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AGRICULTURAL TRACTOR: INFLUENCE TO GEAR SELECTION ON ENERGY DEMAND AND COSTS IN SUGARCANE TRANSSHIPMENT

Arthur G. C. Lopes[1], Aldir C. Marques Filho[2*], Tiago P. da S. Correia[3], Paulo C. Firmino[4], Paulo R. A. Silva[5]

[2*]Corresponding author. Federal University of Lavras/Lavras - MG, Brazil.
E-mail: aldir@ufla.br | ORCID ID: https://orcid.org/0000-0002-9105-0040

KEYWORDS

Saccharum officinarum, fuel consumption, gear scaling, optimization, productivity.

ABSTRACT

Sugarcane is one of Brazil's leading crops, and the transshipment harvesting operation represents a significant portion of operating costs. Among the primary machines used in harvesting is the tractor-transshipment set, with considerable energy demands. This study focused on evaluating the gear selection effect in an agricultural tractor on operational performance and costs during the sugarcane transshipment operation. The treatments consisted of four operational work gears at different engine speeds: r1 – 1150 rpm, r2 – 1230 rpm, r3 – 1360 rpm, and r4 – 1500 rpm on the engine. The analyzed variables were volumetric and specific fuel consumption, operational efficiency, and operational cost. The variables were adapted from ASABE (2011) methodology, and the data were submitted to parametric statistics and regression analysis. The rotation engine selection in tractors directly affected fuel consumption with positive angular coefficients and r2 between 0.92-0.96. Fuel consumption reduces by 37.5%, adopting 1150 rpm compared to 1500 rpm rotation. The highest rotation (1500 rpm - r4) increased the volumetric and productive fuel consumption, enabling savings up to reduced fuel cost by 1.08 US$ ha^{-1}. Thus, training sugarcane transshipment operators is essential to optimize the production process efficiency and reduce costs.

INTRODUCTION

Sugarcane is a raw material for producing sugar and ethanol, generating by-products such as vinasse and electricity. Brazil is the world's largest sugarcane producer, followed by India, China, Thailand, Pakistan, Mexico and Indonesia (FAO, 2020), with an estimated planted area in the 2022/23 harvest of 8.3 million hectares and production of 598 million tons (CONAB, 2022).

Mechanized sugarcane harvesting represents a significant total production cost to commodity. Françoso et al. (2017), evaluating the cutting, transshipment and transport in São Paulo state, found an average value of 5.52 US$ Mg^{-1} . Dias Neto et al. (2023) evaluating three row spacing in sugarcane harvesting management, affirm that operational costs of cutting and loading in 1.5-meter row space is 2.64 US$ Mg^{-1}, while 0.58 US$ Mg^{-1} just on fuel. The initial cost of mechanized harvesting is increased due to the need to purchase machinery and equipment, but in large-scale plantations this process is facilitated. In addition, mechanization has environmental advantages, with the emission of pollutants, reducing 25.8 kg CO2-eq generation and cost in US$ 26.22 for each new job, since it minimizes the need for fire in the sugarcane in the manual harvesting process (Chavez et al., 2020).

Agricultural tractors are among the primary power source in agriculture and are responsible for main fuel consumption, being the most used machine on field operations. The operational performance and tractor energy efficiency depend on driving, operator training and work area characteristics (Lanças et al., 2021 and Farias et al.,

[1] Federal University of Goiás/Goiânia - GO, Brazil.
[3] University of Brasília/Brasília - DF, Brazil.
[4] Integrated Faculties of Bauru/Bauru - SP, Brazil.
[5] São Paulo State University/Botucatu - SP, Brazil

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2017). The fuel cost is very high in agriculture activities and combined with labour can represent between 63 and 71% of operational cost (Mattetti et al., 2022).

Standardized tests on agricultural tractors bring metric parameters to field machines, this methods allow comparison between different engines searching for the most efficient in each field condition and agricultural operation (Lovarelli & Bacenetti, 2019; Wang et al., 2021). Research centers such as the Nebraska Tractor Test Laboratory at the University of Nebraska carry out performance tests following CODE 2 from Organization for Economic Cooperation and Development (OECD) and provide performance reports, serving as a rational selection parameter for this machine, moreover, these tests help develop strategies to save fuel, decrease gas emission, improve performance and thermodynamic efficiency (Lanças et al., 2021; Schlosser et al., 2020).

