

RESEARCH ARTICLE

Enhancing the efficiency of agricultural tractors by optimizing operational conditions to minimize fuel consumption and carbon emissions during field activities

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ABSTRACT

This study aims to assess how agricultural tractor operating conditions (advancing speed and gear ratio) effect on fuel consumption, field efficiency, slippage as well as CO₂ emissions and specific fuel consumption (SFC). The study was performed under real field conditions on an ITMCO 285 G tractor using a factorial experimental design (3 × 3), which included three speed increments and three gear ratios. The findings indicated that operational conditions significantly altered all examined parameters. Higher fuel consumption, slippage and specific fuel consumption, CO₂ emissions were caused by an increase in the rate of advancement and wrong gear selection while field efficiency decreased. The most optimal performance was at 5 km/h of medium gear driving, resulting in the lowest fuel consumption and in the least slip, followed by being most efficient in the field. Statistical analysis was performed with ANOVA (P < 0.05) on all the variables examined. The findings illustrate clearly that the inefficient use of a tractor results in high energy waste and therefore has a much bigger environmental impact. The application of optimal gear ratio and engine speed modulation under various parameters could enable one to improve the operational features of agricultural tractors so as to increase energy efficiency reduce fuel consumption and carbon emissions, thereby enhancing agricultural sustainability, maintaining effective agricultural practices in arid semi-arid regions.

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INTRODUCTION

Agricultural mechanization is a must in order to achieve modernized farming. It enhances production, improves field efficiency, and minimizes labour requirement. At the core of this system is an agricultural tractor. It delivers the majority of mechanical power for most farm work, including cultivation, harvest and transportation operations. The use of fossil fuels

nature People is becoming more concerned about the excessive use of tractors, which has economic and environmental impacts (Herranz-Matey et al., 2025). Rising global fuel prices, along with increased concerns about climate change and greenhouse gas emissions, signify a need to evaluate agricultural machinery efficiency in an economic and environmental context.

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Recent estimates indicate that agriculture contributes significantly to CO₂ emissions, as one being the use of fuel to run tractors and other farm equipment and it has underscored the need for operational strategies and technologies advanced technologies to reduce fuel consumption and enhance energy efficiency without compromising agricultural output. Tillage is the one of energy intensive farming methods. High traction pressure is need and it is done on soils with varied textures and moisture. Investigations indicate that various operational variables (tillage speed, tillage depth, gear selection and effective utilization of engine power) significantly affect the performance of tractors on tillage operation. Poor management of these variables leading to increased fuel use per hectare, decreased field efficiency, increasing slippage and many losses of energy that result in heat and emissions pollutants. This demonstrates the necessity to increase efficiency in order to obtain optimal tractor performance)Damanauskas et al., 2023). With the overall shift of the globe towards sustainably raising agriculture, has emerged as an advanced solution that uses enhanced technologies to improve agricultural practices with excellent accuracy. This notion relies not only on GPS and digital maps, however likewise the field data as well as how a dirt and crop qualities vary at time and space. This contributes to making accurate and situationally correct operational decisions on the field. For agricultural tractors, precision farming can save a lot of energy by determining the optimal speed, determining the optimal tillage depth to reduce energy waste. These methods are crucial for dry and semi-arid regions such as Karbala Governorate, where soils have variable texture and increased ploughing depth requires greater tractor loads of fuel. In these instances, the absence of meticulous scientific oversight is causing energy resources to be exhausted evermore rapidly and driving farmers into deeper costs to maintain their tasks. This requires use of contemporary methods based on scientific analysis of the influence between draft force, SFC and performance operation of the engine over different working conditions.

Another name for this is the «Shift Up – Throttle Back» technique, and it helps save fuel is certainly one of the most important modern operational strategies. Running the tractor at lower)RPM(but upshifting for more power is part of that strategy. This translates to lower fuel usage and a more efficient engine, especially in heat dissipation. Although it is a simple principle,

very few traditional farming systems have adopted it. Operators sometimes run tractors at higher engine speeds, hoping they will perform better. This actually wastes energy and increases carbon emissions.

