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CONTINUOUS AND IMPACT CUTTING SYSTEMS FOR SUGARCANE HARVESTER

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KEYWORDS

Saccharum officinarum, mechanized harvester, damage index, invisible losses.

ABSTRACT

The quality of the basal cut of sugarcane during harvest can affect the longevity of the crop, and the cutting tool is one of the main causes of damage during harvesting. The aim of this study was to evaluate the performance of two cutting tools: an impact cutting system (ICS) using knives and a continuous cutting system (CCS) using saws. Laboratory tests were carried out to obtain the stalk damage index at different device travel speeds and to determine the invisible losses caused by each cutting system. The results showed that both cutting systems presented acceptable levels for the stalk damage index; however, the CCS obtained better cut quality, corresponding with decreased general damage. The invisible losses caused by the cutting tools in relation to the total harvested mass were 0.52% and 0.54% for the CCS and ICS, respectively. The highest invisible losses were obtained at speeds of 2, 3, and 4 km h^{-1} for the ICS, showing a statistical difference in relation to the CCS. No statistical difference was noted for both the systems at 5 and 6 km h^{-1}.

INTRODUCTION

Sugarcane (*Saccharum officinarum*), in addition to the production of sugar and residential alcohol, is considered a great alternative for the production of biofuels; especially ethanol and its by-products. The 2021/22 Brazilian sugarcane yield is expected to be 13.2% lower, due to drought and unusual frost (CONAB, 2021).

Research and development of mechanized sugarcane harvesting presents constant challenges in terms of aiming to rationalize the resources employed, optimize the useful life of the cane fields, and reduce environmental impacts (Stolf et al., 2016; Voltarelli et al., 2018; Bernache et al. 2020).

During mechanized harvesting of this culture, the basal of the stalks are cut by two rotating discs equipped with cutting knives. The discs rotate along the crop line with a convergent motion, simultaneously cutting and feeding the stalks to the internal transport systems of the harvester. This cutting system, causes severe damage to the sugarcane ratoon (Cassia et al., 2014; Silva et al., 2020; Voltarelli et al., 2015; Voltarelli et al., 2017), and in extreme cases completely removes it from the soil.

Damaged ratoons jeopardize crop regrowth in the following cycles and increases susceptibility to attacks by pests and disease (Bernache et al., 2020). Sugarcane harvesting systems are constantly improving, and new crop management and performance alternatives are being applied with the aim of increasing the profitability of the crop and productivity of the field.

According to Martins et al. (2019), the quality of the basal cut is extremely important for the productivity and longevity of the sugarcane field in subsequent years; therefore, this factor affects the economic viability of the crop. Cassia et al. (2014), studied the influence of tool wear on the damage to sugarcane ratoons, and determined acceptable standards.

In order to reduce the damage caused to sugarcane crops during mechanized harvesting, new strategies have been proposed for the base cut through the use of serrated blades, as presented by Mello & Harris (2003), obtaining an ideal basal cut in a continuous cutting system. Replacing the impact cutting of knives with a continuous serrated system requires harvester modifications, and easily interchangeable tools.

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Several authors have obtained promising performance results for serrated cutting systems, with less damage to the crop and higher quality during operation. (Liu et al., 2012; Momin et al., 2017; Testa, 2018; Toledo et al., 2013).

A limited number of studies have been carried out under laboratory conditions to evaluate the basal cut of sugarcane, and it is impossible to evaluate the invisible loss caused by these systems without a controlled environment. Li et al. (2013) developed sugar cane cutting and loading studies using a prototype and stated that the costs of testing and development using this model are lower and offer greater control of the processes.

Voltarelli et al. (2015) stated that for field operations to reach adequate control limits, it is necessary to adjust them according to six parameters: the machine, environment, work, method, raw material, and measurement. Studies in a controlled environment allow the isolation of external variables, providing greater consistency in the results of research related to cutting tools (Liu et al., 2012; Mathanker et al., 2015).

Knowledge regarding sources of losses in mechanized harvesting processes is of fundamental importance and these are classified under two categories: visible and invisible. Visible losses can be detected in the field after harvesting, whereas invisible losses are classified as small pieces of the sugarcane, splinters, sawdust, and sugarcane juice that are not directly quantifiable in the field (Neves, 2015).

