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Comparative Evaluation of Three Sugarcane Supply Strategies in Colombia: Logistics, Energy and GHG Emissions

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Abstract

Sugarcane-based ethanol in Colombia has a prospective opportunity to explore the production of ethanol from lignocellulosic biomass taking into account that a large amount of generated residues (between 50 and 100 t/ha) are left on the field after green harvesting. The use of sugarcane green harvesting residues for ethanol production could be considered as a feasible solution but it is facing high supply costs. A bottom-up engineering cost model was used to estimate the green harvesting residues supply cost for three collection strategies. The model took into account the investment and operation costs of the residues collection, processing, delivery, and machineries including depreciations, repair and maintenance, and labor cost. Overall energy consumptions and life-cycle GHG emissions of the three strategies were analyzed. The integral harvesting showed the best performance in costs (6.01 USD/dry-t), energy consumptions (125.32 MJ/dry-t), and GHG emissions (7.74 kg CO_2-eq/dry-t), followed by the baled and chopped residues.

Keywords: *Green harvesting residues; lignocellulosic ethanol; logistics; sugarcane residues; supply chain.*

1. Introduction

One of the leading options for fossil-fuel substitutes, which have recently received substantial interests all over the world, is the bioethanol. In Colombia, since 2001, the use of bioethanol has been prompted but it was only in the late 2005 that bioethanol production started in the Cauca river valley. Currently, the use of E10 (fuel blending of 10% bioethanol and 90% gasoline) is mandatory in the cities with population over 500 thousand inhabitants. Furthermore, the Colombian Decree 1135 started on January 2012 would require the use of E85 for the new vehicles with motors up to 2000 cm^3 of capacity. The lower net GHG reduction, and land requirement and its competition with food products could be limits to the first ethanol production [1-4]. While the use of the agricultural residues for energy could be an advantage over the energy crops, in general, the high logistics cost is known to be one of the drawbacks in the use of agricultural-based residues for energy purposes [5-7]. Governments will usually allocate subsidies or incentives to enhance the energy security and compensate for the higher production costs of biofuel in comparison to fossil-fuel [7].

Sugar industry is an established sector in Colombia [8-10]. The country has approximately 223.905 hectares of land under sugarcane cultivation as of year 2012 (http://www.asocana.org). After sugarcane harvesting, considerable amount of about 50-100 t/ha of the lignocellulosic Green Harvesting Residues (GHR) are left on the field [11,12]. The variation relies on several factors such as types of harvesting (manual or mechanical), burning practices, topping heights, cane varieties, age of crops, and climate and soil characteristics [12]. Since 1996, burning of GHR has been phased out in the country leaving it a potential reserve for lignocellulosic ethanol productions.

While, there are various theoretical approaches and case study applications of the biomass supply chain modeling in the literature [5,13-16], few studies have addressed the logistics of sugarcane GHR. Michelazzo and Braunbeck [17] analyzed six collection scenarios of sugarcane GHR in Brazil. They found out that handling the whole stalk (integral harvesting) had the lowest cost, followed by the bulk handling of chopped GHR, the round bale, the cotton bale, and finally the pellet and briquette options. Ripoli and Ripoli [18] have also reported a lower delivery cost of GHR using the integral harvesting system instead of baling or transporting of the bulk chopped residues. In Colombia, Briceño and Cock [19] concluded a lower cost for the baled GHR as compared to bulk transportation of chopped GHR. The cost of GHR supply chain is estimated by considering several critical assumptions such as the moisture content, and machinery efficiencies [20].

In order to increase the current capacity of biofuel in Colombia, the implementation of the second generation bioethanol technology from agricultural-based biomass could be a key factor. Nonetheless, due to the GHR scattered distribution and low bulk density, it is necessary to evaluate the biomass logistics options based on the country's resources and practices.

