Ciência e Agrotecnologia
SCIENCE AND AGROTECHNOLOGY

Ciência e Agrotecnologia, 45:e031720, 2021
http://dx.doi.org/10.1590/1413-7054202145031720

Rural Engineering
eISSN 1981-1829

Operational performance and energy efficiency of axial harvesters with single and double rotor systems in soybean seed harvest

Desempenho operacional e energético de colhedoras axiais de um e dois rotores na colheita de semente de soja

Samir Paulo Jasper[1*], Gabriel Ganancini Zimmermann[1], Daniel Savi[1], Lauro Strapasson Neto[1], Leonardo Leônidas Kmiecik[1], Luiz Ricardo Sobenko[2]

[1]Universidade Federal do Paraná/UFPR, Departamento de Solos e Engenharia Agrícola/DSEA, Curitiba, PR, Brasil
[2]Universidade Tuiuti do Paraná/UTP, Curitiba, PR, Brasil
[*]Corresponding author: samir@ufpr.br
Received in November 23, 2020 and approved in February 28, 2021

ABSTRACT

The decision-making capability of the machine to harvest grains must consider a lower fuel consumption with a higher operating velocity allied to a greater performance of the grain cleaning system, along with lower rates of the damage and waste produced. This study aimed at evaluating the operational performance and the energy efficiency of two axial harvesters, having different trail and separation systems in the soybean seed harvest. The experiment was carried out in a completely randomized block design in 500-m bands, consisting of two factors, namely two axial harvesters (single and double rotor) and six target velocities (3, 4, 5, 6, 7, and 8 km h^{-1}). Regarding the operational energy performance, the hourly fuel consumption, operational speed, operational field capacity, fuel consumption per area and mass of the harvested grain, and the handling capacity of the harvest were evaluated. The harvesting performance parameters, such as the percentage losses in the platform and the trail system, broken grains, impurities, and the pods, which did not undergo threshing, were evaluated. The results obtained showed that the single-rotor harvester had a better energy efficiency, while the double-rotor harvester had a better operational performance. The double-rotor harvester was agronomically more efficient.

Index terms: Agriculture; fuel consumption; *Glycine max* L.; target velocity.

RESUMO

A escolha da máquina para realizar a colheita de grãos deve levar em consideração um menor consumo de combustível com maior velocidade de operação, a fim de obter maior eficiência energética e operacional, aliada ao maior desempenho dos sistemas de trilha, separação e limpeza de grãos, com menores índices de danos e desperdícios. Esta pesquisa teve como objetivo avaliar o desempenho operacional e a eficiência energética de duas colhedoras axiais, com diferentes sistemas de trilha e separação na colheita de sementes de soja. Para isso, o experimento foi realizado em delineamento de blocos casualizados, em faixas de 500 m, sendo avaliados dois fatores: duas colhedoras axiais (um e dois rotores) e seis velocidades alvo (3, 4, 5, 6, 7, e 8 km h^{-1}). Em relação ao desempenho energético operacional, foram avaliados os parâmetros de consumo horário de combustível, velocidade operacional, capacidade operacional de campo, consumos de combustível por área e por massa de grãos colhidos e capacidade de manuseio da colheita. Parâmetros relacionados ao índice de colheita também foram avaliados, como porcentagem de perdas na plataforma e no sistema de trilha, grãos quebrados, impurezas e vagens sem debulha. Os resultados obtidos mostraram que a colhedora de rotor um rotor apresentou melhor eficiência energética, enquanto a colhedora de rotor duplo apresentou melhor desempenho operacional. A colhedora de rotor duplo também foi mais eficiente agronomicamente.

Termos para indexação: Agricultura; consumo de combustível; *Glycine max* L.; velocidade.

INTRODUCTION

The growing expansion of the agricultural production in Brazil is directly concerned with the technical combination between seeds and the agricultural machinery, without needing to expand towards new areas (Pereira; Santos; Ferreira, 2019). The harvesting process has great relevance in agriculture, as it encompasses the final stage of all investments made in farming, such as genetic potential, fertilizers, and pesticides, intending to obtain higher qualitative indices in the harvesting operations under different field conditions (Zerbato et al., 2013).

The grain harvester possesses the functions of cutting, collecting, threshing, separating, cleaning, and temporary storage, respectively (Liang et al., 2015). In the field of science and industry, the challenge is to develop machines aimed at carrying out these steps in the shortest period, combined with a lower rate of fuel consumption, reduction of losses and damages along with maximum cleaning of the grains, combined with the need to adapt to the adverse situations at the time of harvest (Paixão et al., 2019; Tabile et al., 2008). Among the Brazilian market options, there are harvesters equipped with several threshing systems such as the radial (tangential), axial, and hybrid threshing system (radial and axial combination) (Liang et al., 2019). The axial harvester has a system made up of a rotor and a concave, which is arranged longitudinally with the incoming material flow, to perform the threshing and separation of the grains (Cunha; Piva; Oliveira, 2009). Aldoshin and Didmanidze (2018) pointed out that the harvesters equipped with axial systems crushed and lost fewer grains compared to the threshing machines having straw walkers.

The amount of material handled depends on the capacity of the trailer, the separation, and the flow of the harvester, following the operational velocity and the fuel consumption (Paixão et al., 2017; Spokas et al., 2014). The system of the single or double axial rotor allows different handling capabilities and also makes a difference in the energy efficiency of the harvester, which provides the necessary scope for research to determine the best choice for each purpose.

Losses of seeds and grains in the mechanized harvest decrease the profitability of agricultural production, as the harvest consists of the final operation of the production process (Júnior et al., 2014). The reduction of losses in the mechanical harvesting of soybeans is necessary for the viability of production (De Lima; Silva; Da Silva, 2017). Interference is experienced from the harvester velocity, height of the platform cut, reel velocity, cylinder rotation, and the degree of the opening between the concave and the type of machine to be used (Toledo et al., 2008). This paper evaluates the operational performance and the energy efficiency of the two axial harvesters (single and double rotors) during the harvest of soybean seed.

