmental, and social points of view. This way, in the implemented methodology, first all the existing information about this industrial process is collected, including fluxes (inputs and outputs), yields, earnings, and distances for transportation of feedstocks and products. For the sugar cane crops, the amount of used and available area, the sugar cane yield, the inputs and outputs (like used water, pesticides, and fertilizers), and the distance between the crops and the mill are considered. Furthermore, all the information for the emissions involved in the supply chain is used for determining the environmental impact assessment. Also, for the social evaluation, the input and output analysis for the social benefit through the generated jobs in the entire supply chain was implemented.

Figure 1 shows the schematic representation for the proposed biorefinery based on sugar cane, where the sugar cane is used as feedstock to produce sugar and bioethanol, which is the main idea in this work. Then, the available biomass is characterized as shown in Fig. 2. Once the biomass is treated to produce a juice rich in sugars, this is transported to a mill. The juice is passed through a series of filters for clarification and then it is crystalized. In this process, several residues are produced, which are considered as raw materials in the retrofitted biorefinery (see Fig. 1b). Based on the previous results, six attractive scenarios were identified to integrate a reconfigured biorefinery from the sugar cane industry. For determining these

Fig. 1 Reconfiguration of sugar cane mills to integrated biorefineries

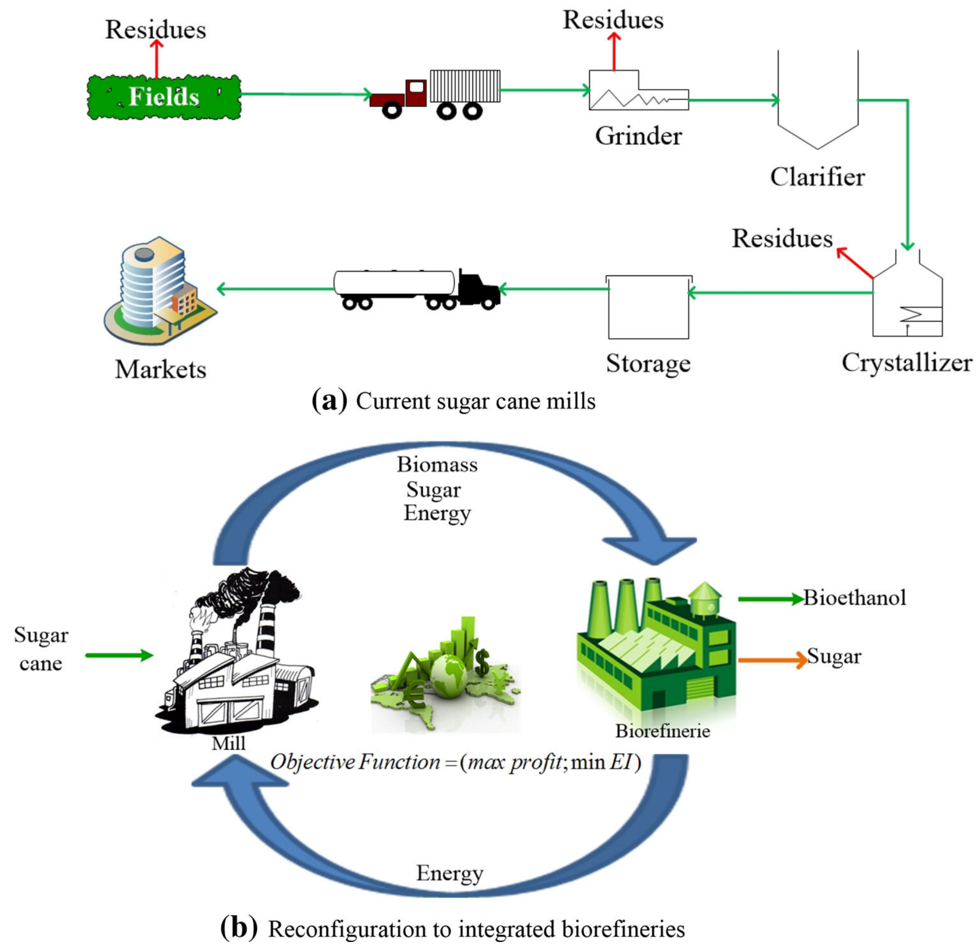
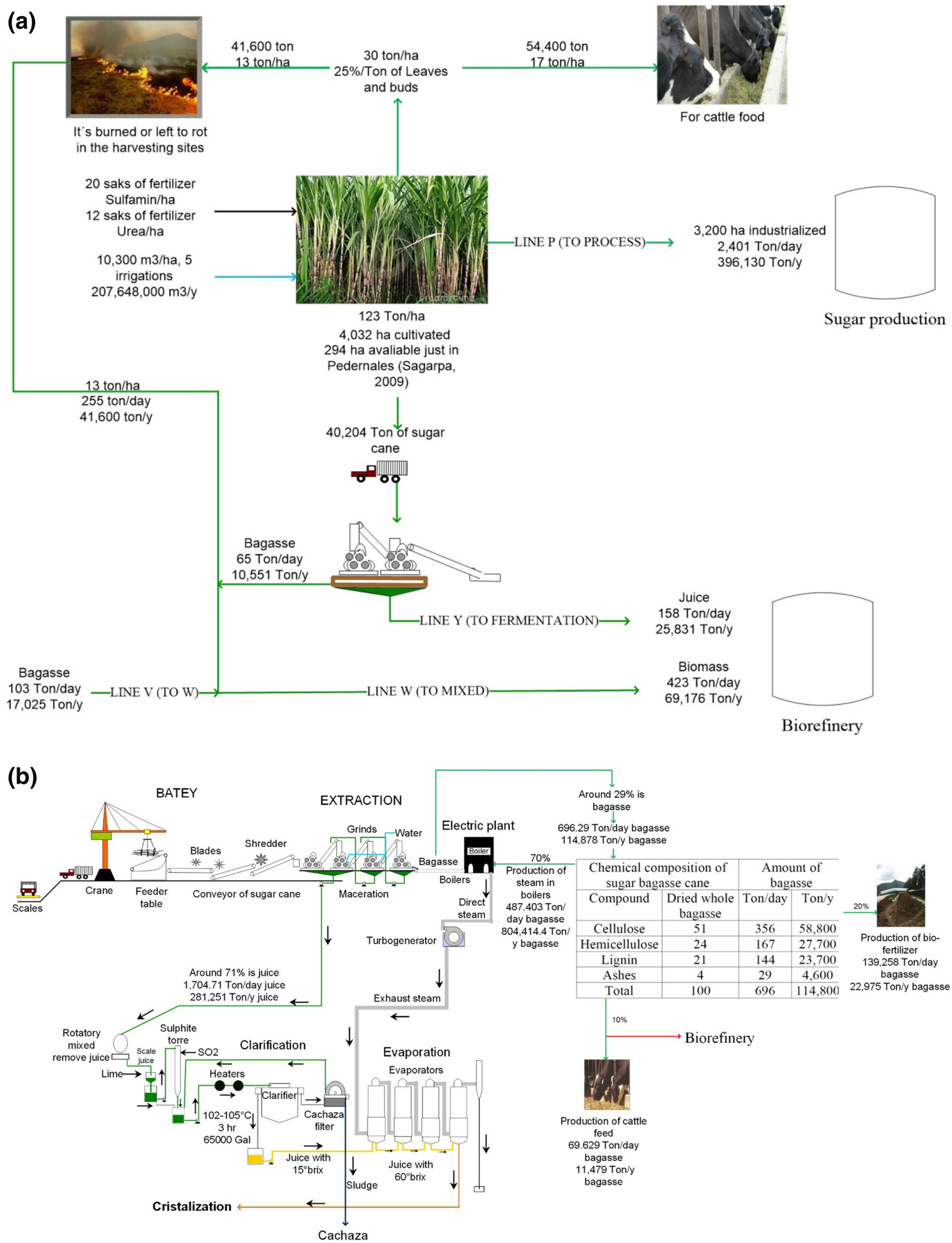


Fig. 2 Sugar cane composition (Veracruz Commission for Agricultural Markets 2010; SAGARPA 2009)

scenarios, reported process design and integration tools were used, and the analysis of the results obtained is described in the next section.

