Energy demand in sugarcane residue collection and transportation

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Abstract: Sugarcane production system is in transition, mainly due to its harvesting process. Harvest through burning has been gradually replaced by mechanized processes, providing another by-product to be explored: sugarcane trash. In Brazil, through the sugarcane trash, São Paulo state produces around 210.4 million BOE – barrel of oil equivalent (1,251,952 TJ), which could supply consumers through cogeneration or for further second generation ethanol. For the sugarcane trash to be collected, mechanized processes are required, such as windrowing, gathering, and transporting. In agricultural production systems, embodied energy is affected by the mechanization level. In order to assess environmental performance by the energy point-of-view, analysis of energy flows provides subsidies for the decision makers. Thus, this study aimed to determine the material and energy flows for sugarcane trash collection and to identify its critical steps. The sugarcane variety grown was RB855113, spaced between rows 1.4 m, in the second cut, and yield of 108 t ha^{-1}. The following mechanized operations were evaluated: windrowing, gathering, and transport, using material and energy flow as supporting tools. Regarding the energy balance, sugarcane trash collection system is feasible. Among evaluated operations, gathering is the one that presented higher energy demand. Fuel in harvesting is the main factor that affects energy demand for having sugarcane trash available.

Keywords: material flow, mechanized harvest, bioenergy, biofuel

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1 Introduction

Due to environmental regulations that guide sugarcane production systems in Sao Paulo state, Brazil, its harvesting is in transition. Harvesting after burning has been gradually replaced by mechanized process. In areas where mechanization is possible the deadline for full adoption of mechanization process is 2014, while in areas where mechanization is not possible, the deadline is 2017. This prohibition to burning provides a large amount of a new by-product to be explored, the sugarcane trash.

Sugarcane trash is composed by leafs and also by stalk fragments, straw, and soil aggregates (Ripoli, 1991). Trash can be used either as vegetal coverage or as energy source. Its use as covering material provides beneficial effects to weed control, fertilizer management, soil erosion, soil water infiltration rates, and soil organic matter dynamics (Arevaldo and Betoncini, 1999, Cerri et al, 2010). On the other hand, it can generate difficulties for the farming and fertilizer's application operations on the following cutting (Aude et al., 1993). Therefore, sugarcane trash must be managed rationally, in order to provide benefits either as soil coverage or as bioenergy source.

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In agricultural production system, energy intensity (EI) or embodied energy (energy per mass) is influenced on mechanization level and yield. Energy balance (EB) is determined by energy flows (input and output), revealing total demand and efficiency in the production processes (Romanelli and Milan, 2005). Besides, it provides indicators for sustainability assessment (Romanelli et al., 2012).

In 2011, the Brazilian Energy Matrix was composed by 45% of renewable source, in which 14% was from hydraulic; 10% from firewood, 4% from charcoal, and other renewable sources, but the most important was from sugarcane with a share of 17% (EPE, 2012).

Regarding energy generation, results from Ripoli (2002) showed that Brazilian sugarcane trash yield 8.79 t ha^{-1} provided equivalent energy of 11.22 BOE ha^{-1} (66.76 GJ ha^{-1}). Also in Brazil, Khatiwada et al. (2012) showed that in yields around 80 t ha^{-1} provide 22.4 t ha^{-1} of the sugarcane trash. The total sugarcane area in Brazil (2011/2012 season) was 8.36 million ha (CONAB, 2011), out of which, Sao Paulo state is responsible for 60.1% of the national production (UNICA, 2012). Assuming the calorific power11.3 GJ t^{-1} for sugarcane trash, São Paulo state can generate 210.4 million BOE (1.251.952 TJ), which can be delivered for consumers.

To obtain sugarcane trash from field, mechanized harvesting is necessary. Several methods are available to perform harvesting. A common harvest processes is composed of windowing, gathering, baling, and transport.

Romanelli et al. (2010) concluded that baling is an energetically viable alternative for collecting sugarcane trash. According this study, baling varied its energy demand from 12% (prismatic bales) to around 26% (cylindrical) of the total energy requirement, while transportation was responsible from 50.3% to 72.5% of the demanded energy. Collecting sugarcane trash without expending energy on increasing density requires mechanized processes, such as windrowing, gathering, and transporting. Due to the importance of sugarcane sector in the Brazilian energy matrix (23% from biomass; EPE, 2012) and potential of co-generating electricity from sugarcane trash, this study aimed to determine the material and energy flows for the sugarcane trash collection and to identify its critical steps.

2 Materials and method

Operational data of sugarcane trash collecting system were obtained from Franco (2003), whose study aimed to assess the operational aspects for windrowing, gathering and transport, considering only diesel oil consumption in the energy assessment of the mechanized system evaluated.

