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Energy Utilization and Greenhouse Gas (GHG) Emissions of Tillage Operation in Wetland Rice Cultivation

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Abstract: In Malaysia, wetland rice is cultivated over two cropping seasons: the main season, from June to November, and the off-season, from January to June. The aim of this study was to investigate tillage operations in rice production in relation to actual field operations and under real field conditions for two rice cultivation seasons. The results showed that 80.7%, 17%, and 2.3% of the total time was spent on the actual operation, turning time, and reversing time, respectively. The results also showed that the mean effective field capacity, field efficiency, and fuel consumption were 1.2 ha/h, 80%, and 7.6 L/ha, respectively. The distribution of energy used in the first, second, and third tillage passes amounted to 37%, 33%, and 30% of the total energy, respectively. Fuel, machinery, and total GHG emissions were 62.4, 7.6, and 70 kg CO_2eq/ha, respectively. Fuel represented the highest contributor of energy expenditure and GHG emissions. The distributions of GHG emissions in the first, second, and third tillage passes were 37%, 32%, and 31% of the total GHG emissions. The results reveal that carrying out minimum-tillage operations led to a reduction in environmental impacts.

Keywords: field performance; energy use; greenhouse gas emissions; tillage operation; environmental impact

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1. Introduction

Rice is the most produced and consumed cereal in Malaysia [1]. The average amount of rice produced in Malaysia in 1968 was 1.4 million tons, which has increased by 57.2%, with 2.3 million tons produced in 2016. With proper infrastructural support and the development of new rice varieties by the government, the country's average yield increased from 2.9 tons/ha in 1980 to 3.8 tons/ha in 2014 [2]. Land preparation in rice cultivation is performed to provide suitable growing conditions for optimum plant establishment. The result of any good land preparation activity is the facilitation of effective weed control and the enhancement of water-use efficiency during the crop-growing season. Tillage is also a concern as it facilitates the movement of air and water through the breaking up and pulverization of soil [3]. Tillage operations in rice cultivation are used to enhance soil surface roughness and aerate soil by increasing porosity and stimulating the decomposition of crop residues. Hence, tillage is considered a key factor in optimizing growth. In rice cultivation, tillage usually takes place at least twice in one growing season. It consumes up to 59% of the total diesel required for all operations in crop production [4]. Performance data on tractors and implements constitute a crucial factor for the management of agricultural machinery; they facilitate and support the optimal selection of suitable tillage machines for a particular farm, which minimizes crop production energy input [5].

Although agriculture is considered a major producer and consumer of energy, agricultural production is positively related to energy input. Agricultural operations need energy in one form or another, including fertilizer energy, fuel energy, animal energy, electricity energy, and human energy [6]. To address the concern about agricultural production's impact on the environment, it is important to determine the relationship between energy consumption and the adoption of conservation tillage [7]. The authors of one study found that tillage contributed 7.5% and 7% of the total energy inputs for transplanting and broadcast seeding, respectively [8]. Soil tillage is a concern because it accounts for the greatest share of energy consumption and it is the most expensive operation among field operations, as it consumes between 55% and 65% of the total direct energy [9]. Since the intensive use of energy inputs harms the environment and, thus, affects human health, crop production following the efficient usage of energy sources can ameliorate these effects, improve agricultural sustainability, and conserve natural resources [10].

Greenhouse gas (GHG) emissions are emissions from gases that are absorbed in the atmosphere and emit radiation within the infrared range. Carbon dioxide is the main contributor to greenhouse gases, and there is a significant correlation between agricultural production, energy use, and CO_2 emissions. GHG emissions can change the environment, and these changes have uncontrolled effects on the agricultural sector. GHG emissions from agriculture come from several sources, such as machinery, diesel fuel, chemical fertilizers, biocides, and electricity. Therefore, an increase in energy inputs in agricultural activities can lead to an increase in GHG emissions. An increase in CO_2 levels in the atmosphere will cause an increase in the average global surface air temperature, with changes in rainfall patterns. So, conducting research on GHG emissions from agricultural production is very important. Wetland rice production contributes more than half of the world's agricultural GHG emissions [11]. Global warming caused by GHG emissions from agriculture has been a primary factor affecting agricultural sustainability. However, GHG emissions from agriculture decreased by 20% in the period from 1990 to 2011 [12].

There is limited information in the literature about the analysis of the energy inputs of soil tillage systems in rice farming and their impact on the environment. The novelty and positioning of this work are demonstrated by the notion that it is expected to significantly contribute to the areas of conserving farm energy, improving tillage operations in paddy fields, and reducing greenhouse gas emissions.

The primary objective of the present study was to assess tillage operations in wetland rice fields. The specific objectives were (1) to investigate the working performance of tractors, (2) to analyze the time motion of the tractors, (3) to determine the energy equivalents of sources in tillage operations used in rice farming, (4) to determine the GHG emissions from tillage operations, and (5) to investigate the working performance, energy use, and GHG emissions based on tillage passes.