The aim of this experiment was to evaluate the performance of two cutting tools used to harvest sugarcane; the first one operating by impact (ICS-knives), and the second one operating in a continuous process (ICC-saws), under controlled conditions.

MATERIAL AND METHODS

The experiment was carried out at the Agroforestry Machinery and Tire Testing Center (NEMPA), belonging to the Faculty of Agronomic Sciences of the São Paulo State University's Botucatu campus. An electromechanical device was developed to test the basal cuts of sugarcane.

The device was assembled on a cutting base which was removed from a commercial harvester and adapted to move on rails. A 7.3 kW electric motor was coupled to the top of the cutting system, and rotated the base columns at 600 rpm. The system was attached to the front of an 89 kW, 4 × 2 TDA tractor that moved it at controlled speeds. The tracks were 1.55 m apart and 15 m long. Steel tube supports, in which the sugarcane stalks were fixed, were placed in the ground between the 2 rails and 10 m from the starting end. Twelve sugarcane stalks were arranged in 3 lines. Figure 1 depicts the operation and installation of the system.

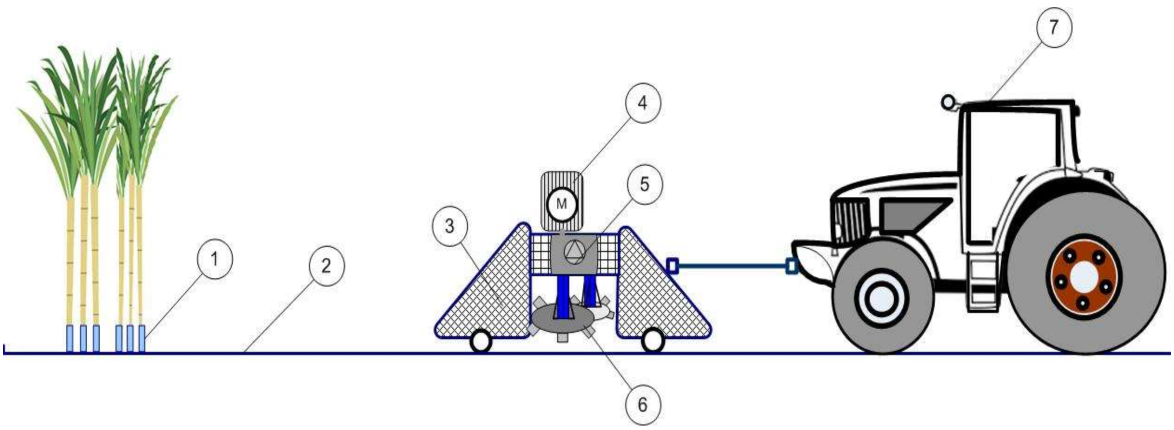


FIGURE 1. Components of the test device for basal cutting of sugarcane (EDBC), 1: tubular steel supports for fixing the cane stalks; 2: steel rail to guide the EDBC device; 3: support for frontal deflection of the stalks before cutting; 4: three phase motor for operating the cutting box; 5: a harvester cutting box and tray support; 6: basal cutting discs with cutting tools; 7: 4 × 2 TDA tractor to move the device.

The EDBC (shown in Figure 2) replicates the mechanized cutting of sugarcane stalks in a controlled environment, and isolating factors such as the surface conditions of the soil, the slope of the terrain, and other covariates of the operation.