MATERIAL AND METHODS

The study was carried out during the mechanized harvest of soybean seeds in the 2019/2020 season (November-March), on an area of 50-hectares in a Dystrophic Red Latosol, irrigated by the center pivot, located in the city of Presidente Olegário, MG, Brazil (latitude 18° 24’ S; longitude 46° 25’ W; 947 m a.s.l.). According to the Köppen climate classification, the local climate is Aw (tropical with dry winter), with an average temperature during the coldest month to be above 18 °C and annual precipitation of 750 mm and above (Alvares et al., 2013). The soybean cultivator harvested was a Monsoy M7739IPRO, designated for seed production, seeded with a row spacing of 0.5 m with 14.2 plants per linear meter, resulting in a plant density of 28.4 plants m^{-2}.

The experiment was conducted in a completely randomized block design having two factors, which are the axial harvester system (single and double rotor) and the theoretical velocity selected on the harvester panel (i.e., target velocity - v_T). The two axial harvesters analyzed were allocated into plots and v_T in subplots (3, 4, 5, 6, 7, and 8 km h^{-1}), which comprised a total of 12 treatments. For each treatment, five repetitions were performed, which made a total of 60 experimental units, in bands of 500-m length each.

The harvesters evaluated were John Deere model S550 (single-rotor – H_{SR}) and New Holland CR5.85 (double-rotor – H_{DR}), manufactured in the years 2017 and 2018, respectively. Both were regulated for the harvest of soybean seeds, following the guidelines from the operator’s manual. At the beginning of the harvest, final adjustments were made in the area of data collection as well. It is emphasized that the operators had experience in using the machines, as well as training in terms of adjustments and maintenance. Moreover, both harvesters were operated while fully fueled and were equipped with a 30-ft (9.14 m) cereal platform along with a conventional conductor (snail), performing the harvest with a full width of the cutter bar. The technical specifications of the harvesters as well as the adjustments, are shown in Table 1.

Two flow meters were installed in the fuel supply system of the harvester (inlet and return to tank), and the hourly fuel consumption (FC_H) was determined by them as described by Neto et al. (2020). The operational velocity (v_O) was monitored depending on the number of pulses emitted through a speed sensor model SVA-60 (Agrosystem Inc., SP, Brazil) having an accuracy of 1×10^{-2} m s^{-1}. The instrumentation was properly connected to a data acquisition system made on a printed circuit board, with an acquisition frequency of 1 Hz (Jasper et al., 2016).

The target velocities and the pre-determined treatments were established in an area parallel to the experiment. The panel velocity of the single-rotor harvester was measured using the StarFire 3000 antenna, while the panel velocity of the double-rotor was measured using the Trimble 272 antenna, while both were measured by a Garmin 61X GPS as well. Moreover, the harvesters

Table 1: Technical specifications of the single (H_{SR}) and double (H_{DR}) rotor axial harvesters used.

Characteristic	H_{SR}	H_{DR}
Nominal power (ISO TR14396) - kW (cv)	202 (275)	198 (269)
Transmission type	Hydrostatic	Hydrostatic
Concave opening (mm)	9	46
Rotor rotation (rpm)	340	610
Rotor diameter (mm)	610.0	431.8
Peripheral rotor velocity (m s^{-1})	10.86	13.79
Cleaning fan rotation (rpm)	950	1050
Cleaning area (m²)	3.83	5.40
Platform	0630F - John Deere	740CF - New Holland
Front axle wheels (double)	520/85R38 - Pirelli	18.4–38 - Pirelli
Rear axle wheels	28L-26 - Goodyear	18.4–26 - Pirelli

operated in the first travel gear, with a 2100-rpm rotation on the diesel engine, which is compatible with the trail system of the harvesters. The adjustment of v_T was carried out through a potentiometer located on the multifunction lever in both the harvesters, placed 100 meters before starting the harvest. Thus, it was possible to monitor v_O along the dimensions of the plot and to indicate how much of the motor load was consumed by the industrial system of the harvester.

The operational field capacity (F_C) was calculated as per Equation 1. For this, the effective working width (E_W) was adopted as the width of the platform, and the efficiency of the operation (η) was 65% as well (American Society of Agricultural Biological Engineers- ASABE, 2011).

$$F_C = \frac{v_O . E_W . \eta}{10} \quad (1)$$

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 the operation (decimal).

Fuel consumption per area worked (FC_A) was calculated using Equation 2 by the ratio between FC_H and F_C (He et al., 2019).

$$FC_A = \frac{FC_H}{F_C} \quad (2)$$

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

The amount of fuel used per megagram (Mg) harvested (FC_M) was obtained by using the product between the FC_A and the mean crop productivity (P), which was 2.9 Mg ha^{-1} (Equation 3), according to Spokas et al. (2014).

$$FC_M = FC_A . P \quad (3)$$

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

Finally, the harvest handling capacity (H_C) was determined using Equation 4, as the product between F_C and PP (Srison; Chuan-Udom; Saengprachatanarak, 2016).

$$H_C = F_C . P \quad (4)$$

where H_C is the harvest handling capacity (Mg h^{-1}).

Regarding the performance of the harvesting operation shown by the two axial systems, the quantitative losses (i.e., in platform and trail system) of the seeds were first measured through the collections made using rectangular frames, constructed using two metal bars and nylon cords, having dimensions of 0.22 × 9.14 m (2 m^2) (Compagnon et al., 2012). In this way, losses were collected from the platform (the area after the passage of the platform and before the material deposited by the chopper and spreader of the machine) and from the machine (after the passage of the entire length of the harvester), made after the stabilization of the feeding system for each analyzed factor. The mass of the losses was obtained with the help of a semi-analytical balance (having precision of 0.01 g), and the water content was subsequently corrected for 13% (dry basis). No natural losses were incurred before the harvest, which was not considered in the analyses conducted.

For the evaluation of the qualitative losses (broken seeds, impurities, and pods without threshing), samples were taken from the grain tank after stabilizing the operational velocity in each treatment and were later analyzed in the laboratory. For the evaluation of broken seeds, 200 seeds were used per plot, subdivided into four replications of 50 seeds, allocated in glass flasks containing 0.075% of tetrazolium solution, following the criteria established by França-Neto and Krzyzanowski (2018). Moreover, impurities and pods without threshing were determined from four 0.2 kg samples for each treatment. The initial masses of the samples were measured using a semi-analytical balance (precision of 0.01 g), and subsequently, the impurities and pods without threshing were manually separated, and their masses and quantities were determined again to obtain the relative values.