2. Materials and Methods

The selected study area is located at 3°29′47″ N and 101°09′56″ E in Sungei Burong, Kuala Selangor, Malaysia. The cultivation area is located within the area that is under the management of the North West Integrated Agricultural Development Authority Rice Scheme. In this study, field tests were conducted on 62 plots across two cropping seasons: the main season, from June to November 2017, and the off-season, from January to June 2018. In the area under research, farmers use KUBOTA M9540 (4WD) tractors. They employ a rotary tillage machine with a 2.7 m working width for soil tillage. This machine is used to pulverize the soil for first and second tillage passes in both seasons. For the third tillage pass, the farmers use a 3 m rotavator. The first and second tillage passes were carried out on fields in their dry state, while the third tillage pass was performed after flooding the field with water (Figure 1). Puddling is the perfect tillage system for rice production because it minimizes weeds and makes soil hardpan, which reduces the permeability of the soil and, thus, minimizes the reduction in water irrigation through percolation [13]. All passes in tillage data, amounting to 186 passes in the 62 lots, were collected and analyzed for the main season and off-season.

(**a**) (**b**) (**c**) (**d**)

Figure 1. A farmer performing tillage in the study area with tractor–rotary tiller combination. (**a**) Four-wheel-drive tractor. (**b**) First Tillage. (**c**) Second tillage. (**d**) Third tillage.

The measured parameters of the field performance of the machine as stated by ASAE Standard S495.1 [14] are commonly used to quantify the work performances of any agricultural machinery performing operations in the field [15]. The determined amounts of agricultural inputs of human labor, machinery, and consumed fuel used in tillage operations were converted to equivalent energy values in MJ/ha by using the energy conversion factor (Table 1). To determine the equivalent energy sources of tillage operations in wetland rice production, the method outlined in [8,16,17] was used. The amount of GHG emissions was obtained by using the method previously stated in [8]. Table 2 presents the implemented GHG emission coefficients.

Many researchers have calculated the human energy expenditure in rice production by using an estimated method in Malaysia [16,18], Myanmar [19], China [20], Bangladesh [21], Iran [22], India [23], Vietnam [24], and Thailand [25].

Table 1. Energy conversion coefficients.

Material	Conversion Coefficient	Unit	Source
Tractor	93.61	MJ/kg	[15]
Diesel	47.80	MJ/L	[18]
Human labor	1.96	MJ/h	[26–28]

Table 2. GHG emission Coefficients ($kgCO_{2eq/unit}$).

Input	Unit	GHG Coefficient	Reference
Diesel Fuel	L	2.76	[8]
Machinery	MJ	0.071	[8]

For the statistical analysis, all data of field performance, energy inputs, and GHG emissions were entered into MS Excel 2016 spreadsheet software and analyzed. A comparison between the main season and off-season and a comparison between tillage passes were conducted by using *t*-tests at a 95% confidence interval, assuming unequal variances [29,30].

The method of determining energy expenditures as well as greenhouse gas emissions is clearly explained in [8].

3. Results and Discussion

3.1. Field Performance of Tractor in Tillage Operation

The calculated parameters of tractor field performance including speed of operation, theoretical field capacity, effective field capacity, field efficiency, labor hour, and fuel consumption are presented in Table 3. These parameters are as mentioned in ASAE standards S495.1. Some authors [14] find that they are commonly used to quantify the work performance of any agricultural machinery performing operations in the field.

Table 3. Field performances of the studied tractor in tillage operations in the main season and off-season.

Performance	Main Season	Offseason	*p*-Value	Difference %
Operation Speed, km/h	5.03 ± 0.183 §	4.975 ± 0.327	0.4230 ns	1.1
Theoretical field Capacity, ha/h	1.605 ± 0.141	1.625 ± 0.185	0.2160 ns	−1.2
Effective Field Capacity, ha/h	1.22 ± 0.055	1.21 ± 0.100	0.2471 ns	0.8
Field efficiency, %	0.775 ± 0.018	0.765 ± 0.040	0.2284 ns	1.3
Labor hour, h/ha	0.83 ± 0.028	0.87 ± 0.139	0.1775 ns	−4.6
Fuel Consumption, L/ha	7.445 ± 0.317	7.76 ± 1.068	0.4124 ns	−4.1

§: At 95% confidence interval. ns: not significant.

The study revealed that there are no significant differences between main and off-season work performance. Figure 2 represents tractor performance in performing tillage operations as an average of the main season and the off-season. The effective field capacity, theoretical field capacity, field efficiency, labor hour, fuel consumption, and operation speed for the studied tractor were found to be 1.2 ha/h, 1.6 ha/h, 80%, 0.9 h/ha, 7.6 L/ha, and 5 km/h respectively.