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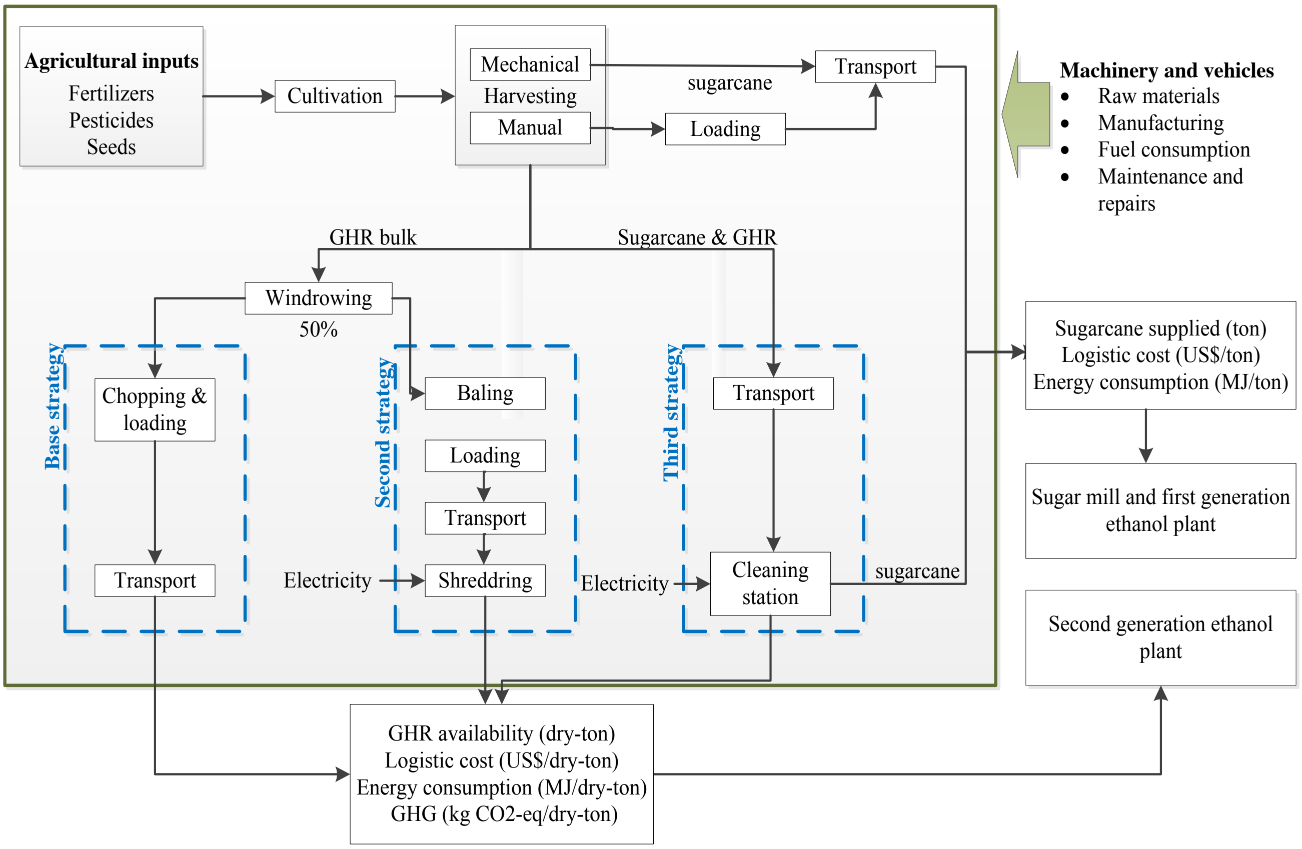

Figure 1. Logistics strategies for GHR supply.

In other words, a sustainable management and development of a whole new infrastructure for harvesting, transporting, storing and refining of the biomass is required. This study aims at contributing to this urge and has suggested three possible supply-chain strategies for sugarcane GHR in Colombia. The fuel delivery cost, the energy consumption and the life cycle GHG emissions for the strategies are also estimated.

2. Methodology

The delivery of GHR to a projected bioethanol plant could be complex due to the low energy density, high moisture content and dispersed characteristics of the fuel which make it economically not feasible on long-distance travel [20,21]. Sugarcane GHR can be used as a potential feedstock for the second ethanol production and hence, hit the ethanol market in Colombia to meet the blending biofuel regulations set by the government.