The importance of the study consists in demonstrating the possibility to enhance work process efficiency of agricultural tractors by using precision agriculture principles and best practices for their functioning. The goal is to use less fuel and release less carbon dioxide while making resource use more sustainable. This research aims to provide a practical scientific perspective that improves agricultural tractor performance while attaining an ideal balance among productivity, economic efficiency, and environmental preservation, in line with current trends in sustainable agriculture.

In recent years, there has been a growing interest in making agricultural tractors more efficient while using less fuel and releasing less carbon dioxide. This has been done by using modern technologies and precision farming methods. (Al-Sager et al., 2024) showed that how much fuel a tractor uses depends a lot on how it is used, such as how fast it is tilled, how deep it is, and what kind of soil it is on. Artificial neural networks have been employed to develop predictive models designed to improve fuel efficiency. (Shen et al., 2022) established that tillage ranks as one of the most energy-intensive and emission-producing agricultural practices. The emission rates of gases including CO, NO_x, and PM_{2.5} fluctuate based on the type of agricultural operation and its operating conditions, underscoring the necessity for enhanced operational management to mitigate environmental pollution

A recent study by (Damanauskas et al., 2023) showed that improving the efficiency of field operating time can cut fuel use by up to 5.5%. This shows how important field engineering is in precision farming methods. (Lajunen et al., 2024) studied how to measure how much energy tractors with different types of propulsion systems (hybrid and electric) use. The results showed that there was a lot of room for improvement in terms of reducing energy use and emissions compared to traditional systems. This would make it easier to switch to sustainable farming. According to)Nagar et al., 2024), perhaps artificial intelligence could be used to apply these approaches through advisory systems based

on field data that are aligned with the principles of precision agriculture and energy management leading to improved engine performance combined with reduced fuel consumption.

(Vlăduț et al., 2026) demonstrated that increasing the speed under optimized settings led to a reduction in fuel consumption and improving energy efficiency, whereas increasing tillage depth considerably increased fuel consumption.)Li et al., (2025 determined that the consumption of fuel can be measured both in relation to the area and by volume of soil this is a key step for improving efficiency in agriculture and reducing energy use. Draft force, in particular, accounts for a significant amount of energy use according to research. According to (Mamkagh., 2019), increased draft force directly correlates with increased fuel use; therefore, using the right equipment is a must.

The recent studies have highlighted the importance of using advanced predictive models to improve agricultural tractor performance and reduce fuel consumption. (Kim et al., 2024) reported that using field operational data during working time in the field improves the accuracy of fuel consumption predictions, which may help reduce fuel use by selecting appropriate gear ratios and operating speeds.

(Zhao et al., 2023) Their study showed that development of the hydromechanical transmission systems in tractors is improving operational performance, and reduces fuel consumption, energy losses as well carbon dioxide emissions. (Janulevičius et al., 2019) As reported by the performance efficiency of agricultural tractors is determined not only by engine power and the characteristics of soil, but that time efficiency is a major influencer on operations during tillage processes noticing that larger fields are greatly affected to configuration. First, field research showed that minimize time losses was more efficient to tractor work by reducing unnecessary stops and maneuvers with consequence the decreasing operational losses. (Lee et al., 2016) argued that computer simulation methodologies are powerful tools for optimizing agricultural tractor operational efficiency in the field. Mathematical models to simulate the tractor's field performance were constructed with the strategy of a maximum equilibrium between fuel economy and operational efficiency.

MATERIAL AND METHODS

Experimental Site

The field experiment was conducted on farmland in Karbala Governorate, Iraq, during the autumn growing season of 2025. The site soil was sandy loam with a moderate moisture content at the time of the experiment. The land was prepared with preliminary tillage to standardize surface conditions and minimize variation between treatments.

Machinery and Equipment

An ITMCO 285 G tractor with a nominal power of 75 hp (Table 1) was used. This medium-powered tractor is based on a Massey Ferguson design and is widely used in traditional farming operations in Iraq. A moldboard plow was also used for field operations. (Figure 1)

The tractor was calibrated before the start of the trials to ensure stable performance and minimize operational errors.