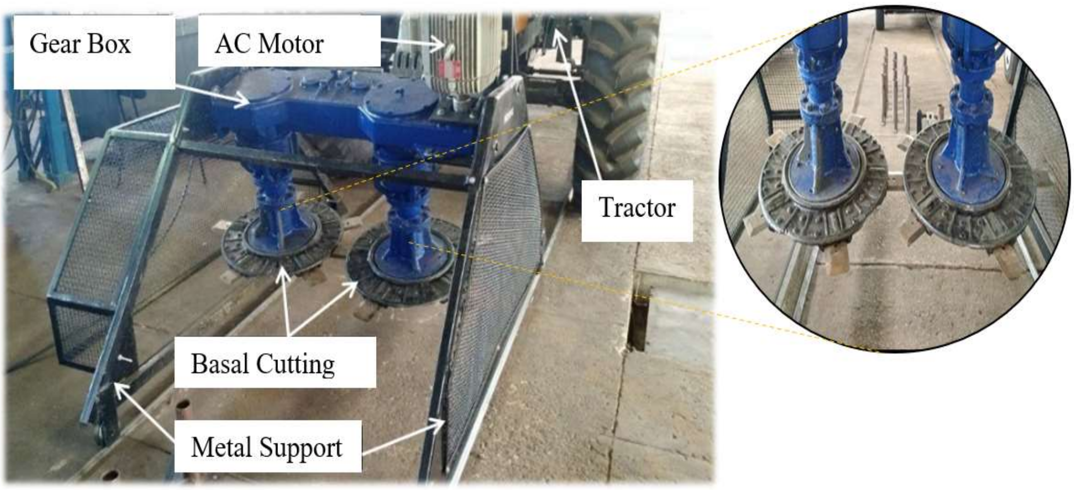


FIGURE 2. Test electromechanical device for basal sugarcane cutting (EDBC).

Unimil steel knives were used in the impact cutting system (ICS). Each knife was 4.75 mm thick, had six holes and could be sharpened at the corners. The cutting device comprised of two circular discs with five knives attached to each (Figure 3 a). The continuous cutting system (CCS) was composed of segmented Kruger saws, model KG3NES, assembled on two rotating discs provided by the manufacturer. Each disc had six semicircular saws, each of which had 21 cutting teeth with a thickness of 4 mm, resulting in a continuous blade (Figure 3 b).

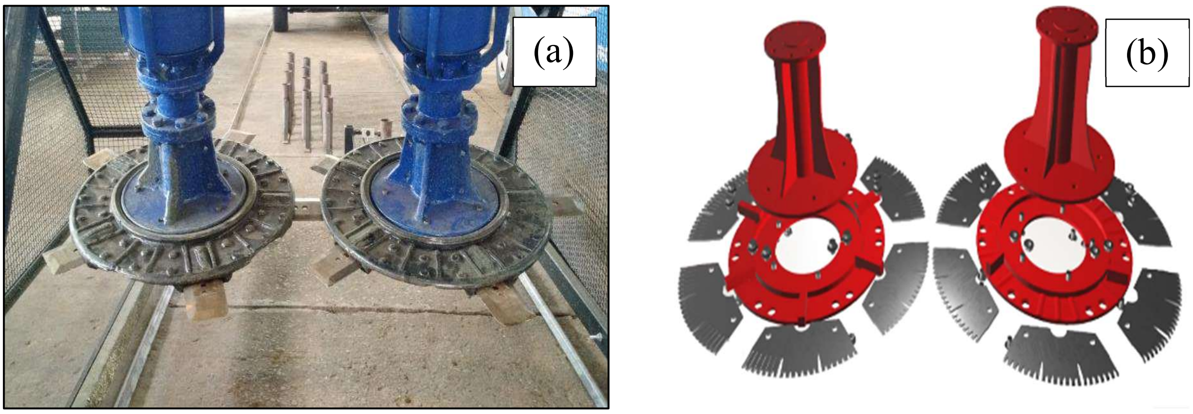


FIGURE 3. a. impact cutting system (ICS); b. continuous cutting system (CCS).

Approximately 300 kg of whole sugarcane stalks (variety: CTC-9004), from a 12 months old, first-cut cane field were used to evaluate the performance of the cutting systems. The sugarcane field was located in Borborema City, São Paulo State, Brazil.

Based on the methodology proposed by Liu et al. (2012), to avoid stalk diameters affecting the results, stalks with a diameter of 30 ± 1 mm were selected, precisely weighed, and numbered at both ends. Average statistical tests were carried out to ensure experimental homogeneity of stalk diameters.

The laboratory tests were divided into two parts: the first determined the damage index of the ICS and CCS cutting tools at five different travel speeds, and the second determined the invisible losses caused by the two cutting systems at the five travel speeds.