The maximum tractor operational efficiency is obtained when it operates close to the rated speed. However, some operations, such as spraying, light soil preparation and planting, do not require maximum engine power and can operate more efficiently at lowest rotations. A pattern recommendation known as "Gear-up and throttle-down" or “long gears and reduced acceleration” technique reduces engine speed using the highest transmition ratio (“fastest gear”) without losing speed, providing up to 22.4% of fuel saving (Farias et al., 2018).

The agricultural tractor fuel consumption varies according to the pulled load, soil conditions, operating speed, engine speed, implement type, working gear, mobilized soil volume, tire inflation pressure and ballast (Lee et al., 2011 and Lee et al., 2019) . However, field tests with specific operational applications are scarce and require strict operational conditions control (Lanças et al., 2021).

Based on the above, it becomes imperative to investigate conditions of greater energy and operational efficiency in the transshipment operation to sugarcane harvest and the impact on operational cost. This study focused on evaluating the effect of gear selection in an agricultural tractor on operational performance and costs during the sugarcane transshipment operation.

MATERIAL AND METHODS

Experimental area and crop characteristics

The study was carried out in a commercial production sugarcane area, in the Pirajuí municipality, central west region of São Paulo state, in an area of 224 ha, coordinates 21°58'33" S and 49°26'11" W (Figure 1). The prevailing climate region is the Cwa type, according to Köppen, characterized by a dry winter and a hot and rainy summer (Alvares et al., 2013). The area's soil is classified as Yellow Red Latosol, according to Santos et al. (2018).

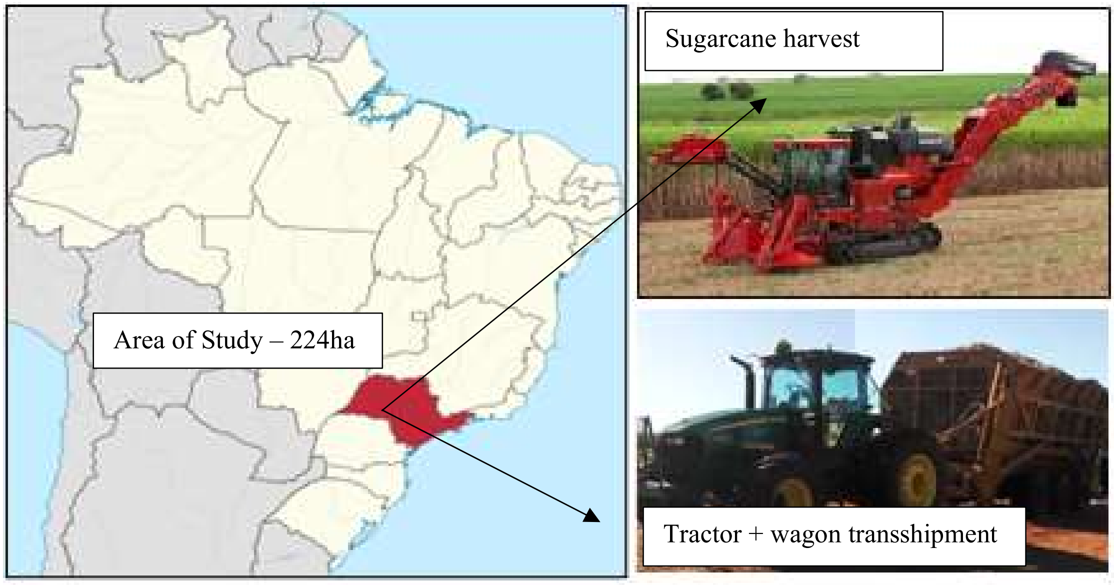

FIGURE 1. Experimental area and machines studied.

The sugarcane variety in the experimental area was RB 867515, characterized as being erect, with planting spacing of 1.5 m between rows, third cut, with an estimated average production of 60 Mg ha^{-1}.