Three logistics strategies are selected for the analysis of costs and energy consumptions of supplying GHR in Colombia. Figure 1 shows the system boundaries including the current sugarcane logistics and the three strategies analyzed for the GHR supply. The objectives are to analyze: the total supply costs, direct energy consumption due to the transportation and the treatment of feedstock; indirect energy consumptions of agricultural machineries including the embodied energy of raw material manufacturing (steel and tires) and maintenance and repairs of machines; and GHG emissions of the operations involved in the three strategies. The labor and machinery cost was calculated for each operation. It is important to leave some proportion of the residues in the field for soil regeneration. There is no conclusive study on the proportion of the GHR to be left in the field for the soil maintenance; based on a literature survey [2, 22-24], this proportion is 50% of GHR, which is considered in this study as well.

In the base strategy, after harvesting the sugarcane, cane is transported to the mill, and the GHR is left in the field. The GHR is windrowed; 50% of it is recycled for the soil protection, and remaining is collected, chopped (90% efficiency) [20], and loaded into the wagons. In the second strategy, the windrowed GHR is baled, transported and treated before feeding in the plant. Rectangular bales of 0.8×0.8×1.9 meters are considered, and baler efficiency is 84%, heavy trucks with attached stacking unit (Stinger Stacker model 6500) carry the bales. In the plant gate, a bale handler is used for unloading, stacking, feeding the processor (shredder). In the third strategy (integral harvesting), the cane and GHR are transported together to the sugar mill. The cleaning system of the harvester has two extractors to remove the GHR; the primary extractor has a speed control, while the secondary extractor has only the on/off switch. Lowering the primary extractor speed increases the load of GHR into the wagon. The GHR and cane separation process takes place in a dry-cleaning station installed next to the mill operating 350 days per year, 24 hours per day. It has an installed capacity of 250 ton per hour and a power consumption of 228 kWh. The efficiency of the cleaning system is 70%, and one operator is required for the shredder [24].

The transportation loss is assumed to be 2% for all strategies. The whole cycle of sugarcane cultivation and harvesting consists of 67 months including 15 months cultivation, and four subsequent 13-month-harvest periods (ratoon). The sugarcane is harvested either manually or mechanically. Currently, approximately 70% of the fields are manually harvested with an average rate of work of 3 tons per day. Mechanical harvesting has an average rate of work of 250 tons per day. The composition of the GHR in the field is approximately: 75-82% of damaged cane, 7-12% of dry leaves, 2-3% of green leaves and 7% stumps. There is a large variation in the moisture content after harvesting from 11.9% in dry leaves up to 78.6% in the stumps. However, in the absence of rain, the residues could reach an average moisture level of 40% in one week due to their natural drying rate (3-4% per day) [19]. The sugar cane variety CC 85-92 is considered as it is currently cultivated on 71.5% of the area [25]. This variety has a cane and GHR yield of 117 and 45 ton per hectare, respectively [11]. The collection efficiency, machinery rates, and the moisture content of GHR have been taken into consideration to estimate the available GHR dry-ton at plant gate. The collection efficiency is defined as the ratio of the actual mass collected to the available mass that can be collected. The machinery rate of work is the theoretical machinery capacity multiplied by the machinery efficiency [26].

The main objective of this study is to measure the GHR availability, logistics costs, energy consumptions and the life cycle GHG emissions of the three strategies shown in Figure 1. The analysis also takes into account the current sugarcane supply system in order to offer a base assessment for the GHR strategies.

2.1 Supply Cost

The estimated global production costs of the second-generation bioethanol in literature currently range from 0.43 to 1.30 USD per liter [27-29].The feedstock cost constitutes around 35-70% of the total ethanol production cost, which is directly influenced by the logistics efficiency [30].

For a working life time of 4200 h/year (350 days and 12 hours per day), the logistic cost is estimated based on the methodology of ASAE standards EP496.2 and D497.4, [26] and [22]. Logistic costs are divided into two categories: Fixed and variable costs. Fixed costs are those that occur regardless of machine use. They include the ownership cost, K_o, in Eq. (1); and taxes, insurance and storage cost, K_t, in Eq. (2).

$$K_o = P\left[\frac{i(1+i)^y}{(1+i)^y - 1}\right] \tag{1}$$

$$K_t = P \cdot 0.02 \tag{2}$$

Where P is the purchase price in USD (Table 1); the lifetime (y) for agricultural machinery and vehicles is 5 and 10 years correspondingly; and the discount rate (i) is 10% [6]. The taxes, insurances and storage costs were assumed to be 2% of the purchase price [22].