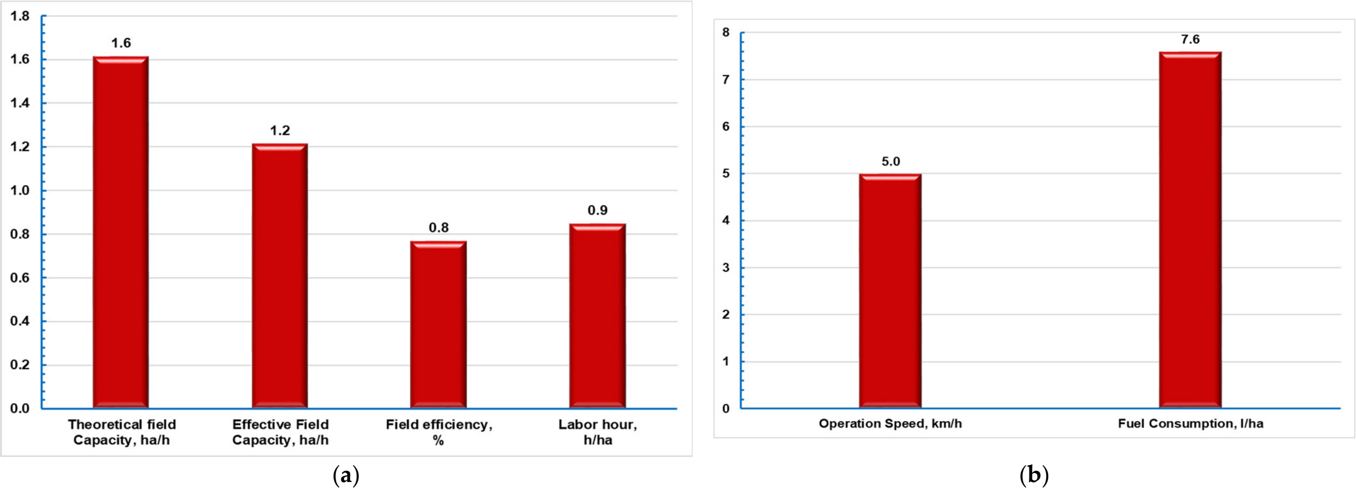

Figure 2. Tractor field performances in tillage operations (average of main season and off-season). (**a**) Field performances. (**b**) Operation speed and fuel consumption of the tractor.

The improvement of the operational efficiency of tractors has been the subject of considerable research. Operation efficiency could be improved by maximizing the work output or reducing fuel consumption [31].

Among the three tillage passes, the results revealed that the highest field capacity and lowest fuel consumption were recorded in the third tillage pass (1.3 ha/h and 6.87 L/ha), while the lowest field capacity and highest fuel consumption were recorded in the first tillage pass (1.2 ha/h and 8.43 L/ha). This reflects the effect of the wide working width (3 m) of the rotary tillers used in the third tillage pass, compared with the working width of the rotary tillers used in the first and second tillage passes (2.7 m). Therefore, less field time was required in the third tillage pass because the wide width necessitates fewer tractor passes to cover the farm area.

Although both the first and second tillage passes were performed using rotary tillers of the same working width of 2.7 m, a 2.8% higher effective field capacity (1.23 ha/h versus 1.18 ha/h) was recorded during the second tillage pass. This is because during the first tillage pass, the land was compacted and full of vegetation which required more tractive effort to pulverize, so more field time was required compared to conditions of the soil during the second tillage pass when the soil was loose with sparse or no vegetation (Figure 3).

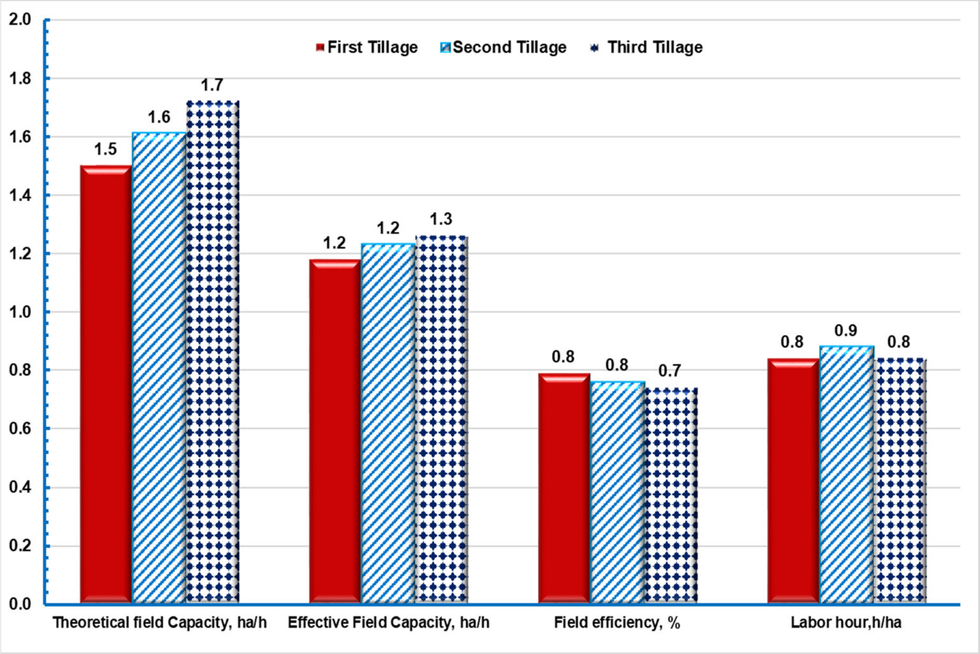

Figure 3. Comparison of tractor field performances among tillage passes (Average of main season and off-season).