Optimization of the process

Sakumara et al. (2015) reported that the biomass transformation into various marketable products requires a well-planned strategy; in this way, the analysis for the retrofitted sugar cane industry to yield an integrated biorefinery must include the entire associated supply chain, including the tasks for feedstock production, harvesting, pretreating, processing, and distribution of products (as shown in Figs. 3a–d). Figure 3a considers a global process associated mainly to the trajectory of the raw material and their wastes, which are included for the sugar and bioethanol production. Figure 3b shows the first processing units for the sugar production (Batey, extraction, clarification, evaporation, and electric plant), and it should be noted in this figure that some residues are reused. Figure 3c shows the following processing units: crystallization, centrifugation, drying, and packing, where there is a significant production of the waste called "*Cachaza*," which can be considered as additional feedstock in the integrated biorefinery. In addition, Fig. 3d shows the processing units for the bioethanol production integrated to the existing sugar cane mills. For the optimization approach, the formulation developed by Santibañez-Aguilar et al. (2014) was implemented. In this formulation, all the tasks involved are considered, and the economic, environmental, and social issues are included in the objective function. The economic objective function accounts for the maximization of the overall profit, and the environmental objective is quantified


(a)
41,600 ton
13 ton/ha
30 ton/ha
25%/Ton of Leaves and buds
54,400 ton
17 ton/ha
For cattle food
It´s burned or left to rot in the harvesting sites
20 saks of fertilizer Sulfamin/ha
12 saks of fertilizer Urea/ha
10,300 m3/ha, 5 irrigations
207,648,000 m3/y
LINE P (TO PROCESS)
3,200 ha industrialized
2,401 Ton/day
396,130 Ton/y
Sugar production
123 Ton/ha
4,032 ha cultivated
294 ha avaliable just in Pedernales (Sagarpa, 2009)
13 ton/ha
255 ton/day
41,600 ton/y
40,204 Ton of sugar cane
Bagasse
65 Ton/day
10,551 Ton/y
LINE Y (TO FERMENTATION)
Juice
158 Ton/day
25,831 Ton/y
Bagasse
103 Ton/day
17,025 Ton/y
LINE V (TO W)
LINE W (TO MIXED)
Biomass
423 Ton/day
69,176 Ton/y
Biorefinery
(b)
BATEY
EXTRACTION
Electric plant
Around 29% is bagasse
696.29 Ton/day bagasse
114,878 Ton/y bagasse
Scales
Crane
Feeder table
Blades
Shredder
Conveyor of sugar cane
Grinds
Water
Maceration
Bagasse
Boiler
Boilers
70%
Production of steam in boilers
487.403 Ton/day bagasse
804,414.4 Ton/y bagasse
Direct steam
Turbogenerator
Exhaust steam
Chemical composition of sugar bagasse cane | Amount of bagasse
Compound | Dried whole bagasse | Ton/day | Ton/y
Cellulose | 51 | 356 | 58,800
Hemicellulose | 24 | 167 | 27,700
Lignin | 21 | 144 | 23,700
Ashes | 4 | 29 | 4,600
Total | 100 | 696 | 114,800
20%
Production of bio-fertilizer
139,258 Ton/day bagasse
22,975 Ton/y bagasse
10%
Biorefinery
Production of cattle feed
69.629 Ton/day bagasse
11,479 Ton/y bagasse
Around 71% is juice
1,704.71 Ton/day juice
281,251 Ton/y juice
Rotatory mixed remove juice
Sulphite torre
Scale juice
SO2
Lime
Clarification
Heaters
Clarifier
102-105°C
3 hr
65000 Gal
Cachaza filter
Evaporation
Evaporators
Juice with 15°brix
Juice with 60°brix
Sludge
Cristalization
Cachaza

◀**Fig. 3** **a** Distribution of raw materials for the integrated biorefinery. **b** First section for the sugar production process (Section B). **c** Second section of sugar production process (Section C). **d** Third section corresponding to the integrated biorefinery (Section D)

as the minimization of the associated Eco-indicator-99 (Geodkoop and Spriensma 2000), this last evaluated through the life cycle analysis from cradle to gate (Mukherjee et al. 2015). For evaluating the social benefit of the retrofitted biorefinery, the number of jobs generated through the entire supply chain was evaluated using the methodology implemented by Santibañez-Aguilar et al. (2014).