Table 1. Input Data for Agricultural Machinery.

	P (US$)	e_{diesel} (l/h)	*RoW*(t/h)
Harvester	341’589	39.75	25.00
Loaders	34’431	7	87.10
Wagons	16’000	-	-
Tractor 105 HP	82’079	39.26	-
Tractor 31 HP	14’502	11.64	-
Windrower	5’141	-	199.32
Chopper	250’000	59.52	30.20
Rectangular baler	57’258	-	9.10

The variable costs are mainly the cost for operating the machinery/vehicle. They vary directly with the use and rate of work of machineries/vehicles, and include: Repairs and maintenance, fuel and lubricant cost. The total variable cost is the sum of all the elements considered in this section. The following equations are used to calculate the repair and maintenance cost in Eq. (3), fuel cost in Eq. (4) and lubricant cost in Eq. (5) for the agricultural operations (USD/t).

$$C_{R\&M-agr} = \frac{TAR}{h \cdot y \cdot RoW} \tag{3}$$

$$C_{f-agr} = \frac{e_{diesel} \cdot dc}{RoW} \tag{4}$$

$$C_{l-agr} = 0.15 \cdot C_{f-agr} \tag{5}$$

The Total Accumulated Repair (TAR) factor represents the accumulated repair and maintenance cost in the life of a piece of equipment according to the machinery purchase price and are taken from [31] in Table 2. The symbols *h* and *RoW* are the annual working hours and the machinery rate of work (t/h), respectively. e_{diesel} is the diesel consumption in liters per hour (Table 1), and dc is the fuel cost in USD per liter. The agricultural lubricant cost is assumed to be as 15% of fuel cost [22].

Table 2. Total Accumulated Repair Factors (TAR) and Manufacturing Energy Coefficients (e_W).

Machine/vehicle	TAR	e_W (MJ/kg)
Loaders	46%	7.38
Harvester	61%	13.01
Trucks, chopper, rectangular baler, bale processor, shredder	61%	14.63
Wagons, telescopic bale grab	76%	7.38
Tractor 31 HP, transport bales	89%	14.63
Windrower	93%	6.28
Tractor 105 HP	89%	14.63

In the case of transportation cost, Eqs. (6)-(8) were adapted; taking into consideration the transport characteristics (USD/t):

$$C_{R\&M-tr} = \frac{P \cdot TAR}{\gamma \cdot V \cdot h \cdot y} \tag{6}$$

$$C_{f-tr} = \frac{e_{diesel} \cdot dc \cdot TR_{cycle}}{V} \tag{7}$$

$$C_{l-tr} = 0.15 \cdot C_{f-tr} \tag{8}$$

where γ is the number of trips per day. The tons transported per trip (V) , is calculated through Eqs. (9) and (10) for tractors and trucks, respectively. φ_λ and φ_Λ are the number of wagons hauled by the tractor or the truck. ρ_{sc} is the sugarcane density (250 kg/m^3). ϑ_λ and ϑ_Λ are the HD8000 and LD24000 wagon volumetric capacity correspondingly.

$$V_1 = \varphi_\lambda \cdot \left(\frac{\rho_{SC} \cdot \vartheta_\lambda}{1000} \right) \quad (9)$$

$$V_2 = \varphi_\Lambda \cdot \left(\frac{\rho_{SC} \cdot \vartheta_\Lambda}{1000} \right) \quad (10)$$

The transport cycle (TR_{cycle}) in hours is the time of loading, round trip hauling and uploading. An average speed of 30 km/h and 35 km/h for the full and empty vehicles (trucks and tractors) were assumed [22]. The bales truck (Stinger Stacker) has an average speed of 60 km/h.