Table (1) Specifications of the agricultural tractor used in the experiment

Item	Specification
Tractor model	ITMCO 285 G
Engine type	Diesel, 4-stroke
Engine power	60–70 kW
Drive type	4WD
Number of cylinders	4 cylinders
Transmission	Manual gearbox
Gear stages	Multiple forward & reverse gears
Fuel type	Diesel fuel
Cooling system	Water-cooled
Application	Field tillage operations

The study was based on a factorial experimental design according to the randomized complete block design (RCBD) with three replicates, to study the effect of operational factors on tractor performance.



Figure (1) The instruments used in the experiment (Experimental Design)

Factors studied:

Forward Speed: Three levels:

S1= 3 km/h

S2= 5 km/h

S3= 7 km/h

(Gear Ratio) Three levels:

G1= Low gear

G2= Medium gear

G3= High gear

Field Procedure

The area was partitioned into uniform experimental units, each corresponding to a distinct treatment. Tillage operations were executed in accordance with the parameters designated for each treatment, while maintaining other operational circumstances as constant as feasible. The duration of each treatment was quantified with a timer, and the distance covered was documented to ascertain the tractor's true velocity. The stability of engine speed was confirmed during operation for each treatment.

Measured Parameters

Fuel Consumption

Fuel consumption was measured using the graduated tank method, where the amount of fuel consumed for each transaction was recorded, and then consumption was calculated on a liters per hour

Field Efficiency

Field efficiency was calculated using the following relationship:

$$\text{Field Efficiency} = \frac{\text{Effective Field Capacity}}{\text{Theoretical Field Capacity}} \times 100$$

The theoretical and practical field capacity was calculated based on the machine's width and advance speed.

Wheel Slip

The slip ratio was calculated by comparing the theoretical speed of the tractor with the actual speed according to the relationship:

$$\text{Slip (\%)} = \frac{V_t - V_a}{V_t} \times 100$$

Where:

V_t = Theoretical velocity

V_a = Actual velocity

(Specific Fuel Consumption)

The specific fuel consumption of the agricultural tractor was calculated based on the relationship between fuel consumption rate and engine power, according to the following equation.

$$\text{SFC} = \frac{\text{Fuel Consumption } \left(\frac{\text{L}}{\text{h}}\right)}{\text{P}_{\text{engine}} (\text{Kw})}$$

CO₂ Emissions Estimation

Carbon dioxide emissions resulting from fuel consumption were estimated using the relationship:

$$\text{CO}_2 \text{ Emissions} = \text{Fuel Consumption} \times 2.68$$

Where:

CO₂ Emissions = Quantity of carbon dioxide gas produced from fuel combustion

Fuel Consumption = Quantity of fuel consumed by the tractor (liters/hour)

The value (2.68 kg CO₂/liter of diesel) represents the standard emission factor.

Statistical Analysis

The data were subjected to analysis of variance (ANOVA) to assess the impact of the examined factors and their interactions on the dependent variables. The least significant difference (LSD) test was employed at a significance level of 0.05 to compare the means.

RESULTS AND DISCUSSION

The effect of operating conditions on fuel consumption

The study results stated that identified operating parameters (advance speed and gear engagement) had a significant effect on the fuel consumption of agricultural tractors during plowing works. The results show that fuel consumption increases with speed and such effect is stronger in lower gears, while it strongly decreases more slowly than the engine speed in higher ratios.

The results also demonstrate a distinct interaction between forward speed and gear ratio, since fuel consumption was dependent on various operating combinations. fuel consumption differed based on the different driving conditions. It can be seen that maximum fuel use was at higher speeds (7 km/h) in lower gear due to engine

load and soil resistance, which used more fuel to compensate for power losses. On the other hand, the lowest fuel consumption was observed at an average speed (5 km/h) in medium or high gears where the engine worked at a much closer range of efficiency. The results showed that, relative to a normal operation mode, the shift-up-throttle-back technique is successful in reducing fuel consumption by 12–18%, demonstrating an important improvement in energy utilization; these data indicate that running at higher engine speeds and low gear ratios produces increased thermal losses as waste heat, lower thermal efficiency, and greater slippage. On the other hand, higher gear ratios at lower engine speeds provide the best power efficiency and lowest energy loss.