3.2. Field Operation Time Distribution in Tillage Operations

The results of the analysis of field operation time distribution based on actual operation time, turning time, and reversing time with respect to tillage operations in the main season and the off-season are shown in Table 4. It was shown that the farmer spent 80.7% of the total tillage operation time performing actual tillage operations while 17% and 2.3% of the total operation time were spent turning and reversing, respectively.

Table 4. Time distribution of tillage operation in the main season and off-season, h/ha.

Performance	Main Season	Off-Season	Average	*p*-Value
Effective Time	0.83 ± 0.03 §	0.77 ± 0.08	0.8 ± 0.06	0.4230 ns
Cornering time	0.17 ± 0.01	0.17 ± 0.03	0.17 ± 0.02	0.2160 ns
Reverse time	0.02 ± 0.05	0.03 ± 0.03	0.02 ± 0.04	0.2471 ns
Total time	1.02 ± 0.03	0.96 ± 0.03	0.99 ± 0.03	0.2284 ns

§: At 95% confidence interval. ns: not significant.

3.3. Distribution of Energy Sources in Tillage Operations

The result revealed that the main season compared to the off-season had no significant differences in energy expenditure from tillage operations. The distribution of energy expenditures of the three energy sources used in tillage operations, namely fuel energy, machinery energy, and human energy, in the main season and off-season are presented in Table 5. Analysis of the result showed that when using a four-wheel-drive KUBOTA M9540 tractor to perform tillage operations, an average energy expenditure of 1204.3 MJ/ha was utilized. The highest contribution of 1090.4 MJ/ha representing 90.99% of the total average energy budget came from fuel energy. The share contributions of machinery utilization and human labor were 9.0% and 0.01% (108.9 and 5.0 MJ/ha), respectively.

Table 5. Distribution of energy sources in tillage operations in the main and off-seasons, MJ/ha.

Mean	Main Season	Off-Season	Average	*p*-Value
Human Energy	4.89 ± 0.20 §	5.12 ± 0.19	5.0 ± 0.20	0.4230 ns
Fuel Energy	1067.94 ± 32.55	1112.94 ± 43.80	1090.4 ± 38.5	0.2160 ns
Machinery Energy	106.41 ± 4.39	111.355 ± 4.16	108.9 ± 4.3	0.2471 ns
Total Energy	1179.24 ± 36.18	1229.415 ± 47.46	1204.3 ± 42.2	0.2284 ns

§: At 95% confidence interval. ns: not significant.

Tillage operations have the second highest mechanization index (0.96) in wetland rice production in Malaysia, second to harvesting operations (0.99) [8].

3.4. Distribution of Energy Sources Based on Tillage Passes

To analyze the variation in tillage energy use based on the number of tillage passes, the energy data from 186 tillage passes of 30 lots in the main season and 32 lots in the off-season were split into three groups depending on the tillage pass numbers (first, second, and third) during tillage operations in the main season and off-season (Table 6). The result showed that the shares of the energy used in the first, second, and third tillage passes were 37%, 33%, and 30% of the total energy, respectively. Figure 4 represents the share of tillage passes in the total energy of tillage operation as an average of the main season and off-season.

Table 6. Distribution of energy sources in tillage passes, MJ/ha (average of main and off-season).

Mean	Main Season	Off-Season	Average	*p*-Value
First Tillage	436.26 ± 27.58 §	444.75 ± 15.45	440.50 ± 21.48	0.4230 ns
Second Tillage	381.16 ± 20.63	415.74 ± 31.85	398.45 ± 26.51	0.2160 ns
Third Tillage	361.82 ± 21.02	370.20 ± 12.99	366.01 ± 17.68	0.2471 ns
All Tillage Passes	1179.24 ± 36.18	1229.42 ± 47.46	1204.33 ± 42.31	0.2284 ns

§: At 95% confidence interval. ns: not significant.

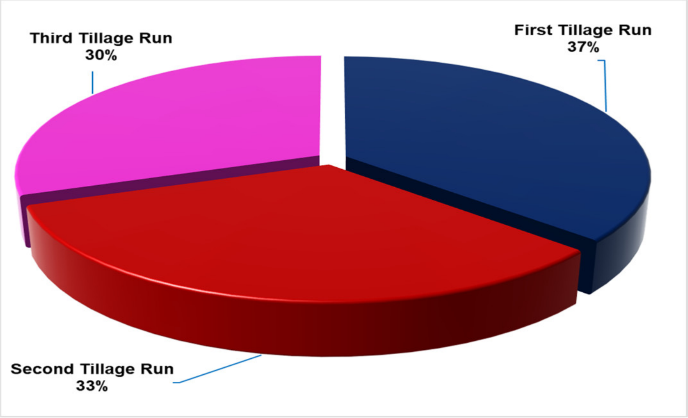

Figure 4. Distribution of energy use in tillage passes (average of main season and off-season).