The machinery rates of work were obtained from field studies done by the Colombian Sugarcane Research Center (CENICAÑA) [11]. Additional information related to the cultivation and planting practices were obtained through direct conversation with farmers and experts from the sugarcane industry. All the cost data is related to the situation in August 2012 (1 US$=1,821 Colombian pesos).

2.2 Energy Consumption

Five main components are included in the sugarcane energy consumption: Agricultural inputs, cultivation, harvesting, transport and the construction of machineries. The main agricultural inputs needed for the sugarcane culture are nutrients, pesticides and seeds; and their energy consumption in MJ/t is calculated through Eq. (11).

$$E_{AI} = \sum \left(\frac{\bar{\phi} \cdot E_{pcc}}{SC_{year}} \right) + E_{her} + E_{ins} + E_s \quad (11)$$

where $\bar{\phi}$ is the average annual use of P_2O_5, K_2O, N and lime in kg/ha-year [32]. For N requirements, soils with good drainage and more than 4% of organic matter were assumed [33]. Production energy ratios (E_{pcc}) *were taken from [34-36] and summarized in Table 3*. SC_{year} is the sugarcane yield per ha-year. E_s is the energy for seeds assumed to be 2.9% of the total energy needed for cane production [35]. E_{her} and E_{ins} stand for the energy for herbicides and pesticides production, which are 11.26 MJ/t and 0.79 MJ/t respectively [35].

Table 3. Agricultural Inputs data.

	Units	Fertilizers			Lime
		N	P_2O_5	K_2O	
Planting	kg/ha	40	11.7	52.1	250
Each ratoon	kg/ha	75	11.7	52.1	250
$\bar{\phi}$	kg/ha-year	340	59	261	1250
E_{pcc}	MJ/kg	56.3	7.5	7.0	1.3

The energy needed for cultivation (E_C) is estimated through Eq. (12) using a mean diesel consumption of 102.6 for planting ($E_{planting}$) and 9.1 l/ha for each ratoon (E_{ratoon}) [35]. SC_{cycle} and SC_{ha} are the cycles of sugarcane cultivation-harvesting; and the sugarcane yield per hectare (117 t/ha).

$$E_C = \frac{\dfrac{\left(E_{planting} \cdot LHV_{diesel}\right) + \left(4 \cdot E_{ratoon} \cdot LHV_{diesel}\right)}{SC_{cycle}}}{SC_{ha}} \quad (12)$$

The energy consumption of the harvesting operations is calculated through Eq. (13), where α is the percentage of cane that is mechanically harvested. In this case, the diesel consumption comes from the harvester use (39.75 l/h) [37]; for the manual harvesting, the fuel consumed by the loader is 10.09 liters/h [34].

$$E_H = \alpha \cdot SC \cdot \left(\frac{e_{diesel} \cdot LHV_{diesel}}{RoW} \right) + (1-\alpha) \cdot SC \cdot \left(\frac{e_{diesel} \cdot LHV_{diesel}}{RoW} \right) \quad (13)$$

Eq. (14) calculates the energy consumed for transportation in MJ/t. In the study, 60% of the cane is transported with tractors towing four wagons and the rest is transported with trucks hauling two wagons [37].

$$E_{TR} = \hat{e}_{diesel} \cdot LHV_{diesel} \cdot d \quad (14)$$

Where $\hat{e}_{diesel}$ is the diesel consumption (l/t-km) and d is the transportation distance in km. The energy used for the machinery/vehicle maintenance (MJ/t) is calculated using Eq. (15). To calculate the energy needed for the repaired parts and maintenance, a machinery reliable life of 82% of the total life is assumed [31].

$$E_{MM} = \frac{\left[(EE + ME) \cdot 0.82\right] + E_{R\&M}}{h \cdot RoW \cdot y} \quad (15)$$

where *EE* is the embodied energy from the raw materials and is calculated using the machinery weight (W_{steel}) and the percentage of weight equivalent to the tires (W_{tires}). Then, the machinery weight is multiplied by the embodied energy coefficient (62.80 MJ/kg for the steel and 85.83 MJ/kg for the tires) $EE = 85.83 \cdot W_{tires} + 62.80 \cdot W_{steel}$. The amount of energy needed for the equipment manufacturing is calculated using $ME = e_W (W_{steel} + W_{tires})$ on the basis of the machinery weight and the coefficient appropriated for its class (Table 2) [31]. $E_{R\&M}$ is the energy from repair parts and materials that would be applied to a piece of machinery over its useful life, and is calculated using $E_{R\&M} = \left[TAR \cdot (EE + ME)\right]/3$ [31]. The total energy consumption (MJ/t) at the mill gate is then the sum of all the components mentioned before. The energy consumption for the GHR supply considers the energy for the collection, processing, transport and the machinery/vehicle manufacturing.