Case study

A case study from the State of Michoacán in Mexico was considered; this corresponds to the sugar cane production from the community of *Pedernales*, where currently the only product obtained is sugar. However, in recent years, the low price for the sugar in the national market has negatively impacted the community. Therefore, it is attractive to consider the reconfiguration of the system to yield an integrated biorefinery, using the residues from the sugar cane industry to produce biofuels. There are several technical (Shareefdeen et al. 2015), economic (Dos-Santos and Siqueira 2015) and environmental (Mukherjee et al. 2015) challenges that must be considered in the reconfiguration of the system. The technical issues involve how to reconfigure the system to produce additional products, where process systems engineering techniques (see El-Halwagi 2012; Gabriel and El-Halwagi 2013; Bamufleh et al. 2013) such as targeting, design, integration, and optimization approaches are very useful. The process information was obtained from the report by the Santos Group (2012). Furthermore, INEGI (2010) reports 4032 ha cultivated with sugar cane but just 3200 ha are industrialized. The harvesting period is carried out during 163 days, and the rest days of the year are used for cultivating the sugar cane. SENER (2013) reported a forecast about the national production and demand of gasoline in Mexico, being 45 % bigger the demand than the production; in this way, it is needed to evaluate other fuel alternatives to satisfy the estimated demands, and thus, the reconfiguration of the existing sugar production process to obtain an integrated biorefinery accounting for social, technical, economic, and environmental aspects becomes an attractive alternative. Four scenarios with different configurations and conditions were obtained and these are discussed in detail as follows.

Results

Four scenarios for a sugar cane industry reconfigured as different integrated biorefineries have been implemented and analyzed, and the discussion for each scenario is given as follows.

Scenario A: current situation

With the current industrialized area, it is possible to produce 396,117 ton/y of sugar cane; the harvesting begins with the burn of the fields causing the partial loses of leaves (41,600 ton/y). Then, the rest of the leaves are cut and used for cattle feed (54,400 ton/y), and the processing of the remaining biomass (300,117 ton/y) produces 45,369 ton/y of sugar. This production generates a profit of US$3,407,799/y. The current process is shown in Figs. 3b and 3c. (Sections B and C).

Scenario B: bioethanol production from residues

Nowadays, one part of the leaves from the sugar cane is burned (70 %) and the rest are used as cattle feed (30 %), and in this scenario is proposed the use of this reside as feedstock for the biorefinery. This amount of leaves can be substituted by the corn crop stubble, which does not have any specific use; currently, the stubble is a residue and its use does not affect the economic balance. Thus, instead of using the leaves as cattle feed, these are used along with the bagasse and molasses generated in the process for the bioethanol production. The amount of each residue is shown in Table 1, and it is important to highlight that for each raw material is contemplated the same pathway that is in the given reference.

Scenarios C and D: reduction of sugar production

For the evaluation of these scenarios, the integration between the Scenarios A and B is considered, and in this analysis, there is a reduction of 50 % and 100 %, in the amount of raw material used for sugar production for Scenarios C and D, respectively. For both scenarios, the life cycle analysis inventory was performed taking as basis the work by Ometto et al. (2009) for each activity associated in each scenario (i.e., Tables 1–8 in the electronic information file) and the environmental impact was measured (EI) by the Eco-indicator-99 methodology (i.e., Tables 9–11 in the electronic information file) (Geodkoop and Spriensma 2000). Similarly, the social impact was evaluated as a function of the generated jobs (Martínez-Guido et al. 2014), and the economic impact was evaluated by the balanced profit between the investment to carry out