The study area is located in Piracicaba, São Paulo state, Brazil (22º40'30" S, 47º36'38" W and altitude of 605 m). The plot area was 9.63 ha and slope of 6.0%. The sugarcane variety grown was RB855113, spaced 1.4 m between rows, in the second cut with yield of 108 t ha^{-1}.

The machines that performed the field test and their technical characteristics are specified in Table 1.

Table 1 Evaluated mechanized operations and their respective agricultural machines

Operation	Machine	Power/kW	Mass/t
Windrowing	Tractor +	65.4	4.35
	Windrow	N.A.	1.22
Gathering	Harvester	353.0	6.50
Transport	Truck	83.1	7.30

Note: N.A. - Not applicable.

The sugarcane trash yield was 23.09 t ha^{-1}, but regarding the clean dry matter, yield decreased to 8.37 t ha^{-1}, with energy equivalent of 121.9 GJ ha^{-1} (i.e. 14.5 MJ kg^{-1} of calorific power).

The mechanized operations performed to obtain sugarcane trash were windrowing, collecting, and transportation. The windrow formed by the machine was, in average, 749-m long, distanced 5.4 m from one another. The material windrowed presented density of 278.5 kg m^{-3} and it was gathered by the harvester (forage harvester adapted with a collecting header), and discharged into a truck wagon (50.1 m^{3} capacity), which took it to the processing local. The distance from the field to the storage was approximately 17.0 km, assuming a diesel consumption of 5.3 km L^{-1}.

The energy flow accounting starts with determining the material flow, which accounts the total quantity of inputs and outputs of the production system (Romanelli and Milan, 2010).

The depreciation of agricultural machinery calculus was based on mass, lifetime, and effective field capacity of the used machinery (Equation (1)).

$$MD = \frac{EI\ Mass}{UL\ EFC} \tag{1}$$

where, MD = energy on machinery depreciation (MJ ha^{-1}); EI = energy intensity of machinery (MJ kg^{-1}); $Mass$ = machinery mass (kg); UL = machinery useful life (h); EFC = Effective field capacity (ha h^{-1}).

The energy flow analysis determines the energy balance, in which the biomass potential can be checked. It also allows investigating the energy return and the energy incorporation of the production system. The energy balance is given by (Equation (2)):

$$EB = Oe - Ie \tag{2}$$

where, EB = energy balance (MJ ha^{-1}); Oe = total energy output (MJ ha^{-1}); Ie = total energy input (MJ ha^{-1}).

The net energy ratio provided by a system and the total energy consumed by the system is called EROI - energy return on energy investment (Murphy and Hall, 2011) (Equation (3)).

$$EROI = \frac{Oe}{Ie} \tag{3}$$

where, $EROI$ = energy return (non-dimensional); Oe = total energy output (MJ ha^{-1}); Ie = total energy input (MJ ha^{-1}).

To relate the energy consumed by the system with its productivity, energy intensity is used. The energy intensity is calculated by the total energy consumed and the total volume of grain produced by crops ratio, according to Equation (4).

$$EI = \frac{Ie}{Yield} \tag{4}$$

where, EI = energy intensity (MJ kg^{-1}); Ie = total energy input (ha^{-1}); $Yield$ = yield (kg ha^{-1}).

Output energy is a result from the available biomass and its calorific power (Equation (5)).

$$Oe = Yield\ CP \tag{5}$$

where, CP = calorific power (MJ kg^{-1}).

Input energy is the sum of machinery depreciation and fuel required to collect the sugarcane trash (Equation (6)).

$$Ie = \mathrm{MD} + (FC\ EI_{Fuel}) \tag{6}$$

where, FC = fuel consumption (L ha^{-1}), from Franco (2003); EI_{Fuel} = energy intensity of fuel (MJ L^{-1}).

A sensibility analysis was done to verify the influence of the factors in the energy flow. Singly for each factor, decrease of the 10% was applied and a new input energy value was calculated (Marshall, 1999).

To show other results from sugarcane trash-collecting system, data from Romanelli et al. (2010) where sugarcane straw collection with two distinct kinds of balers (prismatic and cylindrical) was evaluated and the three kind of windrowing (single, double and triple), were used to compare the results.

3 Results and discussion

Through the information collected from Franco (2003), one could obtain the flowchart of sugarcane trash collection system that was analyzed (Figure 1).

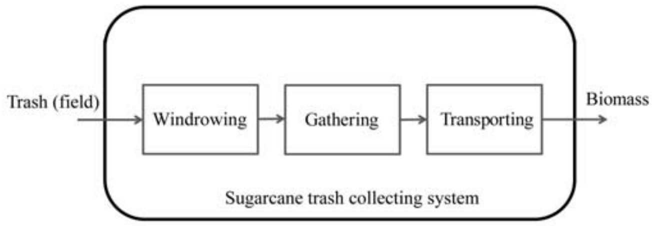

Figure 1 Operational flowchart for sugarcane trash collection system

Gathering was the operation that required the greater amount of input energy of the studied systems, with 1,340.89 MJ ha^{-1} (80.3%), followed by transportation with 189.23 MJ ha^{-1} (11.6%) and windrowing with 134.5 MJ ha^{-1}(8.1%) (Table 2).