2.3 Life Cycle GHG Emissions

The life cycle GHG emission analysis follows the standard LCA methodology, ISO 2006, for the system boundary shown in Figure 1 and for the functional unit of one dry-ton of GHR. It includes the collection, transportation, and treatment of GHR from the field to the gate of the plant for the three strategies. The GHR is an agricultural waste; therefore, the agricultural inputs such as seeds, fertilizers, etc. are allocated to sugarcane production.

Table 4. Biomass Throughput and Supply Cost.

	Unit	Strategy		
		Chopped	Baled	Integral
Sugarcane delivered	t/day	13’000	13’000	13’000
GHR at plan-gate	dry-ton/day	1'230	1'148	1'590
GHR moisture	%	12	15	38
GHR density	kg/m^3	90	223	270
Sugarcane Cultivation	US$/t	21.12	21.12	21.12
Sugarcane Harvesting	US$/t	1.06-6.30	1.06-6.30	1.06-6.30
Sugarcane loading	US$t	0.13	0.13	0.26
Sugarcane transport	US$/t-km	0.88-1.11	0.88-1.11	0.87-1.10
GHR Windrowing	US$/t	0.45	0.45	-
GHR Chopping	US$/t	4.25	-	-
GHR Baling	US$/t	-	2.60	-
GHR loading/unloading	US$/t	0.12	0.86	0.26
GHR bale breaking	US$/t	-	1.84	-
GHR transport	US$/t-km	5.62-6.58	6.96	1.83-2.18
Sugarcane cost	US$/t	30.59	30.59	30.95
GHR cost	US$/dry-t	16.84	18.63	6.01

The Intergovernmental Panel on Climate Change (IPCC) 2007 emission factors of 1 for CO_2, 25 for CH_4, and 298 for N_2O:http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2 s2-10-2.htm, for a time horizon of 100 years are used to estimate the total GHG emissions on the basis of kg CO_2 equivalent (eq) per functional unit following Eq. (16).

$$EM = \sum Q_i \cdot EF_i \tag{16}$$

Where, *Q* is the quantity of gas substance *i* in kg of gas per functional unit of the operation (e.g. kg CH_4/kWh) and *EF* is the emission factor of substance gas *i* (e.g. 25 for CH_4).

The study has used the National Renewable Energy Laboratory (NREL) datasets (http://www.nrel.gov/lci/) for the analysis of CO_2 equivalent emissions of the activities involved in GHR supply. Even though the bagasse could be used to provide energy through cogeneration processes (Selling the surplus power to the national electric grid); no all the sugar mills have it and then trade the bagasse with the paper industry. Due to this, it is assumed that the power for cleaning, shredding and bale processing will be supplied form the Colombian national power grid with CO_2 emissions of 0.285 kg CO_2/kWh (CDM, 2012).

The environmental load of the mobile and stationary operations is the summation of the calculated CO_2 equivalent emissions through the following equations:

$$EL_{ec} = electricity \cdot EM_{rem} \tag{17}$$

$$EL_{dc} = \frac{diesel \cdot EM_{database} \cdot GHR_{wet} \cdot TR_{cycle}}{diesel_{database} \cdot GHR_{dry}} \tag{18}$$

$$EL_{sdc} = diesel \cdot EM_{database} \tag{19}$$

$$GHGE = EL_{ec} + EL_{mdc} + EL_{sdc} \tag{20}$$

where, *EL* is the environmental load of each operation in kg CO_2 equivalent per GHR dry-t; *EM* is the emissions of kg CO_2 equivalent per functional unit of each operation (e.g. kg CO_2 eq/ kWh electricity from mix grid), and GHGE is the total greenhouse gas emissions of the logistics operation in kg CO_2 eq/dry-t GHR.