Determination of the damage index (ID) in tests with CCS and ICS as a function of travel speed

To determine cut quality as a function of travel speed, stalks with diameters within the standard previously used for the two cutting systems (ICS and CCS) were subjected to five displacement speeds, V1 = 2, V2 = 3, V3 = 4, V4 = 5, and V5 = 6 km h^{-1}, and repeated six times. The fixed parts of the stalks in the tubes were then individually analyzed and classified according to the guidelines shown in Figure 4.

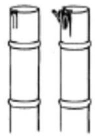
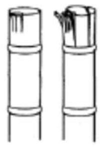
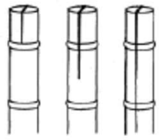
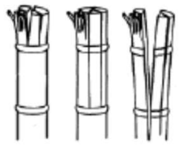
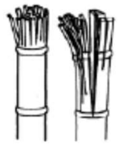
Classification	Lower edge	Upper edge	Weight
Without damage (SD)			-1,00
Partial damage (PD)			0,00
Extreme damage (ED)			1,00

FIGURE 4. Classification of damage caused to sugarcane stumps. Adapted from Melo and Harrys (2003) and Toledo et al. (2013).

Each classification represents a weight used for the formation of the index according to the methodology proposed by Toledo et al. (2013). The damage index represents a way of converting qualitative aspects into quantitative or numerical ones, so the closer the index is to -1.00, the smaller the amount of damage found and inversely, the closer to 1.00, the greater the amount of damage found in the stumps. All analyses were performed by the same evaluator for greater statistical control, and the index was calculated using [eq. (1)]:

$$ID = \frac{p_{SD}.n_{SD} + p_{PD}.n_{PD} + p_{ED}.n_{ED}}{n} \quad (1)$$

Where:

ID is the damage index;

pSD is the weight attributed to the stump without damage;

nSD is the number of stumps without damage;

pPD is the weight attributed to stumps with partial damage;

nPD is the number of stumps with partial damage;

pED is the weight attributed to stumps with extreme damage;

nED is the number of stumps with extreme damage, and

n is the total number of stumps examined.

Determination of invisible losses in tests with CCS and ICS as a function of travel speed

A methodology adapted from Neves et al. (2006) was used for the evaluation of invisible losses. Stalks with a diameter within the previously established standard and 1.5 m long were used, with the upper and lower extremities having been previously numbered for identification after cutting, and weighed. After fixing the stalks to the tubular supports, the EDBC travelled forward at five speeds, V1 to V5, and after cutting, the two parts of the stalk with the same number were brought together and weighed again. The difference between the initial weight (before cutting) and final weight (after cutting) was considered to be the invisible loss of raw material for each tool evaluated.

The experimental design applied to the tests was completely randomized, and the data were analyzed, using descriptive statistics, to assess the quality of the basal cut and the damage index of the stumps. The curves formed by the average stalk damage at different speeds were adjusted using second-order polynomial regression. The average of the results of the invisible losses underwent an Anderson-Darling normality test, analysis of variance, and when applicable, Tukey's test at 5% probability. The loss curves as a function of the five speeds were analyzed by adjusting for linear regression. All statistical tests were performed using the Minitab® statistical software (LLC, USA, v.16).

RESULTS AND DISCUSSION

The average diameter of the selected sugarcane stalks were normally distributed as shown by the Anderson-Darling test, and their average had no statistical differences between the treatments performed, confirming the adequacy of the control design for the co-variable stalk diameter in the study (Table 1). For testing under field conditions, Bernache et al. (2020) evaluated the basal cut of harvesters and found high coefficients of variation in the experiment, concluding that a high dispersion of data is common in tests with mechanized systems.

TABLE 1. Average stalk diameter (m) used in the cut quality test and invisible losses of sugarcane industrialized raw material.

Speed (km h^{-1})	Cut system		Average (m)
	ICS	CCS	
2 (V1)	0.0299	0.0295	0.0297
3 (V2)	0.0304	0.0304	0.0304
4 (V3)	0.0296	0.0290	0.0293
5 (V4)	0.0290	0.0291	0.0291
6 (V5)	0.0292	0.0293	0.0293
Média	0.0296	0.0294	
ANOVA			
F test (Speed)	F test (Cut system)	F test (interaction)	CV (%)
0.89^{ns}	0.42^{ns}	0.03^{ns}	8.2

CV = coefficient of variation; * = significant at 5% probability; "ns" = not significant at 5% probability.