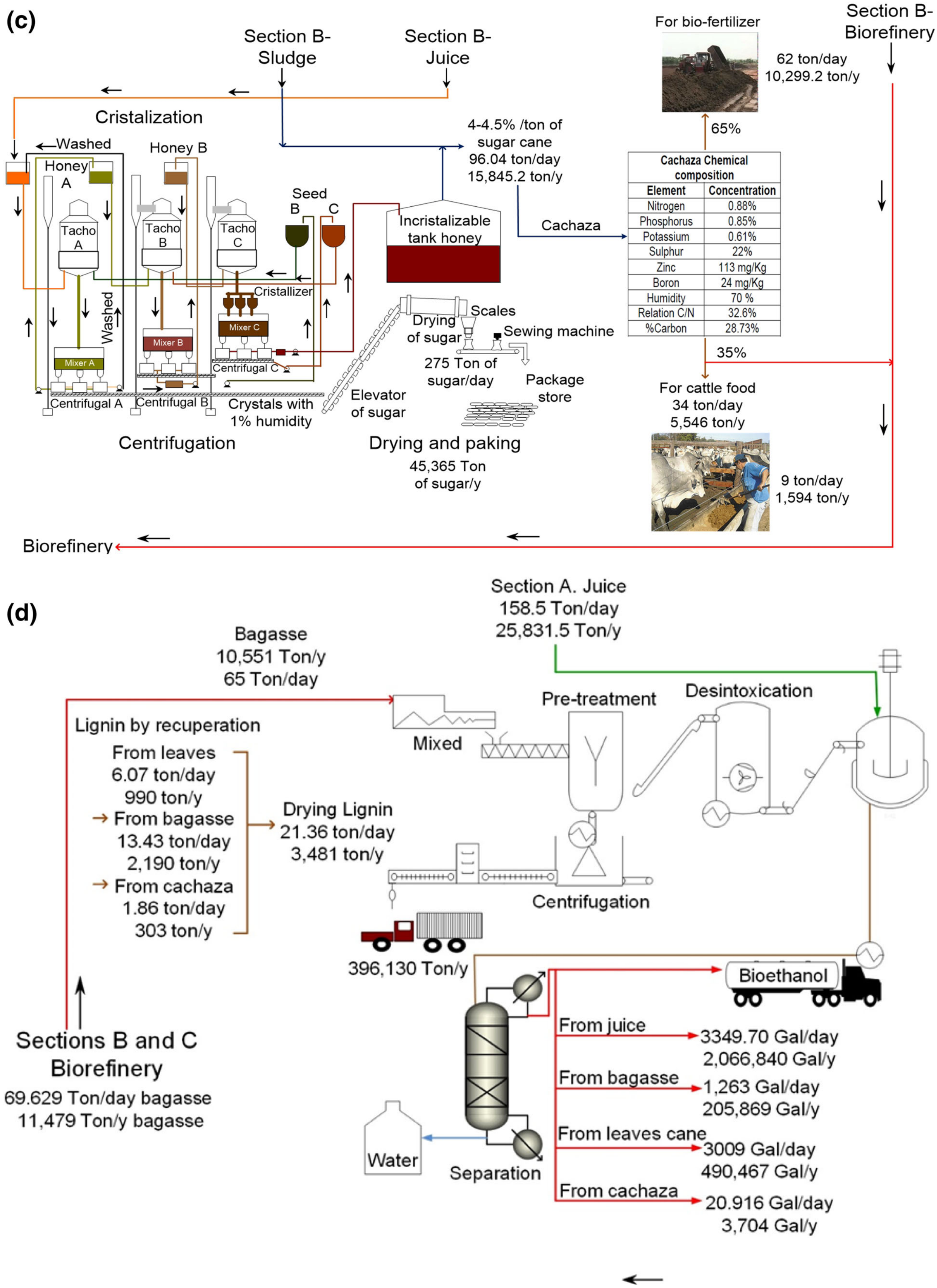


Fig. 3 continued

Table 1 Produced residues from the sugar cane

Residue	Amount of each residue (ton/ton of sugar cane)	Yield bioethanol (gal/ton residue)
Leaves	0.30[B]	38[D]
Bagasse	0.29[B]	48[B]
Molasses	0.045[C]	73[F]
Direct juice*	0.71[B]	21[B]

[B] SENER (2013), [C] Nguyen and Hermansen (2012), [D] da Silva et al. (2010), [F] Pandey (2009)

* The direct juice is contemplated just for the scenarios (C and D)

both processes (installation of the plant for the bioethanol production and all the activities associated to the supply chain) and the generated earnings.