The gravimetric moisture contents for first tillage pass and second tillage pass were found to be 0.36 and 0.32 (g/g), respectively, while the soil penetration resistances were found to be 0.40 and 0.43 (MPa) for first tillage pass and second tillage pass, respectively [3].

The results for the tillage energy expended from the three energy sources in performing the first tillage pass as presented in Figure 5 revealed that energy expended in the form of fuel consumed by the tractor had the highest contribution, representing 91.9% of the total energy expenditure. Energy expenditure contributions due to machinery utilization and human labor were 8% and 0.1% respectively.

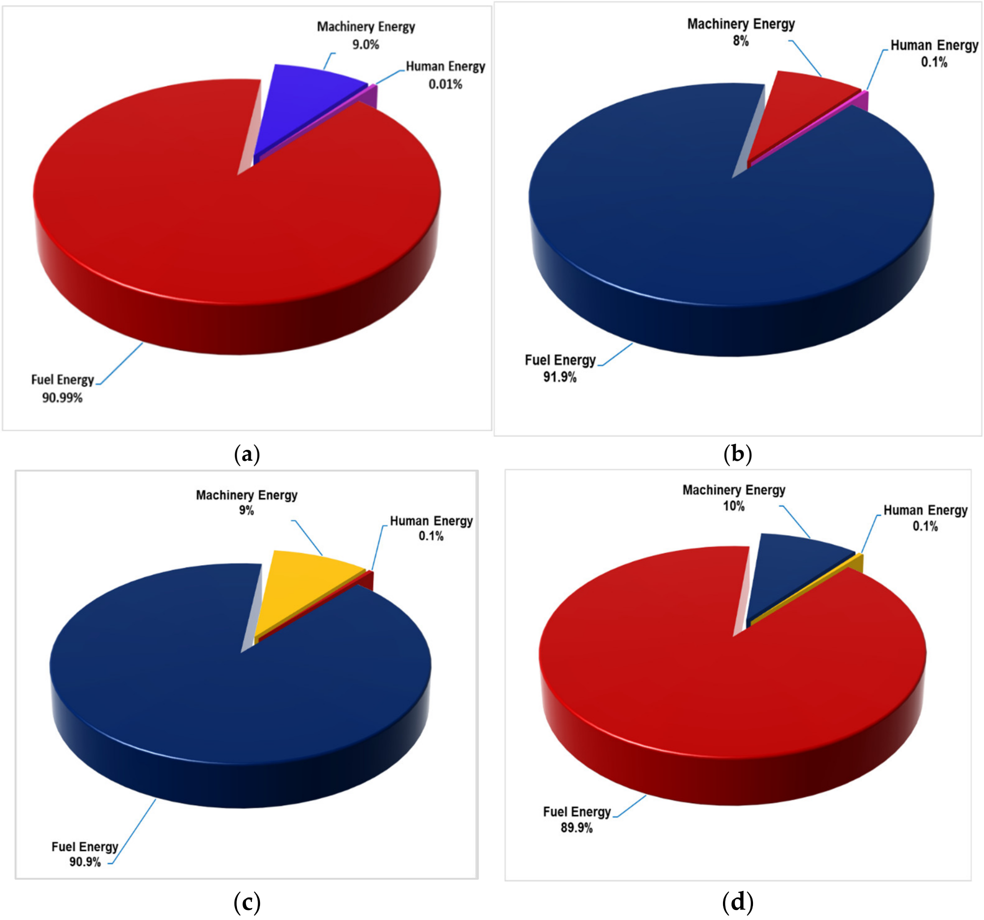

Figure 5. Distribution of energy sources in different tillage operation passes (Average of main season and off-season). (**a**) All tillage passes. (**b**) First tillage pass. (**c**) Second tillage pass. (**d**) Third tillage pass.

The results for the tillage energy expended from the three energy sources in performing the second tillage pass revealed that energy expended in the form of fuel consumed by the tractors had the highest contribution, representing 90.9% of the total energy expenditure. Energy expenditure contributions due to machinery utilization and human labor were 9% and 0.1%, respectively (Figure 5). During the third tillage pass, energy expenditure due to human labor and machinery contributed 10% and 0.1% of the total energy expenditure. Fuel energy expenditure, as in the first and second tillage passes, accounted for the highest share of 89.9%.

The results revealed that in all tillage passes, energy expenditures due to the fuel consumption of the tractor accounted for the share contribution of the total energy and was followed by the energy expended through machinery use. The last contribution among the three energy sources was energy use due to human labor (Figure 5).