The higher energy demand of the gathering process is justified by the engine power of the harvester, which is approximately 5.3 times higher than the power of the tractor used to pull the windrow and 4.2 times higher than truck's power (Table 1). Among the inputs analyzed, it was noted that fuel is responsible for 93.1% of the total energy input. Michelazzo and Braunbeck, (2008) reported the transported distance (influencing directly fuel consumption) and the low density of bulk loading as the main factors for increasing operational energy requirements. Therefore, to improve efficiency, strategies for optimizing routes should be taken in order to reduce fuel demand. An algorithm to generate routes in bale collecting was developed by Gracia et al.(2013), whose experimental results have showed that 15% can be reduced in the total distance when compared with the usually route, reducing fuel consumption and working time.

Table 2 Energy flows for the sugarcane trash harvest

Operation	Inputs	Material flow		Energy Index /MJ unit^{-1}	Energy flow
		Quantity /unit ha^{-1}	Unit		Total /MJ ha^{-1}
Windrow	Depreciation (Machinery)	0.09	kg	68.90*	6.37
	Fuel (diesel)	2.80	L	45.67**	127.67
Gathering	Depreciation (Machinery)	0.93	kg	68.90*	64.15
	Fuel (diesel)	27.96	L	45.67**	1,276.74
Transport	Depreciation (Machinery)	0.71	kg	68.90*	48.04
	Fuel (diesel)	3.21	L	45.67**	146.49
Total Energy input					1,669.47
Output Biomass	Sugarcane Trash	8,370.00	kg	14.57***	121,915.50

Note: *(Ulbanere and Ferreira, 1989); ** (Boustead and Hancock, 1979); *** (Franco, 2003).

The harvested biomass provides unit energy of 121.9 GJ ha^{-1} and the amount spent to collect it represents 1.36% of this value, resulting in a positive energy balance (Table 3).

Table 3 Energy efficiency indices of the sugar cane trash collecting system

Index	Value	Unit
Energy balance	120.24	GJ ha^{-1}
Energy return on investment	73.02	-
Energy intensity	14.56	MJ kg^{-1}

The energy balance indicates that the process is viable from the energy perspective. For every unit of energy invested there is a return of 73.02 units of energy, as demonstrated by EROI. Ripoli and Gamero (2007) also found positive values regarding the system's energy efficiency for collecting sugarcane trash. Energy intensity indicates that sugarcane trash (biomass) consumes 0.199 MJ kg^{-1}, while it provides 14.5 MJ kg^{-1} as calorific power.

Although the indicators showed that sugarcane trash collection system is energetically feasible, is worth noting that, if the inputs that compose the sugarcane cultivation operations were taken into account, the ratios would be adversely affected. However, the sugarcane trash is a by-product, which is available after the crop harvest. So, only inputs that involve the sugarcane trash handling in its collection were taken into account.

Among the inputs that compose the system, the simulation scenario provided by sensitivity analysis shows that the fuel consumption in harvesting is the operation that affects the most the energy input (Table 4).

Table 4 Total energy for standard system and simulated scenarios

Scenarios			Total energy input simulated/%
Operations	Inputs	Alteration	
Standard		0.00	100.0
Windrow	Depreciation (Machinery)	-10%	99.9
	Fuel	-10%	99.2
Gathering	Depreciation (Machinery)	-10%	99.6
	Fuel	-10%	92.3
Transport	Depreciation (Machinery)	-10%	99.7
	Fuel	-10%	99.1

A 10% reduction in fuel consumption in gathering operation, would save 7.7% of the total energy consumption, when compared to the initial condition. Thus, the actions in order to minimize the energy consumption should be focused on gathering operation. Other simulated scenarios provided similar results, resulting in less than 1.0% reduction of the standard condition. According to Börjesson (2009), the use of the more fuel-efficient tractors, as well as more efficient cultivation and manufacture of fertilizers, can reduce the total energy input trough of the minor fuel consumption.

