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ENGINEERING SCIENCES

Whole-plant corn silage harvesting modalities: energy efficiency and operational performance

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Abstract: The need for energy rationalizing in farming operations require research that optimize grain crop conduction. The operations used in the processing and production of silage have limitations in energy optimization due to the lack of studies. This paper evaluated energy efficiency of whole-plant silage operations with the objective of favor the decision making. The adopted design of the experiment was in parcels (with seven replications), consisting of three harvesting modalities: single-line forage harvester, total area forage harvester, and total area forage harvester with support transshipment. The tractors were instrumented with sensors that measured engine rotation, travel speed, and hourly fuel consumption which were used to calculate field capacity, fuel consumption per area and per harvested mass, and production capacity of the harvester-tractor set. The results went to analysis of variance and subsequently to Tukey's test. The single had a faster speed and lower hourly fuel consumption, but smaller field capacity and greater energy expenditure for the mass. The use of support transshipment set with the front harvester allowed an improvement in the operation, with an increase in the worked area, and material processing (18%), and speed (13%), without differing in fuel expenditure. The total-area forage harvester modality showed smaller costs (USD 6.7), followed by the total-area forage harvester with support transshipment set (USD 7.7) and the single-line forage harvester (USD 9.38), respectively. The use of forage harvesters with a wider working width proved to be more efficient in terms of production costs per harvested hectare, validating it's reccomendation.

Key words: Ensilage, fuel consumption efficiency, preserved forage, productivity.

INTRODUCTION

Silage making is a process that involves the harvesting and storage of moist forage, cereals, or their byproducts, with subsequent fermentation. It is widely used in animal feed as a conserved source of nutrients being largely intended for the diet of high-yielding and productive dairy cattle, and as a supplementary food in times of low pasture availability (Ferraretto et al. 2018, Wilkinson & Rinne 2018).

Studies conducted by Bernardes & Do Rêgo (2014) showed that 82,7% of the milking farms in Brazil use maize silage, followed by sorghum, tropical grass crops (Panicum and Brachiaria genus), and sugar cane. The country uses nearly four million hectares to grow silage maize, making this process fundamental to the milk and meat industries, according to Daniel et al. (2019).

Corn (*Zea mays* L.) is the main crop used to produce whole-plant silage and must be harvested when the percentage of dry matter ranges from 30% to 35% in order to obtain better quality silage

(Ferraretto et al. 2018). Allied to this factor, the silo filling time becomes an important factor, aiming to reduce the period of exposure to the external environment, mitigating oxidation, preserving the plant's sugars, and promoting correct fermentation of the material (Mills & Kung Jr. 2002).

The main types of maize silage are high humidity, rehydrated grain, and snaplage (Bernardes et al. 2018). According to Ferris et al. (2022), the outstanding practices for corn silage relate to the number of forage cuts, used equipment, and outsourced workforce. High harvesting frequency results in better nutritional quality, so it is usual to make three cuts due to equipment limitations. The silage processing reduces the material nutritional loss during the stocking period. It also results in easier feeding and allows adding compound cattle feed, improving the diet's nutritional efficiency (Grant & Ferraretto 2018).

Sealing the mass during silage stocking is fundamental to reducing deterioration and maintaining its quality. Low-permeability-to-oxygen barriers address this matter if adequately fixed on the stocking structure (Borreani et al. 2018). The purposes of silage stocking are food availability during the winter, feeding confined animals, and reducing compound cattle feed uses to minimize costs.

The current model of agriculture requires that farmers optimize the use of supplies in cultivation areas to increase profit, which can be achieved through the adoption of new technologies (Feitosa et al. 2018). In this matter, the technologies on silage processing machinery improved in the last decades (Mostafa et al. 2020), especially in individual lines and total area harvesters, with the later one having a greater processing capacity. In the Brazilian market, single and double-line harvesters are more usual due to their low price. However, they have operational and energetic limitations besides the material quality in the terms of construction (Daniel et al. 2019), causing their replacement by total area harvesters.