The obtained data passed the tests of normality (SW–Shapiro-Wilk) and homogeneity of variance (B_0–Bartlett). Given these premises, they were subjected to analysis of variance (ANOVA) to verify the effects of the factors (harvester and v_T) and their interaction through the statistical software SigmaPlot 12 (Systat Software Inc., CA, USA). When the F-test presented a significant probability value (P<0.05), the averages were compared using the Tukey test (P<0.05) for qualitative factors (harvester). The polynomial regression test was applied for the quantitative factors (v_T and interaction), along with the models selected by the criterion having the highest determination coefficient (R^2) and the significance (p<0.05) of the equation parameters.

RESULTS AND DISCUSSION

Operational energy performance

Table 2. shows the ANOVA results of the operational energy performance data, having no necessity to transform the means for all the variables studied, denoting the normality (SW) and homogeneity of the variance residues (B_0). The coefficient of variation (C_V) in all the parameters was categorized as stable, according to the classification postulated by Ferreira (2018). The results demonstrated a significant difference in the harvester factor concerning the H_{DR}, which expressed superior results in the parameters of FC_H, v_O, F_C, FC_A, FC_M and H_C.

Table 2: Synthesis of the analysis of variance and the test of means for the evaluated operational energy performance parameters.

Analysis		Parameters					
		FC_H (L h^{-1})	v_O (km h^{-1})	F_C (ha h^{-1})	FC_A (L ha^{-1})	FC_M (L Mg^{-1})	H_C (Mg h^{-1})
	SW	0.943	0.893	0.893	0.726	0.726	0.893
	B_0	0.296	0.987	0.987	0.042	0.042	0.987
F-test	Harvester	16.65*	2,939.75**	2,939.75**	240.58**	240.58**	2,939.75**
	v_T	123.30**	1,489.89**	1,489.89**	140.07**	140.07**	1,489.89**
	Harvester x v_T	38.39**	207.08**	207.08**	117.29**	117.29**	207.08**
C_V (%)	Harvester	8.68	2.14	2.21	10.45	10.45	2.21
	v_T	4.03	2.16	2.17	4.67	4.67	2.17
	Harvester x v_T	4.24	2.32	2.34	5.13	5.13	2.34
Mean test	H_{SR}	39.66 b	4.98 b	3.42 b	11.86 b	4.94 b	8.14 b
	H_{DR}	44.77 a	5.07 a	3.47 b	13.64 a	5.78 a	8.26 a
	LSD	2.58	0.08	0.04	0.95	0.40	0.10

Values with different letters in a column are significantly different (P<0.05). F-test: NS – not significant; * – P<0.05; ** – P<0.01. Shapiro-Wilt normality test: SW≤0.05 – abnormal data; SW>0.05 – data normality. Bartlett's homogeneity test: B_0≤0.05 – heterogeneous variances; B_0>0.05 – homogeneous variances. C_V – coefficient of variation; LSD – least significance difference – ; FC_H – hourly fuel consumption; v_O – operational velocity; F_C – operational field capacity; FC_A – fuel consumption per worked area; FC_M – fuel consumption per harvested mass; H_C – harvest handling capacity; v_T – target velocity; H_{SR} – single-rotor axial harvester; H_{DR} – double-rotor harvester.

Table 2 shows a significant reduction in the hourly fuel consumption of 5.1 L h^{-1} (11.4%), on average for the single rotor harvester, which is relevant to the operating costs (Sopegno et al., 2016). The highest value of FC_H in the double-rotor harvester is explained by the highest operational velocity achieved (1.8% higher), which results in a greater volume of processed material and, consequently, a greater expenditure of energy (Eisenbies et al., 2017). The higher v_O value is because of the smaller diameter rotors in this harvester, and with the increase in their rotation, a greater centrifugal force is obtained, which acts on the trail process (Cunha et al., 2009). On the other hand, with a higher operating velocity of 1.8%, the fuel consumption of the double-rotor harvester per hectare and Mg harvested were higher than 13.5% and 14.5%, respectively, when compared to the single-rotor harvester (Table 2). These results corroborate with those reported by Srison et al. (2016). Furthermore, the capacity of manipulation of the harvest for the double-rotor harvester was increased by 0.12 Mg h^{-1}, to attain higher kinematic velocities and, consequently, a greater capacity to trail the material, according to Liquan et al. (2020).

Figure 1 shows the isolated effect of v_T on the parameters of the operational energy performance. Linear (FC_H, F_C and H_C), and quadratic trends (v_O, FC_A and FC_M) were obtained with R^2>0.96 in all the cases.