Although a marked increase in machinery energy expenditures is recorded in the third tillage pass compared to the second tillage pass (1.5 MJ/ha), a significant decrease in fuel consumption of about 28.42 MJ/ha was observed. Machinery energy expenditure in the third tillage pass was also 1.24 MJ/ha higher compared to that of the first tillage pass. The reason may be due to the differences in the sizes and, hence, the weight of implements used. A wider rotary tiller with an average working width of 3 m and an average weight of 560 kg was used in performing the third tillage pass, compared to the average working width of 2.7 m and an average weight of 550 kg for the rotary tillers used in the first and second tillage passes. Since machinery energy expenditure is a function of the machine's weight and its field time, the use of heavier implements led to more machinery energy expenditure in the third tillage pass compared to the first and second tillage passes.

Generally, significant reductions in the total tillage energy were observed with increases in the number of tillage passes. A 10.1% reduction in tillage energy was recorded in the second tillage pass compared to the first tillage pass. A further reduction of 6.9% of the energy was observed in the third tillage pass compared to the second tillage pass (Figure 6). A further reduction of 16.2% of the energy was observed in the third tillage pass compared to the first tillage pass. The reason is that during the first tillage pass, the farmlands were virgin, dry, and full of vegetative cover with soil that was relatively compacted, thus requiring greater tractive efforts to till. However, during the third tillage pass, the soil is loose, having no vegetation due to the previous tillage passes, and moist or saturated due to flooding, thereby posing little resistance to the soil-engaging implement, therefore resulting in reduced energy demand. The decreasing trend in energy expenditure with an increase in the number of tillage passes is supported by some researchers [6] who pointed out that vegetative cover, soil type, and moisture status are important factors influencing tillage energy.

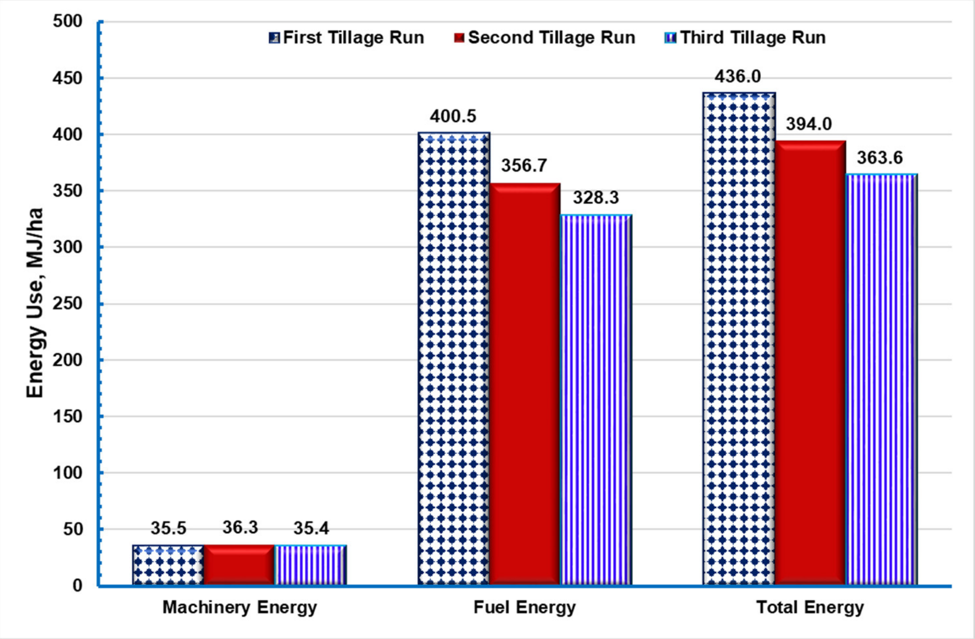

Figure 6. Comparison of energy sources among tillage passes (average of main season and off-season).

3.5. Greenhouse Gas (GHG) Emissions in Tillage Operation

The result revealed that there were no significant differences in the main season compared to the off-season in GHG emissions from tillage operation. The distribution of GHG emissions due to the two GHG emissions sources in tillage operations, namely fuel and machinery, in the main season and off-season are presented in Table 7. Analysis of the result showed that in performing the tillage operations, a total of 70 kg CO_2eq/ha of GHG emissions were emitted. The GHG emissions from fuel and machinery were 62.4 and 7.6 kg CO_2eq/ha, respectively. The result revealed that fuel represents the highest contributor to total GHG emissions: 89%. The share of machinery was 11% (Figure 7). Figure 8 represents the share of energy sources in tillage operation as an average of the main season and off-season.

Table 7. GHG emissions of tillage operation in the main season and off-season, kg CO_{2eq}/ha.

Mean	Main Season	Off-Season	*p*-Value	Difference %
1. Machinery GHG	7.6 ± 0.31 §	7.7 ± 0.30	0.0611 ns	−2.2
2. Fuel GHG	61.7 ± 1.88	63.2 ± 2.57	0.1754 ns	−2.4
Total GHG emissions	69.2 ± 2.13	70.9 ± 2.78	0.1005 ns	−2.3

§: At a 95% confidence interval. ns: not significant.