This type of equipment allows precision cutting, uniformizing the particles, and improving nutritional nourishment compared to single-line options. If the particles are excessively long or non-uniform, the munching period before swallowing gets longer, making their size optimization elementary. In this scenario, the cattle's eating period increases, raising energy consumption, as described by Grant & Ferraretto (2018).

A well-planned biomass production using an efficient process result in significant economic, environmental, social, and energetic benefits (Sun et al. 2020). The logistics of producing silage relate to the simultaneous harvesting, transportation, and compaction (Busato et al. 2019). Thus, the appropriate selection of harvesting sets must be based on field efficiency, not only promoting an increase in productive capacity, but also reducing fuel consumption and polluting gases, making the process more sustainable (He et al. 2019).

In this context, due to the need to optimize whole-plant harvesting of silage based on a higher operational yield, this paper aimed to evaluate the energy efficiency of two whole-plant harvesting machines for corn silage.

MATERIALS AND METHODS

Study site

The experiment was conducted in an environmental preservation area, Pinhais, PR, Brazil (latitude 25° 23' S; longitude 49° 07' W; 911 m a.s.l.). According to the Köppen climate classification, the local

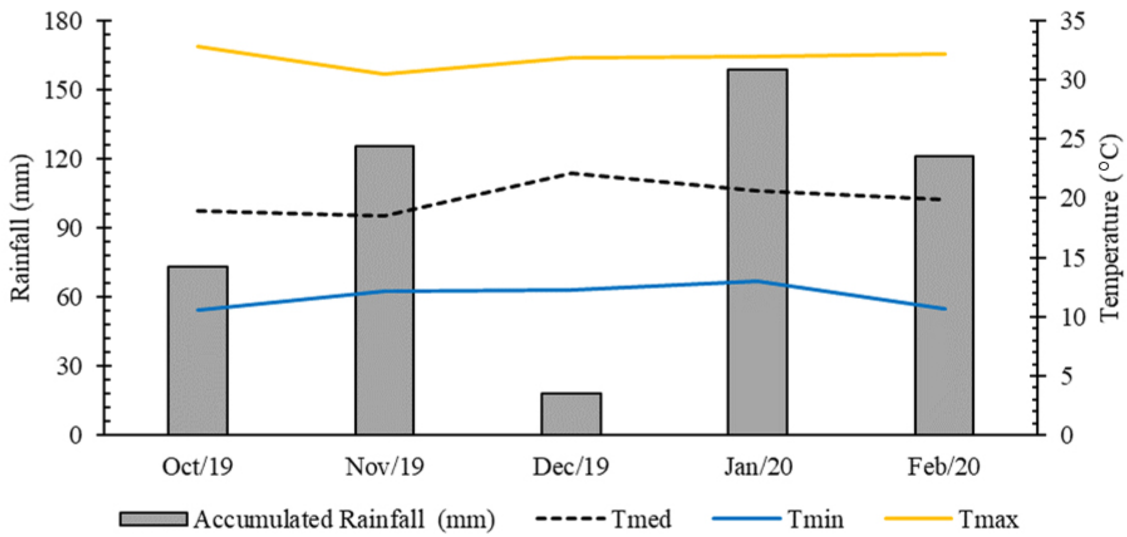

Figure 1. Daily variation of measured mean (T_{med}), minimum (T_{min}) and maximum (T_{max}) air temperature, and rainfall throughout the experimental period.

climate is Cfb (temperate oceanic climate), with well distributed precipitation throughout the year and an annual average temperature below 22 °C (Alvares et al. 2014). Data of mean, minimum and maximum air temperature, and precipitation accumulated throughout the experimental period were collected from an automatic standard weather station located near the experimental field (Figure 1).