Discussion

The Pareto curve (Fig. 4) was generated through the solution of the optimization model for integrating the different analyzed scenarios; in this figure, it is possible to see that the earnings increase 263 %, comparing the current situation with the substitution of sugar by bioethanol production (it means to change the use of all the sugar cane), while the EI increases only 2 % comparing the highest bioethanol production (Point D) with respect to the current situation (Point A). The reason for the small increase in the EI is because the cultivation of sugar cane can fix the CO_2 generated by the bioethanol production process, making this a closed-cycle process. Furthermore, the biggest EI percent is due to the sugar cane cultivation. It should be noted that point A is the current situation in *Pedernales*, and the rest of the points correspond to the integrated processes of sugar and bioethanol production or changing the sugar cane use like in case D. With the obtained results, it is possible to compare the options between the sugar and bioethanol production taking into account the environmental, social, and economic impacts associated to the entire supply chain.

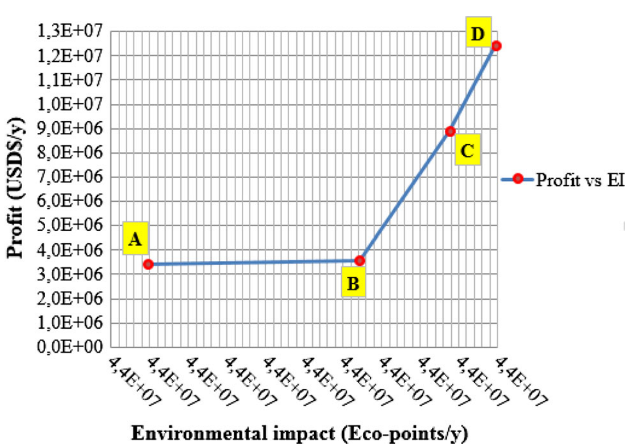


Fig. 4 Pareto solutions for the different scenarios

Environmental impact

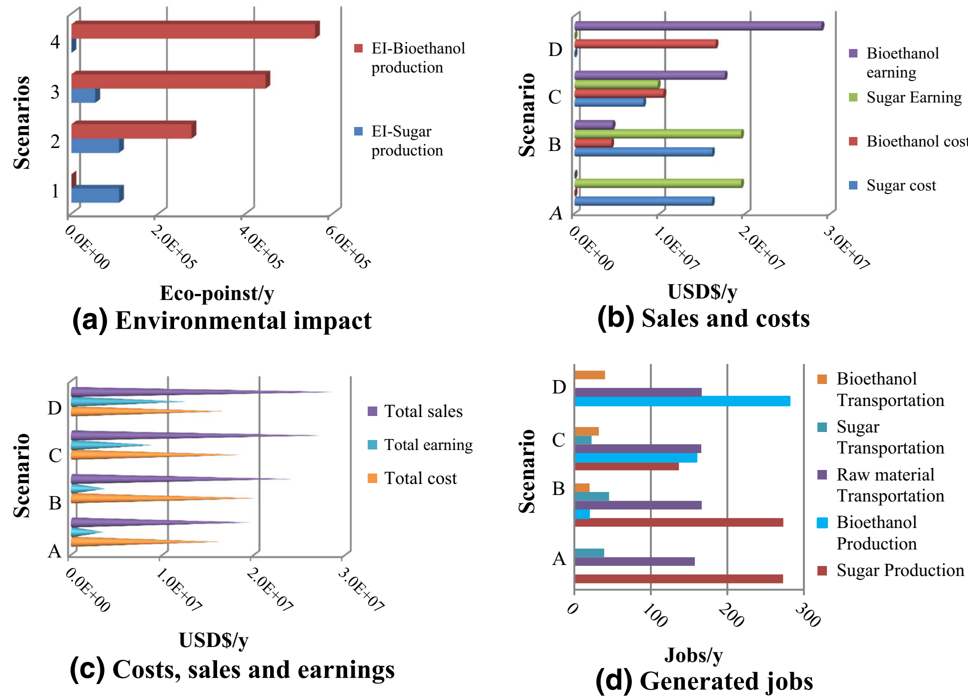
This analysis was done through the Eco-indicator-99 methodology. First, the life cycle analysis for each process in the supply chain (raw material, bioethanol and sugar production) was performed, evaluating the inputs and outputs of each compound needed in the activities. Figure 5a shows the contribution for the EI of each activity needed in the entire SC. Comparing the EI when all the sugar cane is used for obtaining only one of both products, the contribution for the bioethanol production is 80.5 % greater than the one of the sugar production; the EI of both processes is variable in each scenario, while the EI generated by the sugar cane production is the same (43,438,000 Eco-points/y); this is because the amount of raw material (sugar cane) cultivated is the same for all the scenarios.