Reis et al. (2015) stated that the interdependent processes and variables are difficult to control in the field. The low coefficients of variation obtained using the EDBC show greater control of the stalk diameter co-variables through the selection and identification of stalks in the defined pattern, rotation of the discs, displacement surface, and condition of the tools. In field tests, these covariates are difficult to control because the variation in productivity of the cane field, roughness of the soil and operational conditions of the harvester can mask the results of tests with cutting tools.

Figure 5 shows the results of the stalk damage indexes as a function of the EDBC travel speed, resulting in a general average damage index at all speeds of -0.53 for CCS, and -0.30 for ICS, indicating a superior cut quality of the saws relative to the knife systems, with results similar to those obtained by Mello & Harris (2003), Momin et al. (2017), and Testa (2018).

The damage index remained below 0, defined as critical partial damage, which indicates that both cutting systems are acceptable. However, this may be because they are new cutting tools, with few hours of use. Momin et al. (2017), in a study based on a methodology similar to that applied in this study, obtained lower damage indexes for a cutting system with serrated blades, with a value of -0.81, and for straight blades of -0.6, corroborating the results obtained in this work.

At a speed of 2 km h^{-1}, the ICS and CCS had values of -1 and -0.33, respectively; at speeds above 3 km h^{-1} the CCS values were lower and better than the ICS. This was probably due to the amount of time the stump was exposed to the cutting system; for longer exposure durations, the saws caused more damage than the knives, and the opposite held for shorter exposure durations. The difference between the cutting systems increased with the second-order polynomial adjustment at speeds of 4 and 5 km h^{-1}, which indicates advantages for CCS, as most harvests occur at this speed. The correlation between the damage and speed obtained in this study are similar to those obtained by Martins et al. (2019).