The soil classifies as an Oxisol Red-Yellow Alic with a slope of 5% in the harvest direction. The area received conventional soil preparation, with an intermediate harrow and a following grading harrow. The base and cover fertilizations were 350 kg ha^{-1} of NPK 08-20-20 and 400 kg ha^{-1} of urea (46% nitrogen), respectively, applied 45 days after sowing. The 0.5 ha experimental field was planted by a seeder with a mechanical seed distribution system equipped with double discs openers for creating two seed furrows. These received 60 thousand seeds by hectare, with the maize cultivar Biomatrix BM950PR03 at a row spacing of 0.80 m and with 4.37 seeds per linear meter, resulting in a plant density of 5.46 plants m^{-2}, as recommended by the seed company, due to a survival rate of 90%, as clarified in the packaging.

Experimental design

The plants were harvested and converted into silage 120 days after sowing, as recommended by Ferraretto et al. (2018), when the plants achieve 32 to 35% of dry mass. To measure the humidity, an approximation with the method of dry matter determination was used, in which 100 g of the material cooled at 60°C for 72 hours were dried, with subsequent weighing of the dry material, according to De Carvalho Benini et al. (2020).

For the processing of silage, two forage harvesters from the Brazilian manufacturer JF Máquinas Agrícolas were used: model C120, consisting of a single-line lateral harvester; and model 2000 AT, consisting of a total area frontal harvest, as shown in Table I. Both machines had 12 cutting blades, regulated to cut a particle size of 4x10^{-3} m, by changing the space between the knives, according to the methodology proposed by Kononoff et al. (2003), but not equipped with a grain crusher.

Two tractors were used, a Case Farmall 80 and a New Holland T6 130, whose technical specifications are shown in Table II. Therefore, two harvester–tractors sets were formed: A) the JF C120 harvester and the Case Farmall 80 tractor; and B) the JF 2000 AT harvester and the New Holland T6 130 tractor.

The static load of sets A and B were measured with the harvesting equipment in the working position using a CM-1002 scale (Celmi Inc., PR, Brazil), consisting of four 0.40 x 0.46-m load cell shoes, totalizing 32Mg of weight capacity and a precision of ± 4kg (Table III).

For the tractor of set A, GII M1 gear was adopted, with an engine rotation of 2,100 RPM, obtaining 540 RPM in the rear power take-off. Additionally, for the tractor of set B, the GI M1L gear was adjusted to guarantee 1,000 RPM in the front power take-off, meaning 2,200 RPM in the engine. Both tractors had full fuel tanks at start and their auxiliar front-wheel drives were activated during the experiment.

The experimental design adopted was in blocks, consisting of three treatments (harvesting modalities): T_{SL}) single-line forage harvester; T_{TA}) total area forage harvester; and T_{TAS}) total area forage

Table I. Detailed technical silage harvesters specifications.

Model	No.Knifes	No.Rotor	Nº Feed rolls	TDP (rpm)	Mass (kg)	Productivity (ton/ha)*
JF C-120	12	1	4	540	615	Up to 30
JF 2000 AT	24	2	8	1000	1850	Up to 48

*** Productivity can vary with factors such as cutting size, mass per hectare, availability per forage wagon, and tractor potency.**

Table II. Tractors technical specifications.

Tractor	Case Farmall 80		New Holland T6 130	
Nominal power (kW)	58.84		97.08	
Traction type	4 X 2 AFWD*			
	Front tire	**Rear tire**	**Front tire**	**Rear tire**
Tire type and size	Goodyear 12.4 - 24	Goodyear 18.4 - 20	Goodyear 14.9 - 28	Pirelli 18.4 - 38
Tire pressure (kPa)	137	110	220	110

*** AFWD – Auxiliar front-wheel drive.**
Anticipation index: 2.37% Case Farmall 80 and 3.02% New Holland T6 130.

Table III. Static mass specifications of the A and B harvester-tractor sets.