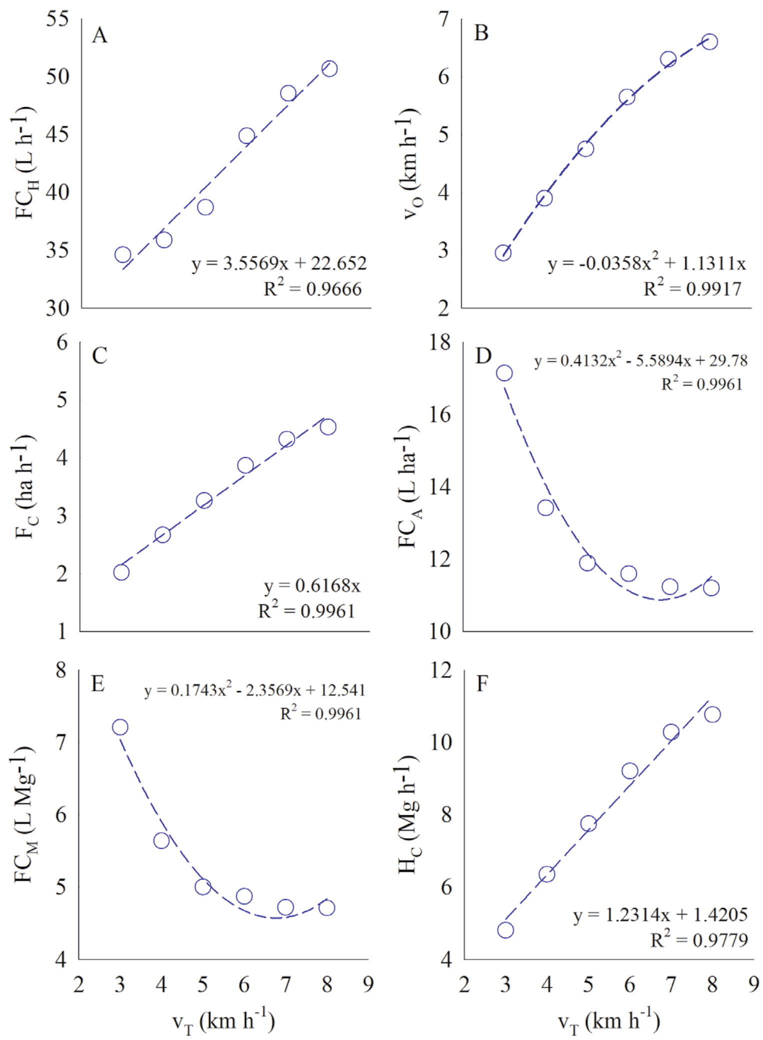

Figure 1: Regression analysis for the isolated target velocity (v_T) factor in the parameters: (A) hourly fuel consumption (FC_H); (B) operational velocity (v_O); (C) operational field capacity (F_C); (D) fuel consumption per worked area (FC_A); (E) fuel consumption per harvested mass (FC_M); and, (F) harvest handling capacity (H_C).

The linear equation generated in Figure 1A shows that, on average, an increase of 3.56 L h^{-1} in FC_H with an increase of 1 km h^{-1}, added to the 22.65 L h^{-1} is required to maintain the kinetic energy of the trail mechanism. Concerning v_O, there is a non-linear trend of this parameter to the detriment of the target velocity, making it possible to reach 92.9±0.06% on an average of the desired velocity due to the occurrence of varied alternations of engine loads (Figure 1B). Also, it should be noted that in the highest value of v_T, 82.5% of the desired speed was obtained due to the higher feed rate and, consequently, a greater load on the engine.

For F_C, a proportional increase with the increase in v_T is observed in Figure 1C, due to the inability of the harvester to reach v_T, and consequently promotes 61.68% of the field efficiency. Fuel consumptions per worked area and harvested Mg showed a contrary behavior to the FC_H at the selected v_T, and lower FC_A and FC_M values were observed when the v_T = 6.76 km h^{-1} as well (Figures 1D-E). And concerning the H_C, a linear increase of 1.42 Mg h^{-1} was observed with an increase of 1 km h^{-1} in the v_T. Similar results were reported by De Lima et al. (2017) while verifying greater variations in engine rotation when the harvester operates at higher velocities. Also, the importance of assessing the fuel consumption per unit area and Mg harvested in experiments with agricultural harvesters is highlighted, regardless of the trail mechanism. So, from this information, it is possible to make a better approximation concerning the efficiency of operating costs (He et al., 2019).

From the significant interactions observed between v_T and the parameters mentioned above, equations capable of representing them were formulated (Figure 2).

The double-rotor harvester showed a superior FC_H in all the selected values o v_T (Figure 2A). There was a greater distance from the FC_H present in the lower v_T and, when analyzing the dependent factor of the generated equation, a greater increase in the FC_H was observed with an increase of 1 km h^{-1} in the single-rotor harvester. The values of this parameter for the H_{DR}, corroborate with those reported by Chioderoli et al. (2012), who evaluated a 290-kW nominal power H_{DR} having FC_H of 48.67 L h^{-1} and operates at 7.1 km h^{-1} in the soybean harvest.

In the case of v_O, both the harvesters presented similar results, with quadratic trends with precision greater than 98% (Figure 2B). Also, it can be noted that the H_{DR} has a greater potential to reach the desired v_T when operated at velocities greater than 7 km h^{-1}. Due to the dimensional similarity between both the cut bars, the F_C varied according to the time spent to travel through the experimental area; thus, presenting a positive linear trend (Figure 2C). Thus, as v_T increases, there is a stronger ability of the H_{DR} to promote greater F_C due to its dependent variables (14.4% superior) and its ability to maintain v_O.

Regarding fuel consumption, the FC_A and FC_M parameters showed quadratic polynomial behavior, with an accuracy higher than 98.6% and 86.5% for H_{DR} and H_{SR}, respectively (Figures 2D-E). Both the parameters were superior for H_{DR} at v_T lower than 7 km h^{-1}; however, they are equal when at the highest velocities. The higher efficiency of the single-rotor at the lowest velocities adopted is due to the energy expenditure of the double-rotor when operated at lower feed rates. According to Spokas et al. (2014), the feed rate is assumed to be rational when the amount of fuel required for handling an Mg of grain is kept at a minimum. According to the generated equations, the lowest levels of fuel consumption per worked area and Mg harvested from the H_{DR} were obtained at a v_T of 7 km h^{-1}, which was superior to the H_{SR} (v_T= 6 km h^{-1}). In this way, the H_{DR} covers a larger area harvested in an hour when working at maximum energy efficiency, compared to the H_{SR}.

For the H_C parameter, both the harvesters showed a linear increase in handling with the increase in velocity (R^2>0.95) (Figure 2F). However, while evaluating the generated equations, there is a greater response from the H_{DR} to the increase in v_T (i.e., increased efficiency when operated at higher velocities). According to Fu et al. (2018), the double-rotor mechanism can increase the threshing capacity by 10%; however, this result was found only at the highest velocities (7 and 8 km h^{-1}).

Harvesting performance

In the case of the parameters related to the performance of the harvesting operation, Table 3. shows the results of the ANOVA synthesis, which also does not require the need to transform the means for all the variables evaluated, denoting normality and homogeneity. The results obtained also showed a significant difference in the harvester factor for the parameters broken grains, impurities, and the pods without threshing.

The axial harvesters did not differ in terms of losses in the platform and the trail system, nor did they exceed the acceptable limit of 1% recommended by Mowitz (2001) for soybean and corn crops (Table 3). Considering the measured losses, a total of 14.79 and 13.34 kg ha^{-1} was obtained for the H_{SR} and the H_{DR}, respectively. Compagnon et al. (2012) pointed out that among the factors that directly influence the harvest losses, ion the cutting height of the platform, reel velocity, rotation and opening of the trail mechanisms, and the travel speed can be mentioned.