Equipment mechanized applied to field tests

A mechanized set formed by an agricultural tractor and load transshipment was applied to conduct field tests. The tractor was a 4x2 with auxiliar front-wheel drive (FWD), 147 kW engine power, direct fuel injection, with a powershift 16-speed transmission, equipped with radial tires type 710/70R38 in the rear axle, and 600/65R28 front axle, the tires were inflated as 140 and 120 kPa pressure, respectively, with gauge adjusted to 3 m to a controlled traffic system.

The tractor had a GNSS antenna and a monitor with radio correction system for operation management. The integrated column monitor determined the fixed operating speed, engine revolutions per minute, and selected gear in each operating condition.

A transshipment trailer, with a volumetric capacity of 49.5 m^3, load capacity of 23 Mg, with dimensions 33.7 x 9.8 x 3.9 m in width, length and height, respectively, was coupled to the tractor's drawbar. A sugarcane harvester single line A8800 model was used, with a cutting line (1.5-m wide) and 243 kW engine power, programmed to operate at a constant speed of 1.53 m s^{-1}.

Test characteristics

The tests were conducted in randomized operating ranges and organized in randomized blocks, composed of four treatments with six repetitions. As an observed covariate in the field tests, the operating speed set was at 1.53 m s^{-1}, and four combination of gear and engine rotation were determined with the same operating speed at different engine speeds. Treatments were four operating gears for harvesting sugarcane at different engine rotation, r1: C2 gear with 1150 rpm engine rotation; r2: B4 gear gear with 1230 rpm engine rotation; r3 - C1 gear with 1360 rpm engine rotation and r4: B3 gear with 1500 rpm engine rotation.

All speeds and rotations were directly calibrated to the field and compared with the rate indicated on the tractor's control panel. Fifteen meters strips marked to area and gears, set speeds to electronic control system tractor (ECU) to obtain 1.53 ± 0.1 m s^{-1}. The experimental plots totaled 200 m in length and 1.5 m in width to the harvester model (single line). The average slope of the work lanes was 5% and was kept constant in all tractor passes and transfers.

The engine rotation and fuel consumption parameters were extracted directly from the ECU tractor at an acquisition rate every 2 seconds and stored in an electronic shape file. Operating times were collected using the GNSS system, recorded in an electronic spreadsheet. The response to field test variables was: fuel consumption (L h^{-1}), loading time for each transshipment (seconds), loading distance (meters), start and stop loading times, route from different gear groups.

The operational efficiency and fuel consumption parameters were adapted from the methodology by the American Society of Agricultural and Biological Engineers (ASABE, 2011). The values used to estimate the operational sugarcane costs for the crop year 2022 are based on the stable exchange rate dollar (US$) at R$5.46 Brazilian reals (BRL) in july, 2022. The values obtained were applied to fuel consumption per mass harvested and fuel cost per harvest area.

To effective field capacity, operational fuel consumption (L ha^{-1}) and consumption per Mg harvested, [eqs (1), (2) and (3) were used.

$$Efc = \frac{Atr}{\Delta t} * 0,36 \tag{1}$$

Where:

Efc = Effective field capacity (ha h^{-1});

Atr = Useful area plot (m^2);

Δt = Time spent traveling (s),

0.36 = Constant Conversion (m^2 s^{-1} to ha h^{-1}).

$$OFC = \frac{Ch}{Efc} \tag{2}$$

Where:

OFC = Operational fuel consumption (L ha^{-1}),

Ch = Volumetric consumption (L h^{-1}),

$$Ct = \frac{OFC}{P} \tag{3}$$

Where:

Ct = Fuel consumption per mass harvested (L Mg^{-1}),

P = Estimated sugarcane productivity.

To determine the transshipment efficiency operation (Eot), we adopt a [eq. (4)].

$$Eot = \frac{Tp}{Tt} * 100 \tag{4}$$

Where:

Eot = Efficiency transhipment (%);

Tp = Productive time (h),

Tt = Total time (h).

To determine to fuel costs per harvest area applied, [eq. (5)].

$$C = Cca * Pc \tag{5}$$

Where:

C = fuel cost per area (US$ ha^{-1});

Cca = consumption per area (L ha^{-1}),

Pc = fuel price (US$ L^{-1}).

The fuel price was determined for the period experiment according to the list price region provided by the National Petroleum Agency (ANP, 2022).