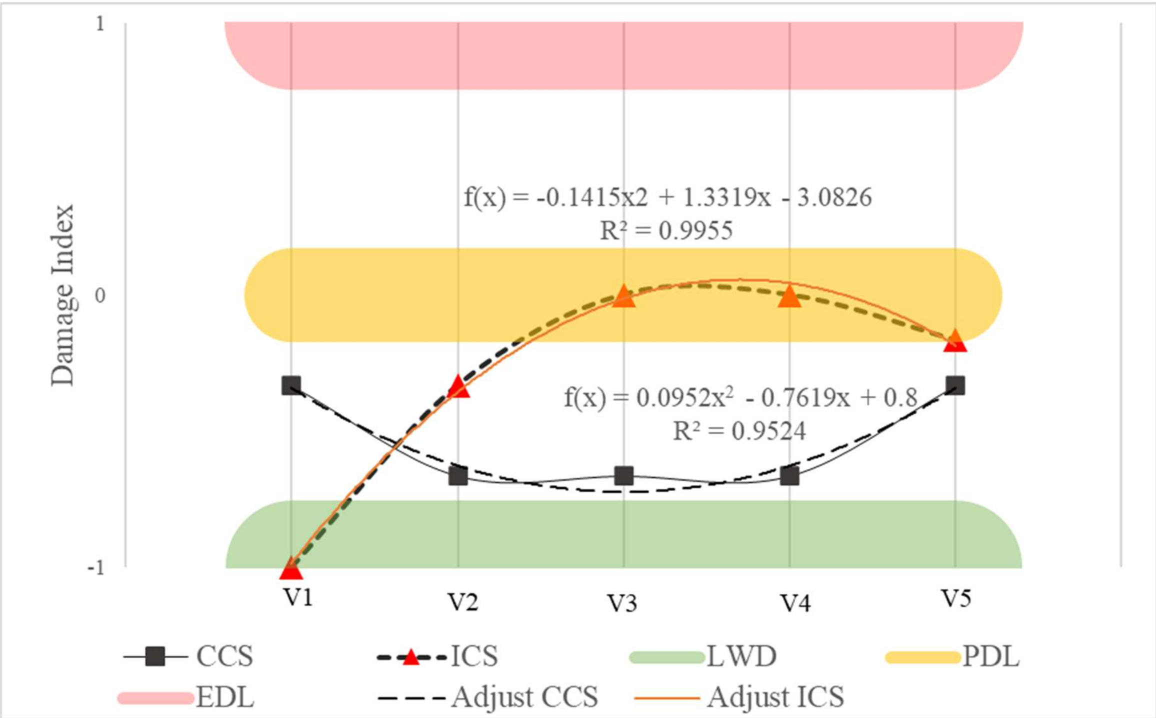


FIGURE 5. Index of damage caused to stumps by the ICS and CCS cutting systems at five working speeds (2; 3; 4; 5 and 6 km h^{-1}), with emphasis on critical damage values: Limits without damage (LWD); Partial damage limits (PDL) and extreme damage limits (EDL).

The frequency of damage to the stalks, expressed as a percentage, is shown in Figure 6. At a speed of 4 km h^{-1}, no partial damage was observed in both cutting systems, and 83.3% of the stalks had no damage when using the CCS, indicating optimal performance at this speed. The number of stalks with extreme damage was equal for both systems at a speed of 2 km h^{-1}, which can be explained by the CCS reaching the same location more than once due to the low travel speed; this also explains the greater amount of partial damage.

At a speed of 6 km h^{-1}, it was observed that the CCS possibly pushed the stalk during the displacement process, causing cracks and lacerations during the cut, doubling the rate of extreme damage compared to the ICS, with similar results obtained by Mathanker et al. (2015). Srivastava et al. (2007) stated that when cutting a vegetable, the fibers are compressed forward and to the sides of the cutting tool, and successive rupture processes occur as the tool advances, confirming the variability of the data obtained in this study.

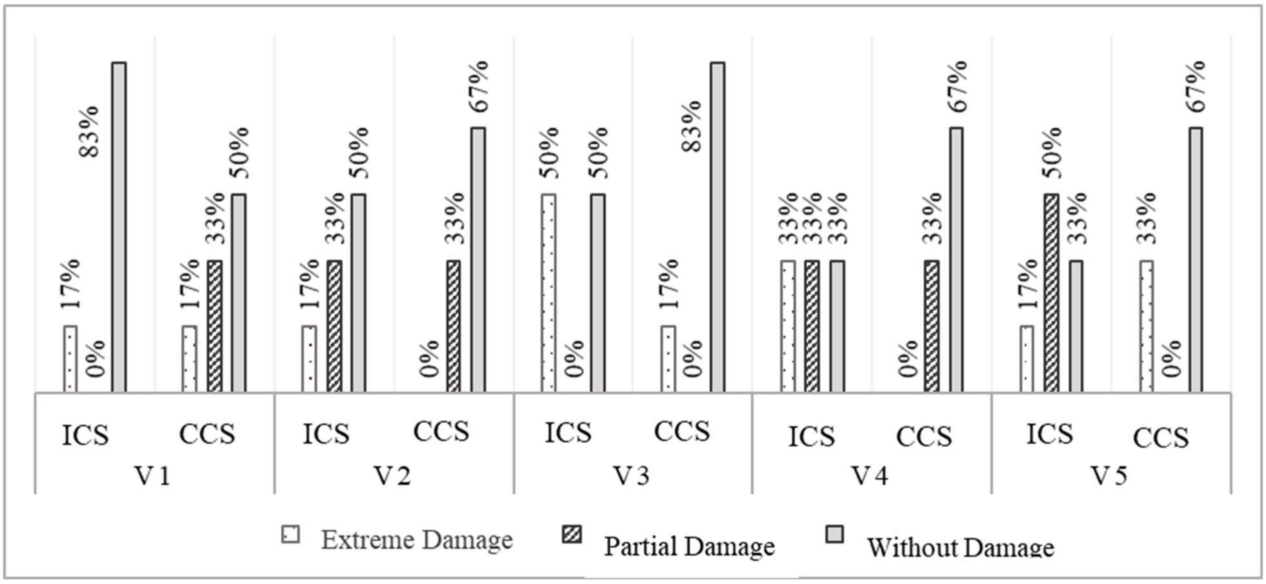


FIGURE 6. Frequency of damage to stumps as a function of travel speed in the impact cutting system (ICS) and in the continuous cutting system (CCS).