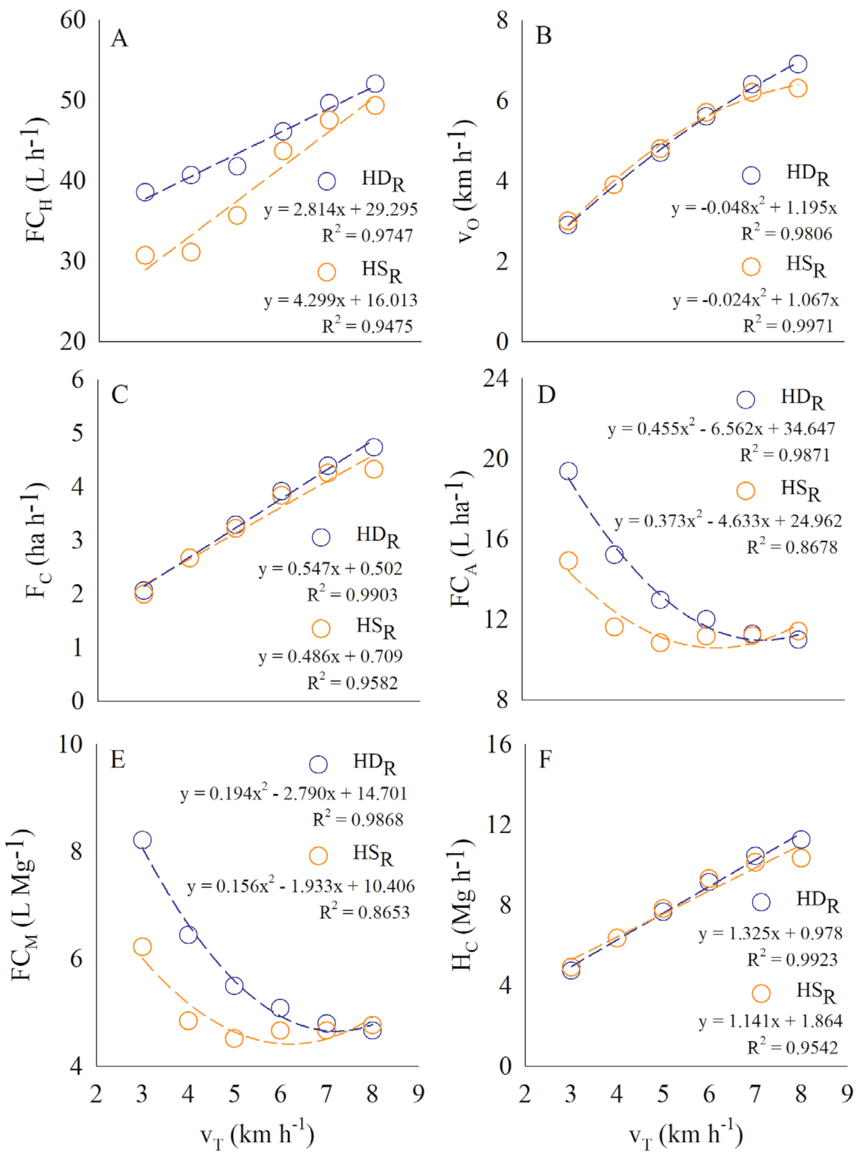

Figure 2: Regression analysis of the interaction harvesters (H_{SR} and H_{DR}) and target velocity (v_T) in the parameters: (A) hourly fuel consumption (FC_H); (B) operational velocity (v_O); (C) operational field capacity (F_C); (D) fuel consumption per worked area (FC_A); (E) fuel consumption per harvested mass (FC_M); and, (F) harvest handling capacity (H_C).

The double-rotor harvester showed a lower frequency of broken grains (29% less) due to the larger concave opening as well as, the greater track area, allowing the grains to be separated through the concave more quickly and without suffering any mechanical damage. This damage occurs due to the impact with the threshing components, which reduces the seed germination rate by 10% when the husk is broken. These findings corroborate with Spokas et al. (2016). Furthermore, it emphasized that the water content of the seeds during the harvest varied between 13% to 16%, being within the ideal range for mechanized harvesting, to favor the reduction of losses and mechanical damages (Carvalho; Novembre, 2012).

Table 3: Synthesis of the analysis of variance and the test of means for the evaluated harvesting performance parameters.

Analysis		Losses		Broken	Impurities	Pods without threshing
		Platform	Trail system			
		------%------				
SW		0.151	0.961	0.994	0.826	0.143
B_0		0.662	0.329	0.106	0.949	0.397
F-test	Harvester	12.74^{NS}	12.79^{NS}	184.17^{**}	191.72^{**}	542.48^{*}
	v_T	16.71^{**}	0.88^{NS}	327.31^{**}	15.52^{**}	$2,169.92^{**}$
	Harvester x v_T	13.26^{**}	0.07^{NS}	85.50^{**}	22.61^{**}	82.36^{**}
C_V (%)	Harvester	15.39	36.19	5.59	7.25	3.47
	v_T	17.39	89.96	6.33	8.69	5.25
	Harvester x v_T	22.64	64.52	6.36	6.16	8.72
Mean test	H_{SR}	0.32 a	0.19 a	0.40 a	0.57 a	0.47 a
	H_{DR}	0.27 a	0.12 a	0.31 b	0.41 b	0.36 b
LSD		NS	NS	0.03	0.05	0.06

Values with different letters in a column are significantly different (P<0.05). F-test: NS – not significant; * – P<0.05; ** – P<0.01. Shapiro-Wilt normality test: SW≤0.05 – abnormal data; SW>0.05 – data normality. Bartlett's homogeneity test: B_0≤0.05 – heterogeneous variances; B_0>0.05 – homogeneous variances. C_V – coefficient of variation. LSD – least significance difference.