3. Results and Discussion

The methodology was implemented using a representative sugar mill as a case study. The lignocellulosic ethanol plant will be located adjacent to the sugar mill in order to take advantage of the current milling capacity of 13’000 cane tons per day. The gross area of 45’199 hectares is available, where 38’902 hectares are planted with sugarcane.

Table 4 presents the results of calculated supply cost for each strategy. In the case of the pull-type equipment, the cost was charged to the tractor. For the evaluation of the sugarcane cultivation, the cost is provided by the Colombian association of sugarcane producers and suppliers (PROCAÑA). Cultivation costs include direct and administrative costs for the ratoon and renovation activities. The cultivation cost accounts for 69% of the sugarcane cost at mill-gate. The integral harvesting strategy has an extra cost of 20% approximately due to the additional application of chemical fertilizers for the absence of GHR nutrients in the field. Transportation represents 7% of the supply cost at mill-gate.

Table 4, highlights that the collection and processing activities represent 9.74, 9.24 and 1.22 USD/t of the total GHR supply cost for the chopped, baled and the integral harvesting, respectively. The transportation cost represents 42% and 50% of the total cost for the chopped and baled GHR, whereas it has a significant value of 80% of the total cost for the integral harvesting with the lowest GHR supply cost.

In the case of the sugarcane supply, there is an increment of 0.36 USD per ton at the mill-gate under integral harvesting. The main reason is partially due to the use of extra fertilizers to compensate for the nutrition of the removed GHR and also due to the high quantity of the loaded biomass. Table 5 summaries the energy consumption for the three strategies.

Table 5. Energy Performance for the Three Strategies.

	Unit	Strategy		
		Chopped	Baled	Integral
Cultivation	MJ/t	8.65	8.65	8.65
Harvesting	MJ/t	17.36	17.36	17.36
Sugarcane loading	MJ/t	2.05	2.05	2.93
Sugarcane transport				
Tractor	MJ/t-km	0.50	0.50	0.50
Truck	MJ/t-km	0.70	0.70	0.70
Agricultural inputs for sugarcane				
Fertilizers & lime	MJ/t	36.80	36.80	41.96
Pesticides & herbicides	MJ/t	7.18	7.18	7.18
Seeds*	MJ/t	3.15	3.15	3.33
Machinery	MJ/t	10.55	10.55	12.05
Windrowing	MJ/t	9.86	9.86	-
Chopping	MJ/t	71.74	-	-
Baling	MJ/t	-	38.54	-
GHR loading/unloading	MJ/t	-	11.94	2.93
GHR transport	MJ/t-km	1.49-2.11	3.61	-
Bale breaker	MJ/t	-	26.40	-
Cane cleaning	MJ/t	-	-	3.28
Machinery	MJ/t	8.76	10.41	20.57
Sugarcane energy consumption	MJ/t	108.71	108.71	116.46
GHR energy consumption	MJ/dry-t	172.16	258.65	125.32
Lignocelullosic ethanol production	liters/day	417,648	389,805	539,886
Energy equivalence	MJ/day	8,786,473	8,200,708	11,358,124
Market price	US$/day	384,653	359,010	497,235

*A piece of cane stalk is used as seed to generate the next ratoon.

The chopped GHR has the highest energy consumption for collection and processing (120 MJ/t), followed by baling (117 MJ/t) and integral harvesting (64 MJ/t). The transport represents 30%, 55% and 49% of the total energy consumed for the three strategies, respectively.

In the case of the sugarcane supply, the energy from the operations (cultivation, harvesting and transport) represents 41% of the total energy consumed, where the transport absorbs 21%. The agricultural inputs contribute to the total energy consumption by 43% with a 2% increment when integral harvesting is used. Table 5 also shows the expected amount of GHR-based lignocellulosic ethanol production and its fuel value. The same ethanol yield of 340 liters per dry-t from corn stover was assumed for the GHR due to the similar composition of both biomasses [6].