	Added solid ballast (kN)		Load (kN)		Total mass (kN)
	Front	Rear	Front-axle	Rear-axle	
Set A	1.766	0.981	14.558 (34)	28.292 (66)	42.821
Set B	-	9.025	56.211 (69)	25.261 (31)	81.472

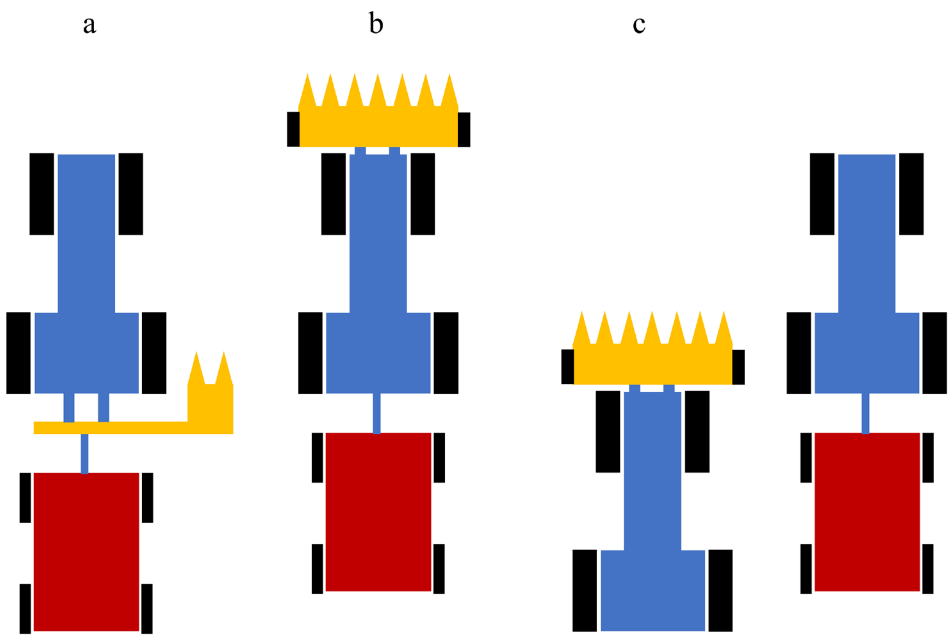

Figure 2. Schematic representation of harvesting modalties T_{SL}(a); T_{TA} (b); and T_{TAS} (c).

harvester with support transshipment. The T_{SL} treatment used the harvester–tractor set A, while treatments T_{TA} and T_{TAS} used set B. Seven repetitions were performed, and each repetition consisted of collecting data for a 20 m of tarvel distance, totalling 21 experimental units.

For T_{SL} and T_{TA}, the collected material's flows were carried in a 13 m^3 transshipment trailer, which was attached to the tractor drawbar (Figures 2a-b). Moreover, once the trailer was full, the harvest was interrupted, and the drawbar was uncoupled and replaced by another tailer of the same volumetric capacity. For T_{TAS}, the material's flow was carried without interruption, in a 13 m^3 transshipment trailer at the overflow system, which was coupled to the drawbar of a 57 kW tractor, forming the support set (tractor–trailer) (Figure 2c). The support set moved as a transshipment, laterally to set B, and, when the volume was complete, there was a replacement of another support set of the same capacity.

Evaluated parameters

Initially, the tractors in both sets were instrumented with sensors connected to a printed circuit board data acquisition system (DAS), with an acquisition frequency of 1 Hz (Jasper et al. 2016).

The first parameter monitored was the engine rotation (E_R), obtained by reading the "W" connector of the tractor alternators through the digital channel in the DAS. For tractors in sets A and B, linear equations ($R^2 > 0.99$) indicated that each pulse represented 4.04 and 3.65 RPM, respectively.

The operational velocity (V_O) was determined using a speed sensor, SVA-60 (Agrosystem Inc., SP, Brazil) with an accuracy of 1×10^{-2} m s^{-1}, using the number of pulses emitted by the sensor during the experiment.