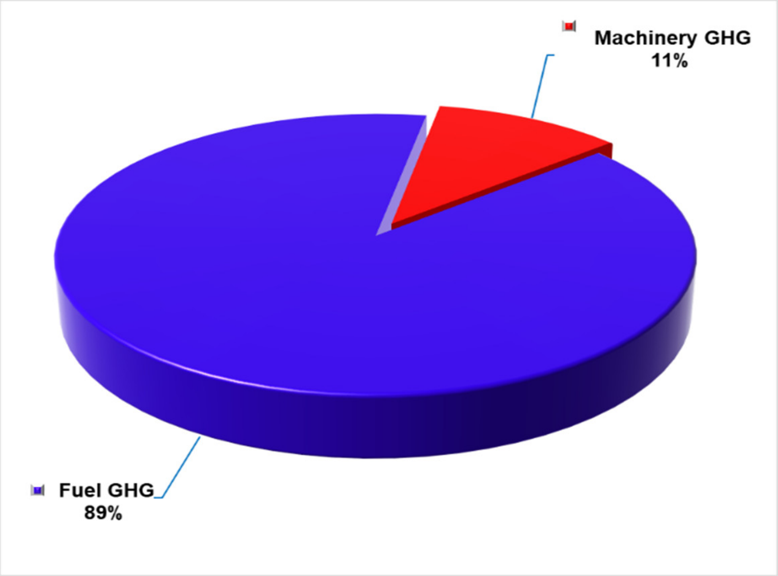

Figure 7. Distribution of GHG emissions sources in tillage operation (average of main and off-season).

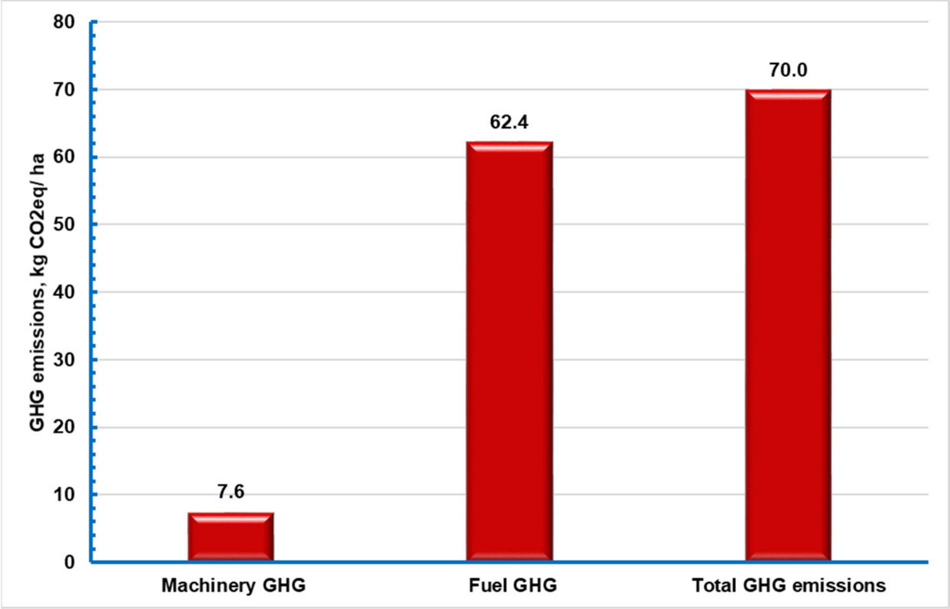

Figure 8. Distribution of GHG emissions sources in tillage operation (average of main and off-season).

Some researchers in their study revealed that the consumption of 1.0 Lof diesel fuel during tractor operation produces 3.76 kg of CO_2 gas associated with the greenhouse effect [32].

A significant decrease in GHG emissions could be possible with good agricultural field practices. Diesel fuel should be reduced in tillage operations by applying minimum tillage and selecting standard machinery or adopting proper technologies that could operate efficiently in the field. Some authors tested the effect of the working speed of a tractor on fuel consumption and GHG emissions; they found that the lowest fuel consumption and the lowest CO_2 emissions per hectare were achieved at a working speed of 2.5 m/s [30]. Some researchers found that improved management reduced CO_2-equivalent emissions between 11% and 16% relative to traditional practices [33]. Reducing greenhouse gas emissions is vital in agriculture. Management options to reduce GHG emissions are broad and include improving the efficiency of the use of inputs such as diesel, increasing the use of renewable energy, and modification of crop rotation systems [34].

Replacing diesel with biodiesel can significantly reduce greenhouse gas emissions because biodiesel is more environmentally friendly and contributes less to global warming than diesel. A 3.9% saving in GHG emissions was achieved by replacing diesel-powered farm machinery with biofuel-powered machinery [35]. The authors found that the change from diesel- to biofuel-powered farm machinery achieved a 3.4% reduction in GHG emissions [32]. Some researchers recorded that although there was a small increase in fuel consumption with increasing biodiesel content, there was a substantial reduction in net CO_2 emissions for tillage operations with higher biodiesel contents [36].

Applying new agricultural machinery and tractors with higher field capacity, selecting appropriate types and sizes of technological machinery, applying all operations with recommended speeds, timely maintenance, and applying minimum tillage operations lead to reducing GHG emissions.