The major contribution for the EI generated is the sugar cane production (see Table 11 of the electronic information file), due to the use of herbicides, emphasizing the use of atrazine, 2,4 D, arsenic, and 2,4,6-trichlorophenol in presentations such as "*Faena, Velconate*®, and *Gesapax*®"; nowadays, these herbicides are used in the fields for weeding, and however, the use of these products has negative effects mainly in the human health and the ecosystem quality. This EI represents between 99 and 98 % of the global EI for all the cases.

Economic impact

Figure 5b shows the processing costs; for the sugar production; the cost is represented by blue bars and for the bioethanol production by yellow bars, while the earnings that are generated by the product sales are represented by gray and orange bars for sugar and bioethanol, respectively. Notice that in the Scenarios A and B, the earnings increase just 4 %, and this is due to the fact that in Scenario

Fig. 5 Main results for the case study



B is contemplated the sale of bioethanol, which is obtained from the generated residues from the current process, while the earnings generated by the sugar production are the same.

Figure 5c shows the comparison between the total cost generated by the SC, the sales, and earnings of the net economic balance. Comparing the total earnings between Scenarios A and D, it is possible to appreciate that without the sugar production (Scenario D), the total earnings increase 263 %. The best economic option corresponds to Scenario D, because this is the option with the major earnings; thinking that the demand of sugar can be satisfied by other crop, this option is feasible. In addition, to be competitive, the sugar would increase the sales by $216/ton.

However, there is a national demand of sugar that must be satisfied, and the considered mill has to provide 33,340 ton/y in order to satisfy this national demand. Attending to this demand, it is necessary to select a middle point between the Scenarios B and C. Under this condition, only 80 % of the current sugar cane cultivated is used to produce sugar, and the rest can be used for bioethanol production. With this constraint, it is possible to reach an increase of 76 % in the total final earnings; being the integrated biorefinery an attractive option to satisfy the sugar demand and at the same time to increase significantly the earnings from the sale of bioethanol.

Social impact

The metric used for evaluating the social impact is the generated jobs. Fig. 5d shows the jobs that each activity creates for all the scenarios; the sugar cane harvesting activity keeps constant in all the scenarios, and also this activity represents the biggest percent of generated jobs (99 % of the total). For the Scenarios B and C, where is contemplated the simultaneous production of sugar and bioethanol, there is an increase in the number of jobs (11 and 9 %, respectively), with respect to the extreme cases (where only one product is considered) of Scenarios A and D. The case with the highest number of jobs is Scenario B (with an increase of 11 %), and comparing it with scenario D (the best economic option), the number of jobs increases just 3 %. This comparison is with respect to the current situation (Scenario A).

Conclusions

This paper presented an evaluation for the reconfiguration of existing sugar cane mills to yield integrated biorefineries. In this analysis, simultaneously have been considered economic, environmental, and social aspects, and different optimal Pareto solutions are presented and discussed. Process integration techniques have been included in the analysis for improving the integrated and reconfigured solutions. A case study of an existing sugar cane mill from Mexico has been presented. Results show that the three issues (economic, environmental, and social) must be considered to obtain compensated solutions according to the level of integration. Furthermore, very attractive solutions since the economic, environmental, and social points of view have been identified in the reconfiguration of the existing sugar cane mill of Mexico to obtain a sustainable biorefinery.

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