Hourly fuel consumption (FC_H) was measured using two flowmeters, MIII LSF41 (Oval Corp., Tokyo, Japan), accurate to 1 cm^3, installed in the tractors' fuel supply systems (inlet and return to tank). The fuel consumption was given by the difference in the number of pulses between the flowmeters, later converted into volume (1 pulse equivalent to 1 cm^3). Moreover, this parameter was measured in all tractors used in the experiment, including the tractor used as the support set in T_{TAS}. It is emphasized that for T_{TAS}, FC_H was obtained from the sum of partial hourly fuel consumptions of B and support sets.

The efficiency of operation (η) was determined based on the methodology proposed by Mialhe (1974) and ASABE (2011), by monitoring the time spent in the silage harvesting activities: harvest operation, trailer change, maneuvers at the ends of the area, blade sharpening, and maintenance.

The operational field capacity (F_C) was calculated according to Equation 1. For this, effective working width (E_W) values of 0.8 and 2.4 m were adopted for sets A and B, respectively.

$$F_C = \frac{V_O \cdot E_W \cdot \eta}{10} \tag{1}$$

where, F_C is the operational field capacity (ha h^{-1}), V_O is the average operating velocity (m s^{-1}), E_W is the effective working width (m) and η is the efficiency of operation (decimal).

Fuel consumption per worked area (FC_A) was calculated by the ratio between FC_H and F_C:

$$FC_A = \frac{FC_H}{F_C} \tag{2}$$

where, FC_A is the worked area fuel consumption (L ha^{-1}) and FC_H is the hourly fuel consumption (L h^{-1}).

The amount of fuel used per unit of harvested silage mass (FC_M) was obtained using the product between FC_A and the mean crop productivity (P) (Eq. 3). For sets A and B, respectively, P was 28.6 and 34.3 Mg ha^{-1} of wet mass harvested. Furthermore, these values were measured after the harvest of each experimental block, using the shoe scales described above.

$$FC_M = FC_A \cdot P \tag{3}$$

where, FC_M is the fuel consumption per harvested mass (L Mg^{-1}) and P is the mean crop productivity (Mg ha^{-1}).

Finally, the production capacity of the set (P_C) was determined by the product between F_C and P:

$$P_C = F_C \cdot P \tag{4}$$

where, P_C is the production capacity of the set (Mg h^{-1}).

The silage production total cost analysis followed the methodology of Jasper et al. (2009), covering fixed (depreciation, tax rates, storage and insurance) and variable parameters (maintenance repairs, fuel, lubricants, grease, salary and social taxes), according to Table IV.

Table IV. The silage production total cost analysis covering fixed and variable parameters.

Depreciation		Fixed costs			Variable costs		
		Taxes	**Insurance**	**Maintenance**	**Fuel**	**Charges**	
TSL	Tractor	6.4	2.5	0.7	3.9	10.4	8.3
	Harvester	6.4	1.2	0.1	3.4	-	-
TTA	Trator	10.7	4.2	1.2	6.4	25.8	8.3
	Harvester	20.8	3.8	0.3	11.1	-	-
TTAS	Trator	17.1	6.8	1.8	10.4	30.1	16.6
	Harvester	20.8	3.8	0.3	11.1	-	-

Single-line forage harvester (TSL); total area forage harvester (TTA); and total area forage harvester with support transshipment (TTAS). Quotation Brazil R$ 5.19 / 1 USD (19/01/2023).

The data collected from the described parameters were assessed for normality by the coefficients of kurtosis and asymmetry. Given the assumptions, the analysis of variance (ANOVA) was submitted and, when significant, Tukey's test. The statistical analysis was performed using Sigmaplot 14 software (Systat Software Inc., CA, USA).

RESULTS AND DISCUSSION

Table V shows the results of the ANOVA and the means test for the parameters analyzed. The evaluated parameters showed normal distribution, because, according to Montgomery (2004), when the coefficients of symmetry and kurtosis are in the range of −2 to 2, the data can be considered normal. According to the classification proposed by Ferreira (2018), C_V values were lower than 10% for variables, resulting in great experimental precision. Therefore, it can be observed that among the modalities of whole-plant silage harvesting evaluated, all the parameters analyzed presented a statistical difference, except for the parameter referring to fuel consumption per area worked (FC_A).