Romanelli et al. (2010) evaluated sugarcane straw collection with two distinct kinds of balers (prismatic and cylindrical) and the kind of windrowing (single, double and triple). The options studied were: P/S (prismatic bale and single windrowing), P/D (prismatic bale and double windrowing), P/T (prismatic bale and triple windrowing), C/S (cylindrical bale and single windrowing) and C/D (cylindrical bale and double windrowing). The harvested sugarcane had a yield of

78 t ha^{-1}. The machinery used in the operations was: Tractor 4x2 FAT (90 kW, 6100 kg); Windrow (358 kg), Conventional sugarcane loader (55 kW, 2,300 kg); Prismatic baler (6,650 kg), and Cylindrical baler (2,452 kg). The energy flows for the five evaluated options for the straw collection showed the importance of transportation in the process (Table 5). The average energy demand for transportation was 51.4% for the prismatic and 69.5% for cylindrical. Loading was the less energy intensive operation. The energy required for baling was higher in the prismatic bale treatments (from 25.4% to 28.6%). The authors explained this variation due to the power demanded to pressure the prismatic bales (211 kg m^{-3}) which were denser than the cylindrical ones (185 kg m^{-3}). The disadvantage during the baling is compensated by transportation, since loads of prismatic bales occupy the truck more efficiently. Labor and machinery depreciation did not present major importance on the energy demand, indicating that improvements should be focused on baling and transporting. The highest energy demand was presented by the double windrowing treatment (highest bale yield). The net energy value for the collected straw was 17.01 MJ kg^{-1}, directly applied to the bale yield, providing the output energy. The highest energy balance came in the treatment C/D, followed by P/D, C/S, P/T and P/S. So although C/D has showed the highest demand, it is the best energy source since it delivers more energy to be used by the boiler and provides the less intense straw (188.7 MJ t^{-1}). The best energy balance occurs because the energy output in C/D was 190.3 GJ ha^{-1}, from the highest yield. Collecting straw, without compressing it, demanded 199.0 MJ t^{-1}, close to the value found in treatment C/D. The scenario (C/S) presented energy intensity 3.2% higher, with transport being responsible for 66.5% of the energy demand (Table 5).

The energy demand for transportation was 66.5% and the loading (7.0%) was the less energy intensive operation. The energy required for baling was 14.9%, to obtain 185 kg cm^{-3}density in cylindrical bale. The disadvantage during the baling is compensated by transportation, since loads of cylinder bales occupy the truck more efficiently.

Table 5 Energy indicators in the straw collection through baling (Adapted from Romanelli et al., 2010)

Harvest	Mechanized Operation	Total MJ ha^{-1}	Total %	Yield /t ha^{-1}	Energy Intensity /MJ t^{-1}	Energy balance /GJ ha^{-1}
C/S	Windrowing	198.8	11.7			
	Baling	253.5	14.9			
	Loading	118.9	7.0			
	Transport	1134.6	66.5			
Total		*1705.8*	100.0	*8.3*	*205.5*	*139.1*
C/D	Windrowing	231.8	11.0			
	Baling	229.9	10.9			
	Loading	118.9	5.6			
	Transport	1533.4	72.5			
Total		*2113.9*	100.0	*11.2*	*188.7*	*188.3*
P/S	Windrowing	198.8	12.8			
	Baling	445.1	28.6			
	Loading	118.9	7.7			
	Transport	791.0	50.9			
Total		*1553.8*	100.0	*7.2*	*215.8*	*120.7*
P/D	Windrowing	236.0	12.8			
	Baling	509.2	27.7			
	Loading	118.9	6.5			
	Transport	973.6	53.0			
Total		*1837.7*	100.0	*8.9*	*206.5*	*148.7*
P/T	Windrowing	265.3	16.8			
	Baling	402.3	25.4			
	Loading	118.9	7.5			
	Transport	796.5	50.3			
Total		*1583.0*	100.0	*7.2*	*219.9*	*121.6*

A benchmarking between results from this work (bulk transport) and the results from (Romanelli et al., 2010) showed that in both cases the yield was 8.3 t ha^{-1} and the total energy input in bulk transport was less than total energy in balling transport. Concerning the mechanized operations, the windrowing operations have a similar energetic demand. For this study, the gathering operation, collect and cut the sugarcane trash, consuming 80.3% of the total energetic demand and the transport operation just 11.6%. Romanelli et al. (2010) showed that baling and loading operations together consumed 21.9% and the transport 66.5%. Ripoli et al. (2005) have concluded an energetic feasibility for the simple and double windrowing system in sugarcane trash baling. In this study, for the evaluated conditions, the bulk method was viable, as well as other studies cited. Therefore, the mechanized sugarcane trash harvest can be considered as a feasible option.

The biomass use has been studied and reported as an important energy source, an alternative to fossil fuels. It has tremendous potential to generate surplus electricity (Macedo et al., 2001; Khatiwada et al., 2012). However, this potential in turn can potentially promote negative environmental, social, and economic impacts. In this study, the results indicate the feasibility of sugarcane trash collection, indicating that more studies should be done in order to promote the use of biomass trash as well as improving the efficiency indices.

4 Conclusion

The sugarcane trash collection system is feasible from an energetic view. Among the windrowing, gathering and transport operations, for sugarcane straw collection, gathering presented the highest energy demand. Fuel consumption in harvesting should be reduced to decrease the energy demand.

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