Statistical difference was detected and compared between various treatments that were analyzed. this is clear from the least significant difference (LSD = 4.14), which indicates that all differences were statistically significant at various number of hours operated. As presented in Table (2) and Figure (2), the maximum amount of fuel consumed was obtained for treatment (G1-S3) compared to the other treatments, with 14.2 liters/hour, and this difference also proved highly significant. Treatments (G3-S1, G1-S1, G3-S2 and G2-S2) were assigned to the second lowest values and classified into one group at a level of significance. These results are consistent with recent studies that indicate optimization of operating conditions such as advance speed, tillage depth and gear ratios improves fuel consumption performance characteristics (specific unit demand reduces) and gives the tractor a better operational efficiency under high-traction tillage tasks (Tang., 2025).

Field Efficiency

Results from the study showed a very significant effect of the operating conditions (advance speed and gear engagement) on efficiency, which ranged from 62.4 % to 84.7 % in several situations

The best efficiency in the field (84.7%) was achieved at a moderate speed (5 km/h) with a medium gear, since it mediates between high operating speed and minimum wasteful downtimes: e.g. turning the machine on tracks or overlapping.

In contrast, the minimum field efficiency (62.4%) with speed (7 km/h) & low gear was resulted from increased slippage due to frequent abnormal stops and higher time spent in rectifying the tractor path into the field.

Table (2): Interaction effect of forward speed and gear ratio on fuel consumption ($L h^{-1}$)

Gears (G)	speed (S)	Fuel consumption (liters/hour)
G1	S1	9.2
G1	S2	10.5
G1	S3	14.2
G2	S1	9.8
G2	S2	9.5
G2	S3	12.0
G3	S1	9.0
G3	S2	9.3
G3	S3	11.5
LSD (0.05)	—	4.14

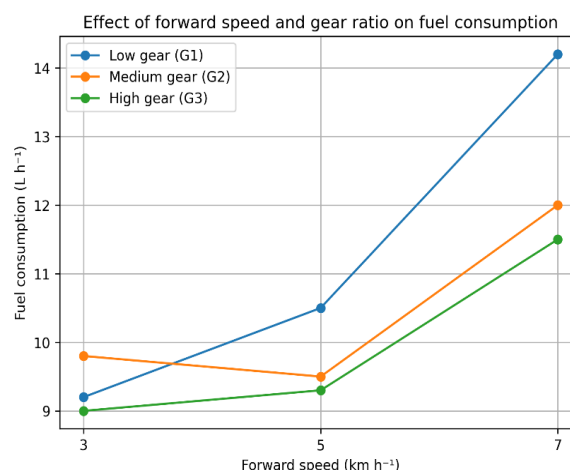


Figure (2): Effect of forward speed and gear ratio on fuel consumption ($L h^{-1}$)

The results showed that the use of an improved operation strategy (by upshifting gears and downshifting engine speed) increased field efficiency by 10–15% compared to conventional operating procedures. Points out that field efficiency depends not only on the useful power of a tractor, but on how well actual time spent in the field is utilized. Traveling at inappropriate speeds, or using low gears leads to excessive time loss due to slippage and the need to pass back the same route and unnecessary longer turning maneuvers at field boundaries. On the contrary, by running at a optimal speed with the right gear requires very little lost time and adds positively to field efficiency.

Statistical analysis showed that significant differences occurred between the studied treatments (LSD = 5.61), indicating that the field efficiency in different cultivated treatments was statistically significant. the highest field efficiency 84.7% and significantly different with most of treatments was achieved by the Treatment(G2S2), while (G1S3) registered the lowest values 62.4%, as indicated in Table 3 and Figure 3.

The results support the claims made by (Janulevičius et al., 2019) rapidly increases field efficiency and reduces time losses in the field due to improvements in operational conditions of agricultural tractors.

wheel slip

The study findings indicated that the wheel slip rate of agricultural tractors was markedly influenced by varying operating conditions (advance speed and gear ratio), with slip values ranging from 6.8% to 18.9% during field tillage operations.

Slip value was found to be maximum (18.9%) at high velocity (high speed) of 7 km/h with low gear. This comes down to an increased load on the rear wheels where engine speed falls behind soil resistance, resulting in a significant power loss to unproductive slippage.