The efficiency values, determined as described, served as the basis for the other parameters presented. The values calculated and adopted in the experiment were 72%, 79%, and 85% for T_{SL}, T_{TA}, and T_{TAS}, respectively.

Roeber et al. (2017) pointed out that a tractor's power take-off is the main coupling mechanism for transmitting energy from the engine to the implement and is still widely used due to the high

Table V. **Analysis of variance synthesis and mean test for the evaluated parameters.**

	Evaluated parameters						
Analysis	**E_R (RPM)**	**V_O (m s^{-1})**	**FC_H (L h^{-1})**	**F_C (ha h^{-1})**	**FC_A (L ha^{-1})**	**FC_M (L Mg^{-1})**	**P_C (Mg h^{-1})**
Kurtosis (%)	−1.59	−1.13	−1.48	−1.63	−0.05	−0.07	−1.62
Asymmetry (%)	−0.65	−0.04	−0.58	−0.47	0.50	1.04	−0.52
CV (%)	0.70	5.29	6.21	7.00	11.91	0.27	7.23
LSD	21.91	0.23	1.88	0.04	8.17	12.50	1.53
F-test	182.73**	64.74**	400.72**	318.04**	0.41^{NS}	4.29*	375.01**
T_{SL}	2,091 B	1.01 A	9.95 C	0.21 C	47.46	1.66 A	6.02 C
T_{TA}	2,224 A	0.73 C	24.82 B	0.50 B	49.67	1.45 AB	17.30 B
T_{TAS}	2,231 A	0.84 B	28.94 A	0.61 A	47.14	1.37 B	21.08 A

Parameters: engine rotation (E_R), operational velocity (V_O), hourly fuel consumption (FC_H), operational field capacity (F_C), worked area fuel consumption (FC_A), fuel consumption per harvested mass (FC_M), production capacity of the set (P_C). Single-line forage harvester (TSL); total area forage harvester (TTA); and total area forage harvester with support transshipment (TTAS). C_V – coefficient of variation. LSD – least significant difference. F-Test of the analysis of variance (ANOVA): NS - Not significant; *p < 0.05 and **p < 0.01. In each column, for each factor, means followed by the same capital letters do not differ according to Tukey's test (p < 0.05).

efficiency values obtained in this form of transmission, reaching up to 90% according to ASABE (2015). Variations in E_R can interfere with an implement's correct operation, since the transmission relationship between the engine and the power take-off is made through gears, in addition to higher engine rotations promoting greater torque available in the power take-off (Kim et al. 2013). The E_R was lower in T_{SL} and the same for T_{TA} and T_{TAS} (Table V). This can be explained by the sets used, since set B was used in T_{TA} and T_{TAS}, which only varied the flow of the collected silage, with different results not expected between these modalities.

The V_O parameter was higher for T_{SL} by 38% and 20% in relation to T_{TA} and T_{TAS} modalities, respectively (Table V). However, when analyzing the harvester of set B, the T_{TAS} presented a 15% increase in the travel speed in relation to T_{TA}, due to the energy demand necessary for the transshipment trailer traction having been transferred to the support tractor, which allowed the tractor of set B to provide greater energy for moving and processing material in T_{TAS}. This result was confirmed by Simikic et al. (2014), who, when studying different forces on the drawbar, concluded that the force pulled on the drawbar is inversely proportional to the travel speed.

Fuel consumption in the harvest process is directly related to the feed rate and the type of material being processed (Tieppo et al. 2019). The FC_H parameter was lower in the single-line harvest modality, since set A had a less powerful tractor and less mass in relation to the components of set B. A similar result was found by Tavares et al. (2017) in a study using a tractor with the same power range as set A with an implement coupled to the power take-off. For the other harvesting modalities that used set B, it is noted that T_{TAS} accounted for the highest fuel consumption, being 16.6% higher compared to T_{TA}, where the tractor of the set itself pulled the trailer (Table V).