Concerning the impurity and frequency of the pods without threshing after the trailing process, the H_{SR} was less efficient than the H_{DR}, a fact explained by the increase in centrifugal force consisting of a higher peripheral velocity (Table 1). This is because the centrifugal force acting on the mass of an axis is related to the square of the speed, Mei et al. (2020) reported that the centrifugal force increases rapidly under high peripheral velocities. These results corroborate with Pishgar-Komleh et al. (2013) and Chansrakoo and Chuan-Udom (2018) while evaluating the efficiency of a single-rotor harvester operated at different velocities of rotation and consequently obtaining different centrifugal forces. The authors have identified that the increase in rotor velocity increases the threshing efficiency and reduces loss.

Figure 3. shows the analysis of the isolated effect of v_T on the analyzed harvesting performance parameters of the harvest. For losses on the platform, a linear trend was obtained (R^2>0.98) (Figure 3A), while for losses in the trail system and the pods without threshing, a quadratic polynomial trend was obtained (R^2>0.84) (Figures 3B-E). Moreover, for the harvesting factors of broken grains (Figure 3C) and the impurities (Figure 3D), it was incapable to adjust mathematical models to explain them. This may be due to the parameters being closely related to the peripheral velocities of the rotors, the water content of the grains, and the impact contact to the threshing components, and not to the v_T (Fu et al., 2018).

By the equation generated in Figure 3A, an increase of 5.29% in losses was observed when increased to 1 km h^{-1}, due to an increase of fallen and unharvested plants as well as the impact of the reel because of increase in rotation (Bawatharani; Bandara; Senevirathne, 2016). Regarding trail losses, it is noted that a speed of 6.86 km h^{-1} provided the lowest percentage of losses. Values similar to the cleaning efficiency were found by Ahmad et al. (2013) when studying the improvements in the wheat thresher designs, noting that new fan exhaust direction systems allowed the cleaning efficiency to increase from 97.44% to 98.18%, which results in the elimination of grain loss through the straw blowing process. Furthermore, according to the equation generated in Figure 3E, a decrease in values with an increase in v_T can be observed, also that the v_T = 7.25 km h^{-1} provided a maximum threshing efficiency, as reported by Chansrakoo and Chuan-Udom (2018).

Through the significant interactions presented in Table 3, in Figure 4 the values of the same are presented as a function of v_T.

In case of H_{SR} in the different v_T of Figure 4A, on an average, a minimal loss was seen on the platform at speeds of 3 to 5 km h^{-1} (0.16±0.04%), and as the v_T increased, the losses increased to an average of 0.48±0.05%, which was also observed by Cortez, Syrio and Rodrigues (2019). The double-rotor harvester, on the other hand, incurred a higher occurrence of losses on the platform at v_T of 3 to 5 km h^{-1} (0.28±0.02%) along with a subsequent reduction to an average of 0.25±0.03% for the upper v_T. This can be explained by the increase in the cutting height of the harvester with the configuration of a single-rotor at higher velocities. Furthermore, the C_V= 64.52% (Table 3) for the losses in the trail process may be due to uncontrollable factors, such as the variability of the agricultural area (i.e., soil type, climate, and other cultivation conditions), and the factors, which characterize the losses are not of uniform occurrence in the area (Cortez; Syrio; Rodrigues, 2019; De Lima et al., 2017).

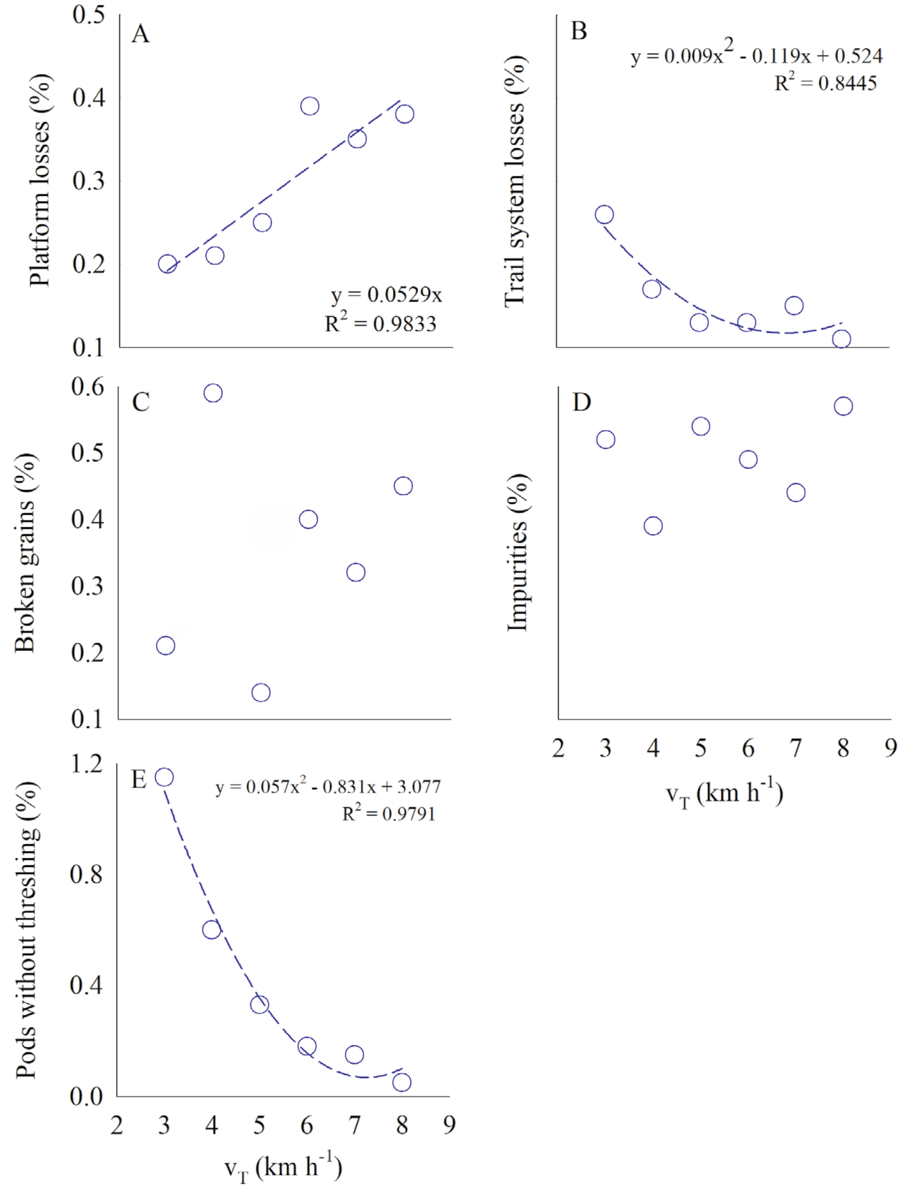

Figure 3: Regression analysis for the isolated target velocity (v_T) factors in the harvesting performance parameters: (A) platform losses; (B) trail system losses; (C) broken grains; (D) impurities; and (E) pods without threshing.