Statistical analysis

The results were analyzed using parametric statistics to field capacity and operational efficiency tests. The energy consumption averages analyses underwent the Anderson-Darling normality test, variance (ANOVA), and, if applicable, Tukey test at 5% probability. Volumetric fuel consumption, fuel consumption per Mg and operating costs underwent linear regression tests for different engine gears. All analyzes were performed using to statistical system R Software (2020).

RESULTS AND DISCUSSION

Table 1 describes the results obtained in evaluating effective field capacity, volumetric fuel consumption and consumption per mass of sugarcane harvested as a function of different engine speeds.

TABLE 1. Effective field capacity; volumetric fuel consumption and fuel consumption per mass harvested as a function of different engine speeds.

Treatments	Effective Field Capacity	Volumetric Consumption	Consumption per Mg Harvest
	ha h^{-1}	L h^{-1}	L Mg^{-1}
r1	0.71*	6.51 C	0.12 D
r2	0.67*	7.04 B	0.14 C
r3	0.70*	8.14 A	0.15 B
r4	0.67*	8.52 A	0.17 A
DMS	0.13	0.51	0.002
CV%	0.94	2.52	0.94

r1: C2 gear with 1150 rpm engine rotation; r2: B4 gear gear with 1230 rpm engine rotation; r3 - C1 gear with 1360 rpm engine rotation, r4: B3 gear with 1500 rpm engine rotation. Means followed by capital letters in the column do not differ by Tukey's test (α=5%). *NS-Not significant difference at 95% probability. DMS: minimal significant difference. CV (%): Coefficient Deviation.

The effective field capacity remained unchanged due to the constant operational speed and working width maintenance. However, the work rotations significantly affected the volumetric consumption and per Mg harvested raw material.

An alternative to enabling the energy agricultural tractors' performance, from fuel economy and reduction of polluting gases emission, is the gear shifting automation, disabling the operator's action during the course, which, when not trained, focuses only on yield operational and fuel economy (Zhao et al., 2019 and Li et al., 2018).