On the other hand, lowest slip (6.8%) observed at 5 km/h in medium gear presented an efficient balance point between traction and soil resistance. This improvement in traction gave less power loss. Results showed that the use of a modified operating strategy (increased gear and decreased engine speed) reduced slippage by 20–30% compared with

Table (3): Interaction effect of forward speed and gear ratio on field efficiency (%)

Gears (G)	speed (S)	Field Efficiency%
G1	S1	70.2
G1	S2	75.4
G1	S3	62.4
G2	S1	78.3
G2	S2	84.7
G2	S3	74.6
G3	S1	76.8
G3	S2	81.2
G3	S3	72.5
LSD (0.05)	—	5.61

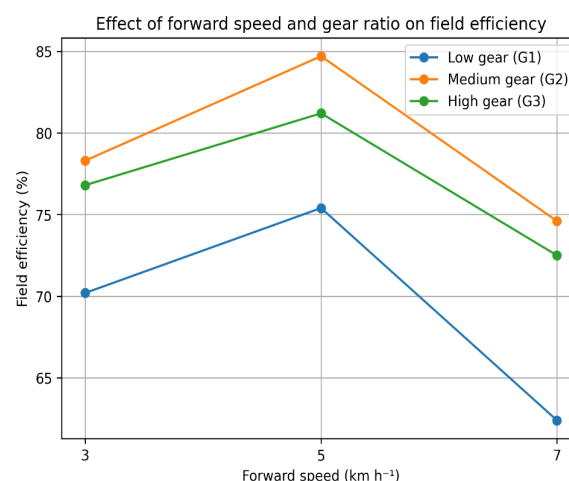


Figure (3): Effect of forward speed and gear ratio on field efficiency (%).

standard operating techniques, thus improving tractor performance and fuel consumption. The differences between the treatments studied were found to be significant (LSD = 2.99) as confirmed statistically through analysis of variance slippage levels were statistically significant. as showed in Table 4 and Figure 4.

The results are in accordance with (Hamid., 2024), who found that slippage of agricultural tractors is an important parameter for evaluating the field performance efficiency, as a high value hinders machine ability to reach higher operational efficiency.

Table (4): Interaction effect of forward speed and gear ratio on wheel slip (%)

Gears (G)	speed (S)	wheel slip (%)
G1	S1	12.4
G1	S2	10.2
G1	S3	18.9
G2	S1	8.5
G2	S2	6.8
G2	S3	17.3
G3	S1	7.4
G3	S2	8.1
G3	S3	14.7
LSD (0.05)	—	2.99

Specific fuel consumption (SFC)

The results showed that specific fuel consumption values changed from 0.24-0.41 liters/kWh, as the operating conditions varied.

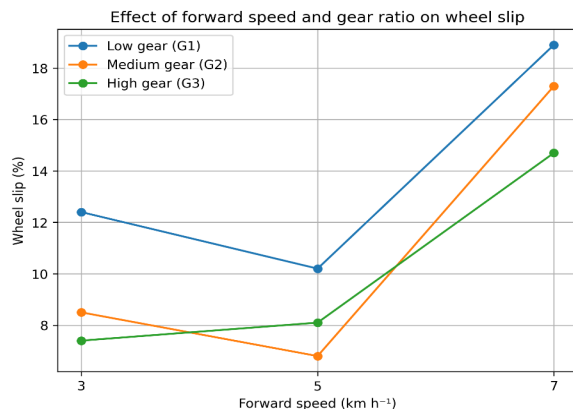


Figure (4): Effect of forward speed and gear ratio on wheel slip (%)

The lowest value (0.24 liters / kWh) was at a medium tractor speed (5 km/h in the middle gear, implying that the tractor operated with efficiency parameters of engine functioning within the range from optimal to low load).

Alternatively, the maximum (0.41 liters/kWh) happened at high speed (7 km/h) in low gear due to higher engine load, increased slippage losses as well as lower efficiency of power transmission.

Results showed that use of an improved operational method (higher gear and lower engine speed) reduced specific fuel consumption by 15–22% compared to baseline operating methods.

The results suggest that specific fuel rate is an extremely important index of the energy conversion efficiency in internal combustion engines, as lower specific fuel rates are associated with improved utilization of available power. The more logical explanation would be that running a tractor at higher engine speeds (in low gears) will lead to higher fuel consumption without the expected increase in power output, causing specific fuel consumption (SFC) values to rise.