The results in Figure 2 indicate that the supply using integral harvesting emits considerably less GHG emissions by 57% and 84% compared to the first and second strategies. This advantage is mainly due to the fact that in the integral harvesting a higher quantity of the GHR can be collected and transported to the plant, and the fuel consumption for the cultivation and harvesting process is totally allocated to the sugarcane.

However, one important drawback is that in the integrated harvesting less proportion of GHR is left on the soil, therefore, the consequent nutrient deficiency should be compensated from other sources. Evidently, implementing of the chemical fertilizers would create additional GHG emissions for the third strategy. Taking into account this negative point, the overall GHG emissions of this strategy would increase to 9.54 kg CO_2-eq/GHR dry-t which is still favorable compared to the other two strategies. Another alternative is to recycle the sludge or wastewater produced in the bioethanol plant to the field which could be considered as an environmental friendly substitution. Due to the data uncertainty, this alternative has not been considered.

4. Conclusions

The paper analyzed the techno-economic and environmental assessment of sugarcane and green harvesting residues in the sugar-ethanol supply chain. Three different strategies to supply the sugarcane to the mill and the GHR to the lignocellulosic biorefinery were studied calculating the amount of biomass delivered, logistic cost, energy consumption and GHG emissions. The daily liters of lignocellulosic ethanol were also calculated. The integral harvesting showed the best performance in costs (6.01 USD/dry-t), energy consumptions (125.32 MJ/dry-t), and GHG emissions (7.74 kg CO_2-eq/dry-t), followed by the baled and chopped strategies. A potential lignocellulosic ethanol production of 539,886 liter per day could be reached under the integral harvesting.

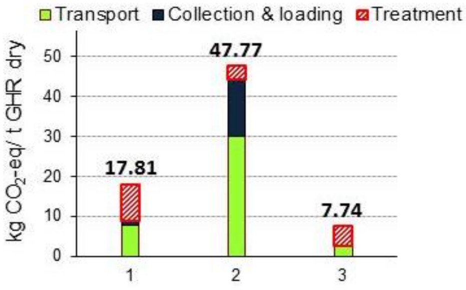

Figure 2. GHG emissions of the three GHR logistics strategies.

Nomenclature

d	travel distance, km
dc	fuel cost, USD/l
C	variable cost, USD/t
E	energy consumption, MJ/t
EE	embodied energy from the raw materials, MJ/t
EF	emission factor of gas substance, unit-less
EL	environmental load for each operation, kg CO_2-eq/ GHR dry-t
EM	Emissions per functional unit of each operation, kg CO_2-eq/kWh or kg CO_2-eq/t-km or kg CO_2-eq/l
$\hat{e}$	diesel consumption, l/t-km
e	diesel consumption, l/h
GHR	green harvesting residues, dry-t
GHG	greenhouse gas, kg CO_2-eq
GHG	total greenhouse gas emissions, in kg CO_2 eq/GHR dry-t
h	annual working hours, h/year
i	discount rate
K	fix cost, USD
LHV	lower heating value, MJ/kg
ME	energy needed for the equipment manufacturing, MJ/t
P	purchase price, USD
Q	quantity of substance, kg per functional unit of the operation
RoW	rate of work, t/h
SC	sugarcane
TAR	total accumulated repair factor, %
V	amount of tons transported per trip, t/trip
y	lifetime, years

Greek symbols

α	percentage of cane that is mechanically harvested
γ	vehicle trips per day
φ	number of wagons
λ	tractor
Λ	truck
ρ	density, kg/m^3
ϑ	wagon volumetric capacity, m^3
$\bar{\phi}$	average annual use of agricultural inputs, kg/ha-year

Subscripts and superscripts

agr	agricultural operations
AI	agricultural inputs
c	cultivation
dc	diesel consumption
ec	electricity consumption
f	fuel
H	harvesting
ha	hectare
her	herbicides
i	Substance gases i (CO_2, N_2O and CH_4)
ins	insecticides
l	lubricants
MM	maintenance and spare parts
pcc	production
rem	regional electricity mix
R&M	repairs and maintenance
s	seeds
sdc	stationary diesel consumption
t	taxes, insurance and storage
TR/tr	transport

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