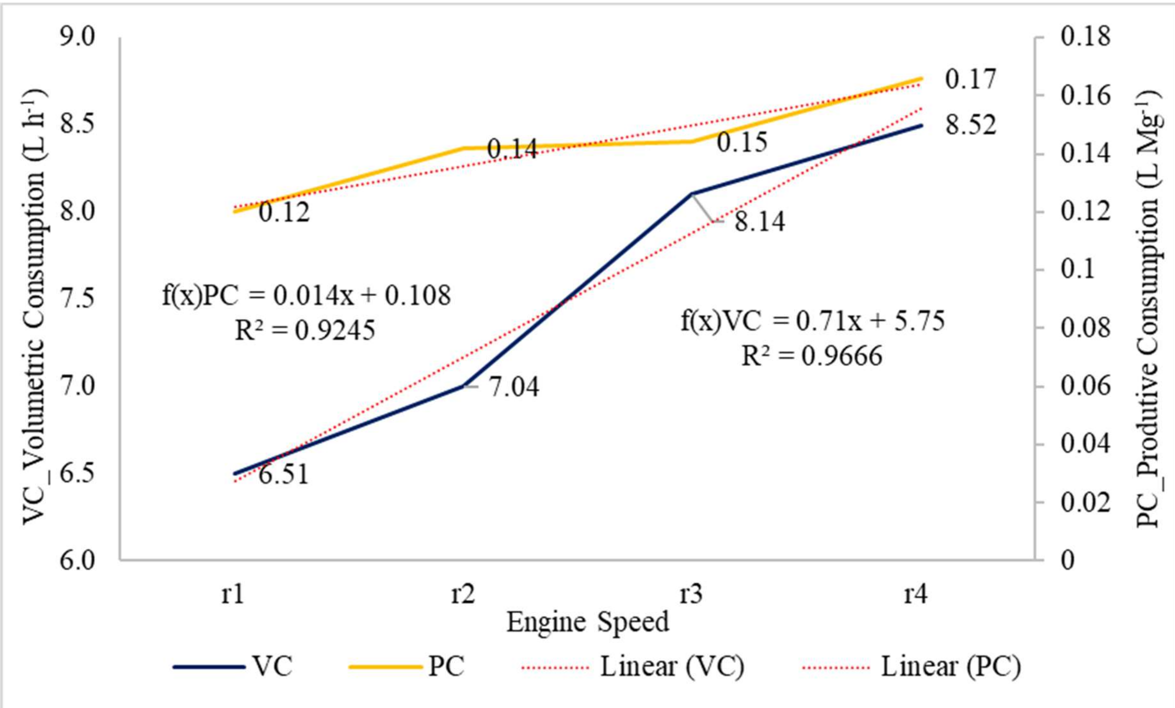

FIGURE 2. Volumetric and Produtive consumption as a function of different work rotations of the agricultural tractor in the sugarcane transshipment operation.

Given the data shown in Figure 2, verify from gear operation r4 (1500 rpm) provided the highest fuel consumption. At the same time, gear r1 presented better results in three to four analyzed indicators. It is noticed that, except for transshipment efficiency operation, all treatments indicated present significant differences in gears evaluated.

Adopting rotation r1, we verified a reduction of 37.5% in fuel consumption per hectare worked to treatment r4. Thus, the most costly operation is related to the highest engine rotation. Considerable differences were observed between r1, r3 and r2 so that fuel consumption increases from 13 and 20% between gear shifts are verified.

The positive angular regression coefficient, $r^2 = 0.92$ and 0.96, indicates a linear adjustment between increased engine speed and fuel consumption. The same occurs when the energy consumption per Mg transported is extrapolated; in these cases, rotations r4, r2 and r3 presented consumption from 16 to 41% higher than r1. The highest rotation increased volumetric fuel consumption by 18.1% and 22.9% to fuel consumption per Mg sugarcane harvested, about other rotations average, the reason is that higher engine rotation requires more engine cycles and fuel in combustion chamber, elevating volumetric and produtive consumption.

Monteiro et al. (2011), changing from gear B2 to B3 in a 4WD tractor and three conditions of liquid ballast, reached a higher working speed, from 6.5 to 7.5 km h^{-1}, and achieved a 9.5% reduction in specific fuel consumption, gaining operational efficiency. The results corroborate Farias et al. (2019) that accelerating the tractor engine is inefficient in gaining operational efficiency. Reducing acceleration reduces fuel consumption in a tractor by up to 29%.

We verified that rotation r1 presented higher efficiency indexes, the results agree with Lanças et al. (2021) since the maximum tractor efficiency point, when it exceeds the power limit at maximum torque, tends to suffer a specific fuel consumption increase; thus, at reduced engine speeds, better performance machine is found.

Tests carried out by Siddique et al. (2023) on an agricultural tractor with the power-shift transmission in traditional driving mode, Power and ECO during plow tillage, rotary and asphalt conditions showed excellent fuel economy to ECO mode for all field conditions. The results showed savings between 44.7 and 21.4% (asphalt), 25.9 and 19.6% (plow tillage) 42.4 and 28.4 (rotary tillage) for ECO mode compared to Power and Power mode compared to traditional, respectively. The authors conclude that the traditional mode with maximum engine speed, used in most cases, makes poor efficient engine operation.

Tractor operation is based on the correlation between work speed and traction force. These parameters are defined by engine speed and gearbox transmission, where the most varied combinations result in adequate power for specific operations. Between choosing a more extended gear and reducing engine speed, these driving strategies ensure fuel economy and operating efficiency (Park et al., 2010).