On the other hand, moderate loads matched by appropriate selection of gear help in maintaining thermal efficiency of tractor engine and avoid power loss thereby reducing specific fuel consumption. The negative correlation of SFC and slippage shows that when power output is increases with high slippage (no labor), it causes higher specific fuel consumption (SFC), which agrees with this study. Statistical analysis showed that there were significant differences between the studied treatments (LSD = 0.03), confirming that

the observed differences in specific fuel consumption were statistically reliable. Moreover,from the analysis, it was noted that treatment (G2S2) had the minimum specific fuel consumption of (0.24 LkW⁻¹h⁻¹), however, treatment (G1S3)gave the highest value of (0.41 LkW⁻¹h⁻¹) Table (5) and Figure (5).

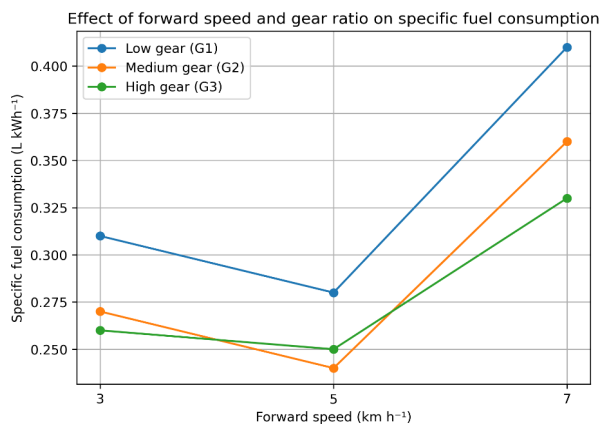
The results of the study support those of (Amer., 2024) who maintained that fuel utilisation and operational efficiency of agricultural tractors is affected by a combination of operating conditions, advance speed and tillage type. Inefficient operations lead to increased fuel consumption and reduced performance in the field.

Table (5): Interaction effect of forward speed and gear ratio on specific fuel consumption

Gears (G)	speed (S)	Specific fuel consumption (SFC) (L kWh ⁻¹)
G1	S1	0.31
G1	S2	0.28
G1	S3	0.41
G2	S1	0.27
G2	S2	0.24
G2	S3	0.36
G3	S1	0.26
G3	S2	0.25
G3	S3	0.33
LSD (0.05)	—	0.03

CO₂ Emissions Estimation

The results showed that carbon dioxide emissions ranged from 3.9 to 39.4 kg CO₂/hr, depending on



Figure(5): Effect of forward speed and gear ratio on specific fuel consumption (L kWh⁻¹).

operating conditions. The maximum emissions value (39.4 kg CO₂/hr) was derived at high speed (7 km/h) with low gear due to the high consumption which implicated those adjustment conditions. In contrast, the lowest value (23.9 kg CO₂/hr) occurred at a medium speed (5 km/h) in a medium gear at a medium speed (5 km/h) with a medium gear

.Results showed that an improved operating strategy (upshifting and downshifting) resulted in a 12%–18% reduction of carbon emission, relative to traditional operating procedures.The findings imply a direct link between the emissions of carbon dioxide and fuel consumption in the diesel engine which exhibit an inevitable increase in carbon emissions due to combustion, and therefore this relation reflects their nature. Furthermore, improper operation condition like using too high gears when the speed is higher will increase the energy loss and it will increase more fuel consumption which directly related to more carbon emission. Conversely, appropriate gear selection and operational speed limits fuel consumption and environmental impacts associated with agriculture. Some of the tested treatments were statistically different from each other indicated by the lowest significant (LSD = 4.49), which confirms that differences in CO₂ emissions were statistically important according to statistical analysis. As shown in table (6) and Figure (6), treatment (G2S2) has the lowest emissions level with 23.9 kg CO₂/hr, and the highest value 39.4 kg CO₂/hr obtained on treatment (G1S3).