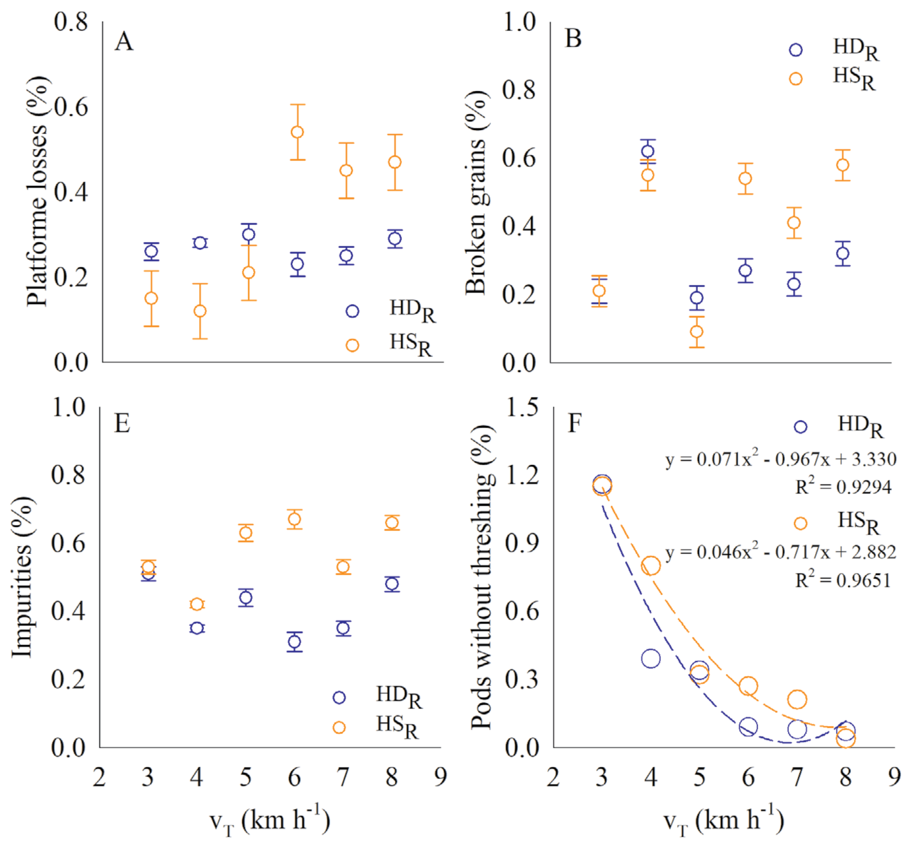

Figure 4: Regression analysis of the interaction harvesters (H_{SR} and H_{DR}) and target velocity (v_T) in the harvesting performance parameters: (A) platform losses; (B) broken grains; (C) impurities; and (D) pods without threshing.

There was a similar pattern shown among harvesters at v_T of 3 to 5 km h^{-1} regarding the number of broken grains (Figure 4B). Moreover, in v_T above 6 km h^{-1}, the double-rotor harvester provided, on average, 0.24% less broken grains compared to the single-rotor, showing a higher efficiency when under higher velocities (Figure 4B). The greater efficiency of the double rotor system can also be seen while analyzing Figure 4C, in which the number of impurities at velocities greater than 5 km h^{-1} was, on average, 0.24% lower than the other system, which can be assigned to the largest sieve cleaning area. According to Miu and Kutzbach (2008), this cleaning area is important to promote the correct method of capturing free grains through the openings present in the concave.

For the frequency of pods without threshing, both harvesters presented quadratic trends with $R^2 >$ 0.92 (Figure 4D). The H_{SR} showed higher values at the target speed of 4 km h^{-1}, making it possible to observe a significant reduction in its frequency with the addition of v_T up to 5 km h^{-1}. In the other system, a reduction of up to 4 km h^{-1} was observed, and speeds higher than those mentioned did not show significant variation in the frequency of pods without threshing. According to the equations generated, both the harvesters H_{SR} and H_{DR}, had the lowest frequency of pods even without threshing at speeds of 7.78 and 6.84 km h^{-1}, respectively. The reduced amount of pods without threshing from the axial harvesters showcase a greater efficiency regarding harvesters with a tangential trail system, according to Mokhtor, El Pebrian and Johari (2020).

CONCLUSIONS

Under the conditions in which the work was carried out, it can be concluded that the single-rotor harvester portrayed better energy performance, while the double-rotor harvester had a better operational performance. Concerning the harvesting performance, the double-rotor harvester proved to be more efficient, showing reduced damage, impurities, as well as greater threshing of pods.

REFERENCES

AHMAD, S. A. et al. Design improvement of indigenous beater wheat thresher in Pakistan. **Pakistan Journal of Agricultural Sciences**, 50(4):711-721, 2013.

ALDOSHIN, N.; DIDMANIDZE, O. Harvesting *Lupibus albus* axial rotary combine harvesters. **Research in Agricultural Engineering**, 64(4):209-214, 2018.

ALVARES, C. A. et al. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, 22(6):711-728, 2013.

ASABE - American Society of Agricultural and Biological Engineers. **Agricultural machinery management data**. St. Joseph: ASABE, 2011. 6p. ASABE standards D 497.7

BAWATHARANI, R.; BANDARA, M. H. M. A.; SENEVIRATHNE, D. I. E. Influence of cutting height and forward speed on header losses in rice harvesting. **International Journal of Agriculture, Forestry and Plantation**, 4:1-9, 2016.