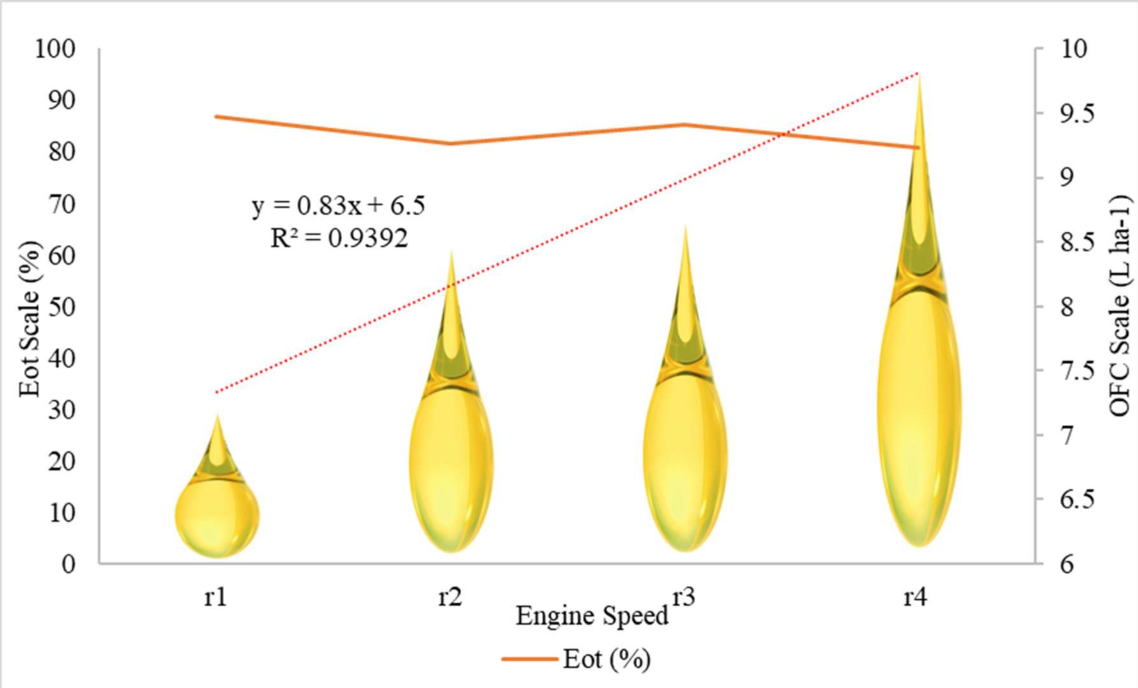

FIGURE 3. Operational Efficiency (Eot) and Operational Fuel Consumption (OFC) as a function of different engine speeds of the agricultural tractor in the sugarcane transshipment operation.

The transshipment efficiency operation did not differ significantly between gears, and operating speed was constant in all treatments; therefore, the effective field capacity, given as a speed transfer function displacement to tractor-transshipment set through the worked area, was not changed. From these results, it is possible to prove that the way the tractor is driven directly affects its energy consumption. It emphasizes the importance of rational machine use, focusing on productivity and economy, which directly depends on human action, emphasizing the need for constant training among agricultural machine operators.

According to Janulevičius & Damanauskas (2023), there is a direct relationship between efficiency during operation, hourly fuel consumption and operational capacity, with efficiency dependent, in addition to working width and speed, on the field length. The research also explored which terrain variables can influence engine rotations, speed and consequently the amount of fuel admitted to maintaining the mechanized set productivity.

In the sugarcane transshipment operation in sloping terrain, fuel consumption may increase at low speeds due to engine speed oscillation to momentary mechanized set overloads. For greater efficiency in tractor use and better conversion of engine available power, it is necessary to find the correct working speed through field tests (Lanças et al., 2021).

The obtained results partially confirm the results of Santos et al. (2022), where the operational cost is reduced by increasing the availability of the set throughout the agricultural cycle. In our study, no available test results affected intrinsic factors with size, sugarcane productivity and harvester performance.