A measurement method, and essentially that was already based on internationally accepted default emission factors as further indicated in the Intergovernmental Panel on Climate Change (IPCC) guidelines

These results show that by improving the productivity of agricultural tractors, we not only meet economic factors but also substantially reduce CO₂ emissions and contribute to sustainable agriculture goals.)Balać et al. 2025)

CONCLUSION

Based on the results reported under field conditions in this study, conclusions can be drawn regarding:

- A powerful tractor engine combined with optimum

Table (6): Interaction effect of forward speed and gear ratio on CO₂ emissions

Gears (G)	Speed (S)	CO ₂ emissions (kg h ⁻¹)
G1	S1	28.5
G1	S2	26.8
G1	S3	39.4
G2	S1	25.4
G2	S2	23.9
G2	S3	34.7
G3	S1	24.8
G3	S2	25.1
G3	S3	30.6
LSD (0.05)	—	4.49

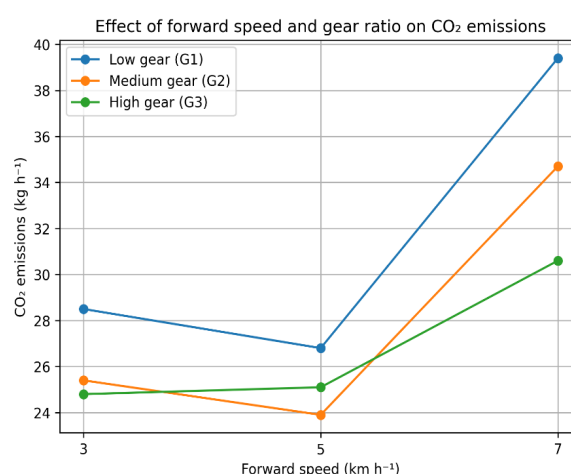


Figure 6. Effect of forward speed and gear ratio on CO₂ emissions (kg h⁻¹).

working speed improves fuel efficiency among all tillage tools.

- Optimum input-output performance between the tractor system parameters and field operating conditions are obtained through moderate forward speed if used in moderate gear ratio providing low specific fuel consumption and high apparent fuel economy.

- Slippage is an important factor in Agricultural Power Transmission System When it experiences a imbalance between traction force and soil resistance and no work is done on the wheels, a high slippage ratio implicates low delivery of power, harming global efficiency and fuel consumption. Specific fuel consumption (SFC) is a very important parameter in terms of assessing the potential operating efficiency



of an engine, since low SFCs correspond to optimal engine performance and are closely related to energy efficient operation. As suspected, there is a linear relationship of fuel consumption with carbon dioxide emissions signifying also that reduction of environmental pollution from agricultural operations can be achieved through optimizing operational efficiency. The findings confirmed that better working conditions of agricultural tractors may be used as a useful and cost-effective means for increasing energy efficiency and fulfilling the needs of sustainable agriculture.

Recommendations:

- operating agricultural tractors at reasonable rates (proper gear selection)
- Also recommended is a higher gear ratio with lower engine speed (Shift-up/Throttle-back) as it positively influences consumption and CO₂ emissions.
- Soil conditions (moisture and texture) have a direct influence on soil resistance, slip and overall performance efficiency which is why these should be monitored prior to any tillage operation. More so, timely upkeep of farm tractors is imperative to preserve engine effectiveness while reducing energy wastage.
- Training of tractor drivers on proper operating conditions (speed, gear ratio, load) should also be done to allow for agronomy extension work in good energy practice and sustainable agricultural development.
- More research is needed on how different soil kinds and tillage machinery impact tractor performance and fuel consumption. More extensive research is warranted on gaseous emissions (e.g., NO_x and CO₂), and more efforts should be made to support the use of other sources of energy or biofuels for the purpose of reducing dependence on fossil fuel.

.ETHICS STATEMENT:

This study did not involve human participants or animals. All experimental procedures were conducted in accordance with institutional and national guidelines for plant research.

ORIGINALITY AND PLAGIARISM:

The author confirms that this manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. All sources used have been appropriately cited, and the manuscript has been prepared in compliance with plagiarism and publication ethics standards.

CONSENT FOR PUBLICATION

Not applicable.

COMPETING INTERESTS:

The author declares no competing interests.

DATA AVAILABILITY:

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS:

The author solely conceived and designed the study, conducted the experiments, collected and analyzed the data, and wrote and revised the manuscript.

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