CARVALHO, T. C.; NOVEMBRE, A. D. L. C. Qualidade de sementes de soja colhidas de forma manual e mecânica com diferentes teores de água. **Semina: Ciências Agrárias**, 33(1):155-166, 2012.

CHANSRAKOO, W.; CHUAN-UDOM, S. Factors of operation affecting performance of a short axial-flow soybean threshing unit. **Engineering Journal**, 22(4):109-120, 2018.

CHIODEROLI, C. A. et al. Perdas de grãos e distribuição de palha na colheita mecanizada de soja. **Bragantia**, 71(1):112-121, 2012.

COMPAGNON, A. M. et al. Comparação entre métodos de perdas na colheita mecanizada de soja. **Scientia Agropecuaria**, 3(3):215-223, 2012.

CORTEZ, J. W.; SYRIO, M. G.; RODRIGUES, S. A. Types of header, operating speed, and geometry of collection frames on the total losses of soybean harvest. **Engenharia Agrícola**, 39(4):482-489, 2019.

CUNHA, J. P. A. R.; PIVA, G.; OLIVEIRA, C. A. A. Efeito do sistema de trilha e da velocidade das colhedoras na qualidade de sementes de soja. **Bioscience Journal**, 25(4):37-42, 2009.

DE LIMA, F. B. F.; SILVA, M. A. F.; DA SILVA, R. P. Quality of mechanical soybean harvesting at two travel speeds. **Engenharia Agrícola**, 37(6):1171-1182, 2017.

EISENBIES, M. H. et al. Biomass, spacing and planting design influence cut-and-chip harvesting in hybrid poplar. **Biomass and Bioenergy**, 106:182-190, 2017.

FERREIRA, P. V. **Estatística experimental aplicada as ciências agrarias**. Viçosa, MG, Brasil: Editora UFV, 2018. 588p.

FRANÇA-NETO, J. B.; KRZYZANOWSKI, F. C. **Metodologia do teste de tetrazólio em sementes de soja**. Londrina, PR, Brasil: Embrapa Soja, 2018. 108p.

FU, J. et al. Review of grain threshing theory and technology. **International Journal of Agricultural and Biological Engineering**, 11(6):12-20, 2018.

HE, P. et al. Reducing agricultural fuel consumption by minimizing inefficiencies. **Journal of Cleaner Production**, 236:117-119, 2019.

JASPER, S. P. et al. Desempenho do trator de 157KW na condição manual e automático de gerenciamento de marchas. **Scientia Agraria**, 17(3):55-60, 2016.

JÚNIOR, A. M. L. et al. Influence of the sample area in the variability of losses in the mechanical harvesting of soybeans. **Engenharia Agrícola**, 34(1):74-85, 2014.

LIANG, Z. et al. Development and testing of a multi-duct cleaning device for tangential-longitudinal flow rice combine harvesters. **Biosystems Engineering**, 182:95-106, 2019.

LIANG, Z. et al. Structure optimization of a grain impact piezoelectric sensor and its application for monitoring separation losses on tangential-axial combine harvesters. **Sensors**, 15(1):1496-1517, 2015.

LIQUAN, T. et al. Development and experiment on 4LZ-4.0 type double speed and double action rice combine harvester. **International Journal of Frontiers in Engineering Technology**, 2(3):1-15, 2020.

MEI, X. et al. A passively self-tuning nonlinear energy harvester in rotational motion: Theoretical and experimental investigation. **Smart Materials and Structures**, 29(4):1-15, 2020.

MIU, P. I.; KUTZBACH, H. D.; Modeling and simulation of grain threshing and separation in threshing units - Part I. **Computers and Electronics in Agriculture**, 60(1):96-104, 2008.

MOKHTOR, S. A.; EL PEBRIAN, D.; JOHARI, N. A. A. Actual field speed of rice combine harvester and its influence on grain loss in Malaysian paddy field. **Journal of the Saudi Society of Agricultural Sciences**, 19:422-425, 2020.

MOWITZ, D. Cranking up combine capacity. **Successful Farming Magazine**, p.7, 2001.

NETO, L. S. et al. Interference of the number of remote control valves in use on the energy performance of an agricultural tractor with productivity management. **Engenharia Agrícola**, 4:356-362, 2020.

PAIXÃO, C. S. S. et al. Operational performance and losses in mechanized soybean harvesting as a function of field shap. **Comunicata Scientiae,** 10(2):308-318, 2019.

PAIXÃO, C. S. S. et al. Influence of the plots format on the performance index of the soybean combine harvester. **Engenharia Agrícola**, 37(5):961-972, 2017.

PEREIRA, L. A. G.; SANTOS, I. J. F.; FERREIRA, W. R. Geografia do comércio de commodities, dinâmicas 354 espaciais da logística de transportes e dos fluxos de exportações do setor de soja no Brasil. **Geografia Ensino & Pesquisa**, 23(3):e3, 2019.

PISHGAR-KOMLEH, S. H. et al. Assessment and determination of seed corn combine harvesting losses and energy consumption. **Elixir Agriculture**, 54:12631-12637, 2013.

SOPEGNO, A. et al. A web mobile application for agricultural machinery cost analysis. **Computers and Electronics in Agriculture**, 130:158-168, 2016.

SPOKAS, L. et al. Reduction of fuel consumption of two rotors axial flow combine harvester. **Journal of Food, Agriculture & Environment**, 12(2):329-333, 2014.

SPOKAS, L. et al. The experimental research of combine harvesters. **Research in Agricultural Engineering**, 62(3):106-112, 2016.

SRISON, W.; CHUAN-UDOM, S.; SAENGPRACHATANARAK, K. Effects of operating factors for an axial-flow corn shelling unit on losses and power consumption. **Agriculture and Natural Resources**, 50(5):421-425, 2016.

TABILE, R. A. et al. Perdas na colheita de milho em função da rotação do cilindro trilhador e umidade dos grãos, **Scientia Agraria**, 9(4):505-510, 2008.

TOLEDO, A. et al. Caracterização das perdas e distribuição de cobertura vegetal em colheita mecanizada de soja. **Engenharia Agrícola**, 28(4):710-719, 2008.

ZERBATO, C. et al. Controle estatístico de processo aplicado à colheita mecanizada de milho. **Engenharia na Agricultura**, 21(3):261-270, 2013.