The F_C had a lower result for the harvest in a single line, which even with a higher V_O, had a smaller working width, reflecting the lower average of F_C between harvesting modalities (Table V). A similar result was found by Farias et al. (2018), who, when evaluating different implements for soil preparation, concluded that the increase in working width allows reaching larger areas worked in the same period, compensating for differences in travel speeds. Among the modalities of total area harvesting, the one that had support (T_{TAS}) showed a F_C 22% higher than the other (Table V), because of the faster travel speed and the greater efficiency obtained in the operation due to the use of the transshipment set, and as a consequence, the harvest interruption time was shorter. The use of the set of T_{TAS}, presented an operational capacity 290% higher than T_{SL} due to the greater working width, providing an increase in the area worked in less time (Martins et al. 2018). Mahl et al. (2004) demonstrated that the increase in the speed of displacement of the group promotes an increase in the field capacity, which may lead to a reduction in operational consumption.

Regarding the FC_A parameter, the energy consumption per mass of plant harvested was similar by using single-line and total area harvesters when both pulled the trailer (Table V). The modalities of harvests in the total area (i.e., T_{TA} and T_{TAS}) also did not show differences in the energy consumption per mass of plant harvested, even with the use of an additional tractor for the support set. Furthermore, this fuel expenditure in T_{TAS} was 17.4% lower than in T_{SL}, demonstrating that the use of larger equipment, with greater productive capacity, promotes better efficiency in the use of fuel (He et al. 2019).

The production capacity values of the set (P_C) were higher for the total area harvesting modality with support, due to the greater working width and faster travel speed (Table V). Ramos et al. (2016) points out that an increase in travel speed leads to greater harvesting capacity for the group. In the

Table VI. Synthesis of the total cost of production analysis.

Modalities	Production cost per harvested hectare	Production cost per harvested megagram
TSL	USD 268.24	USD 9.38
TTA	USD 228.33	USD 6.7
TTAS	USD 262.49	USD 7.7

Single-line forage harvester (TSL); total area forage harvester (TTA); and total area forage harvester with support transshipment (TTAS). Quotation Brazil R$ 5.19 / 1 USD (19/01/2023).

present work, the use of transshipment in the support set allowed a 21.8% increase in the material handling capacity, that is, processing of the entire corn plant.

Table VI shows the difference between modalities, with the total cost per hectare of USD 268.24 for TSL, USD 228.33 for TTA, and USD 262.49 for TTAS. The higher cost per area of TSL compared to TTA (USD 39.91) and TTAS (USD 5.75) is due to its lower operational/energetic capacity and yield, justifying the addition of USD 2.68 Mg^{-1} from the TTA set to TSL. According to Ferris et al. (2022), the total area harvester shows greater material processing capacity and operational yield when compared to single-line ones, affecting production costs.

CONCLUSIONS

The use of silage machinery sets with a greater working width, even if traveling at a lower speed, allowed greater work areas and quantity of material processed per time, without significant variation in fuel consumption per area and less energy expenditure per amount of material harvested.

The use of a support set in the transshipment of the harvested material, with the shortest possible interruption time during the harvest, promoted a greater worked area and material processing capacity by time for the harvester-tractor set, reflected in lower fuel consumption per harvested material.

The total area forage harvester showed lower production costs per harvested hectare and megagram, followed by the total area forage harvester with support transshipment and the single-line model.

To optimize silage production and reduce operating costs, it is recommended to use silage machines with a larger working width, even when operating at lower speeds. Furthermore, it is advisable to use a support set for transshipment of the harvested material, to minimize the interruption time during harvesting. These practices will increase the area worked and the material processing capacity per unit of time, resulting in lower fuel consumption per amount of material harvested. The use of forage harvesters with a wider working width proved to be more efficient in terms of production costs per harvested hectare.

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