At displacement speeds of 4 and 5 km h^{-1}, the ICS had a high percentage of extreme damage, 50% and 33%, respectively, indicating significant losses. Extremely damaged sugarcane ratoons usually experience delayed regrowth and less agronomic vigor. Momin et al. (2017), in an evaluation of different basal cutting tools on sugarcane and a harvester operating speed of 6.3 km h^{-1}, found that 83% of stalks were undamaged, 11.3% were partially damaged, and 5.65% were extremely damaged when using a continuous cutting system with serrated edges. Silva et al. (2020) stated that after the third hour of use, the impact of the knives negatively influenced the performance of the next harvest. Bernache et al. (2020) found an increase in the damage index caused by the wear of cutting tools, but they did not find any relation to crop regrowth.

The low travel speed may have caused more damage as the cutting tool passed more than once over the cane stalks. The increase in damage between V3 and V4 was likely because, in V4, the extreme damage is reduced by the lower contact times with the cutting tool owing to the high speed.

Thus, in V4, the cutting tool makes fewer passes, and the extreme damage that would have occurred during V4 was reduced to partial damage. The relationship with travel speed is better explained by grouping the extreme and partial damage together (50% for V2, 50% for V3, and 66% for V4).

The percentage of damaged stalks are similar to those obtained by Martins et al. (2019) in a field study; where 87.5% of sugarcane ratoons were undamaged at a speed of 3 km h^{-1}, and only 37% were undamaged at a speed of 7 km h^{-1}. Mathanker et al. (2015) obtained similar results relating increased speed and the quality of the cut in a test of harvest.

The ICS and CCS had an average invisible loss of 7.23 and 6.50 g, respectively. The average mass of the stalks used in this study was 1.2 kg. Thus, a sugarcane field with 12 stalks per meter and an average productivity of approximately 100 Mg ha^{-1} can reach a total invisible loss of 0.52%. Neves et al. (2003) found invisible losses to average 1.2 to 2.3% using the base cutting system in sugarcane harvesters, which is superior to the results of this study; however, the authors used cutting tools in different stages of wear.

The smallest amounts of invisible losses were observed for the CCS and ICS at speeds of 2–4 and 5–6 km h^{-1}, respectively. A peak occurred at a speed of 3 km h^{-1}, with 3.67 g of losses per stalk for the ICS. Figure 7 shows the regression analysis and the average tests for each system, with the capital letters in bold representing the difference between the average for the ICS and the CCS at a given speed, and the small letters representing the statistical differences between the speeds for the same cutting system (ICS or CCS). Average values with equal letters did not statistically differ when using Tukey's test at a 5% probability.