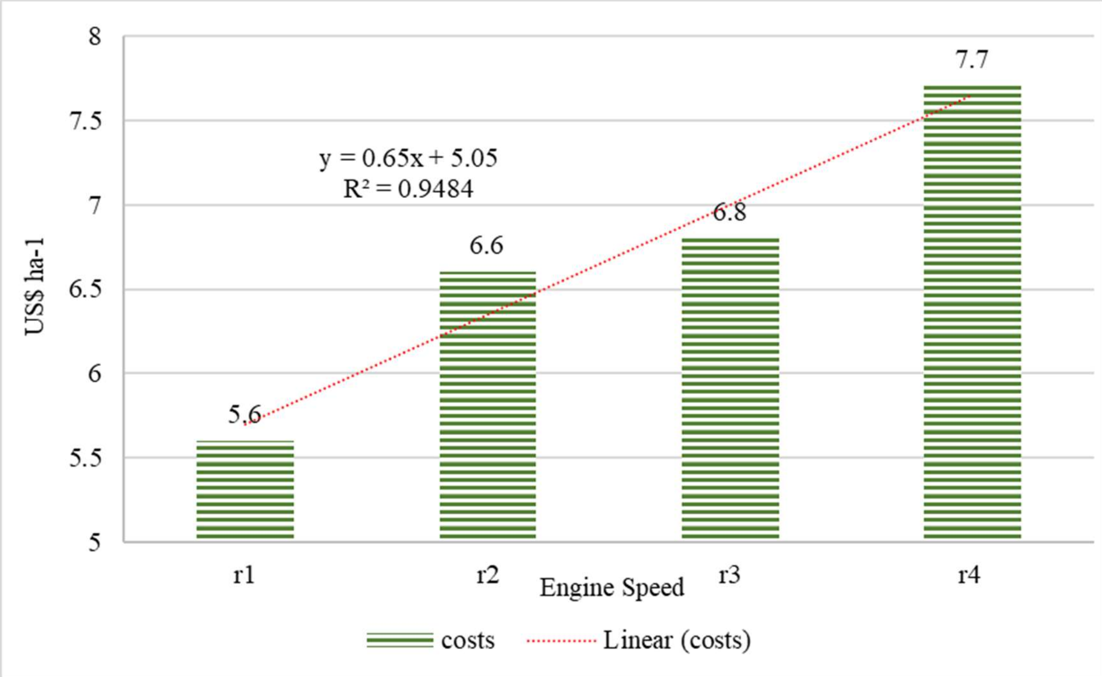

FIGURE 4. Fuel tractor operating costs in different engine speeds to sugarcane transshipment.

The positive linear coefficient verifies it and the straight adjustment line with r^2=0.94 increases engine speed and transshipment operation costs. Chaya et al. (2019) obtained superior cost results to productivity (10 to 12 US\$ Mg^{-1}). However, the authors evaluated mechanized operation total cost in small and medium-sized properties, which raises production costs.

Our research showed that losses could occur due to increased speed and engine speed under adequate operating speed conditions. Through regression analysis, indicated line in Figure 4, it is possible to verify a positive linear relationship between speed and fuel consumption, in which proportionally, higher speeds demand more power and increase fuel consumption. When analyzing the cost of fuel per hectare worked, it is possible to verify that when using the r4 rotation in the transshipment operation, the amount spent on fuel was 7.7 US\$ ha^{-1}, and this index was reduced as the ratio gears that provide less force were adopted.

Finally, when analyzing r1, it presented a better cost-benefit ratio due to fuel economy, with an estimated 5.6 US\$ ha^{-1}. Adopting the r1 rotation reduced the fuel cost by approximately 1.08 US\$ ha^{-1} compared to the other treatment's average (Figure 4). The result can be explained by more extended gear, lower engine revolutions per minute and complete cycles, reducing the diesel admission in the combustion chamber and lowering operating costs.

The results collaborate with those obtained by Kichler et al. (2011), in which the gears choice affected tractor performance and fuel costs. However, the authors stated a lower fuel cost in advanced gears, explained by greater effective field capacity provided by higher operating speed.

During agricultural operations, fuel costs are the most considerable portion of variable costs (Simões & Silva, 2012); thus, fuel economy at any scale can maximize profits in agricultural activity, reducing greenhouse gas emissions and environmental impact.

Kim et al. (2013) reaffirm that gear selection affects the costs of agriculture and can lead to losses for producers; this information corroborates the data obtained in our study.

CONCLUSIONS

We determined the regression equation to describe the increase in fuel consumption as a function of rotation in the sugarcane overflow operation. The rotation engine selection in tractors directly affected fuel consumption with positive angular coefficients and r^2 between 0.92-0.96.

Adopting the lowest working rotation, 1150 rpm, fuel consumption reduces by 37.5% compared to 1500 rpm rotation. The highest rotation (1500 rpm - r4) increased the volumetric and productive fuel consumption compared to the other rotations.

Adopting the lowest working speed (1150 rpm - r1) reduced the fuel cost by 1.08 US\$ ha^{-1} compared to other engine speed selections. Thus, training operators to operate tractors in the sugarcane transshipment stage is essential to optimize the efficiency of the production process and reduce costs.

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