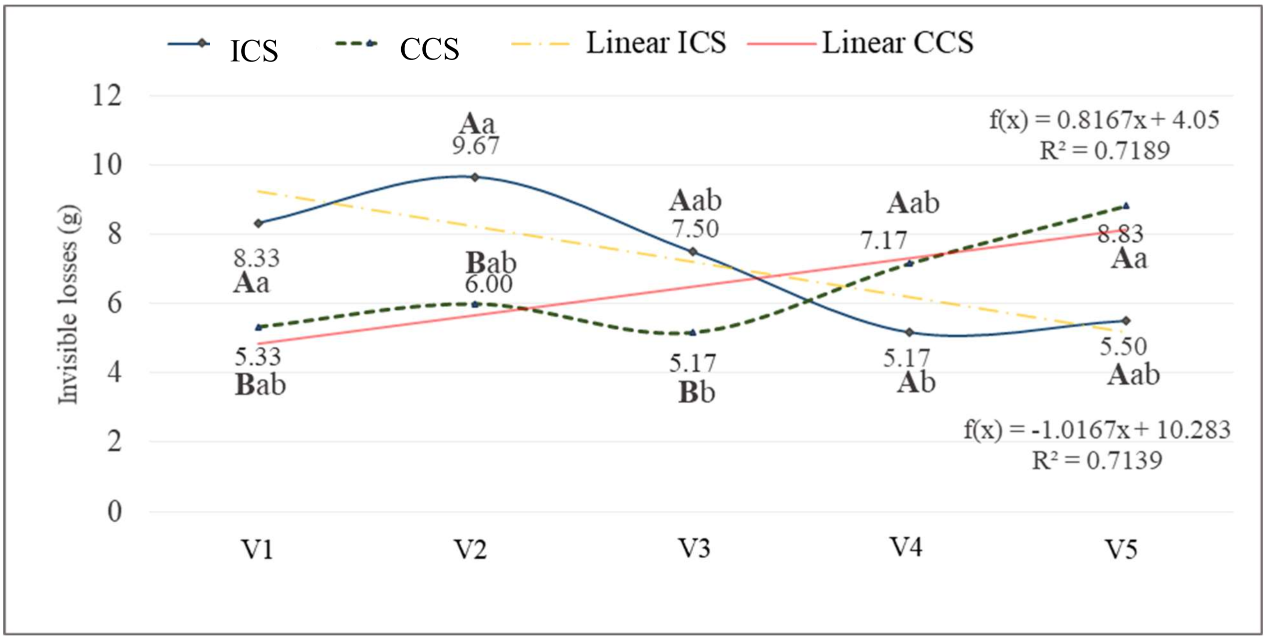


FIGURE 7. Invisible losses of sugarcane industrialized raw material as a function of travel speed for different cutting systems: ICS (Knives) and CCS (Saws).

The highest invisible losses occurred at speeds of 2, 3, and 4 km h^{-1} for the ICS, which showed a statistical difference in relation to the CCS, possibly due to the greater number of blade passes at these speeds. Each additional blade pass of the cutting tool removes additional plant material, thus, increasing the invisible losses of raw material.

For the CCS, the positive slope of the line indicates that at higher speeds, the invisible losses were higher, although without statistical differentiation between treatments. It can be inferred that, at these speeds, stalk flexion occurs immediately before the cutting process, causing damage and generating greater amounts of chips and sawdust. Liu et al. (2012) and Srivastava et al. (2007) explained this phenomenon based on the principle of viscoelastic behavior of plant material, where the pressure of the cutting tool initially causes a deformation in the plant stalk, which is a function of the contact time, tool thickness, and cutting tool, which causes plant fibers to break completely.

Neves et al. (2006) stated that invisible losses are representative of the cutting mechanisms that occur in all stages of harvester processing. The authors obtained total invisible losses between 9.8% and 10.7% for the internal systems of the harvester, which does not include the basal cut system.

Voltarelli et al. (2015), after testing various basic tools for cutting sugarcane, found the results of invisible losses were influenced by the operator and machine, other factors that were better controlled in laboratory tests using the EDBC, and the influence of the cutting tool. The effects of the cutting tool were evident.

Paixão et al., (2019), Momin et al. (2017), Testa (2018), Voltarelli et al. (2015), and Voltarelli et al. (2017) obtained promising results in tests using new sugarcane-based cutting tools. The development of new systems and prototypes, such as EDBC, contributes to scientific improvement and better understanding of the sugarcane cutting process.

Mathanker et al. (2015) obtained a low coefficient of variation using a prototype developed for the analysis of cutting tools, while Cassia et al. (2014) and Reis et al. (2015) obtained high coefficients of variation in the evaluation of sugarcane base cutting systems in the field and found that the soil and operator strongly influenced the results.

CONCLUSIONS

The impact cutting system (ICS) and continuous cutting system (CCS) presented acceptable stalk damage index values; however, the CCS showed better cut quality, with lower rates of general damage.

It was possible to accurately evaluate the invisible losses caused by the cutting tools, and the difference between the invisible losses caused by the CCS and ICS was 0.52% and 0.54%, respectively. The highest invisible losses were obtained at speeds of 2, 3, and 4 km h^{-1} for the ICS, showing a statistical difference in relation to the CCS. The other speeds (5 and 6 km h^{-1}) did not statistically differ for the ICS and CCS.

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