3.6. Greenhouse Gas Emissions in Tillage Operation-Based Run

The results revealed that in all tillage passes, GHG emissions from fuel consumed by the tractor accounted for the highest share of the total GHG emissions and was followed by machinery GHG emissions (Figure 9).

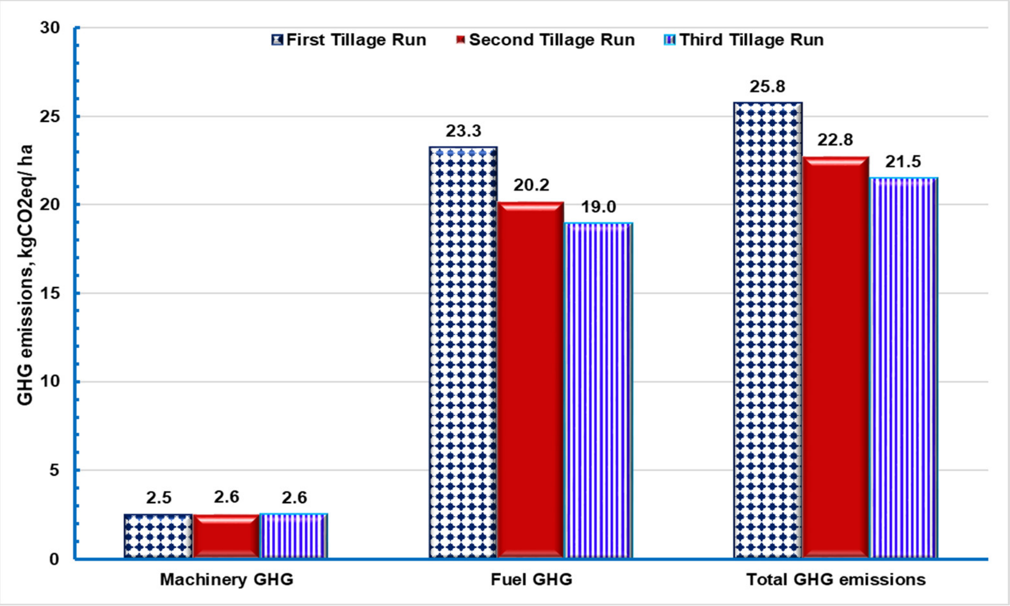

Figure 9. Distribution of GHG emissions sources in tillage passes (average of main and off-season).

The result showed that the distribution of GHG emissions in the first, second, and third tillage passes were 37%, 32%, and 31% of the total GHG emissions, respectively. Figure 10 represents the share of tillage passes in the total GHG emissions of tillage operations as an average of the main season and off-season. Researchers found that reducing the number of tillage passes has a lower environmental impact compared to conventional tillage systems [37].

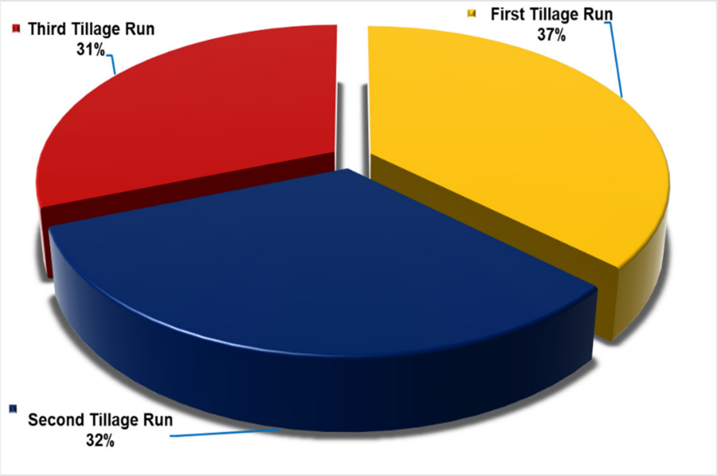

Figure 10. Distribution of GHG emissions in tillage passes (average of main season and off-season).

4. Conclusions

This study is limited to lowland rice fields and was conducted to investigate the working performance of a four-wheel tractor (KUBOTA M9540), distribution of field operation time, distribution of energy expenditure, and greenhouse gas GHG emissions from tillage operations under actual field operations in real field conditions for two rice cultivation seasons. From the results of the study, the following conclusions are drawn:

- The effective field capacity, theoretical field capacity, field efficiency, labor hour, fuel consumption, and operation speed of the tractor were 1.2 ha/h, 1.6 ha/h, 80%, 0.9 h/ha, 7.6 L/ha, and 5 km/h, respectively;
- Among the three tillage passes commonly made on rice fields, the study revealed that the highest field capacity and lowest fuel consumption were recorded in the third tillage pass (1.3 ha/h and 6.87 L/ha). The lowest field capacity and highest fuel consumption were recorded in the first tillage pass (1.2 ha/h and 8.43 L/ha);
- The farmer spent 80.7% of the total time performing actual tillage operations while 17% and 2.3% of the total operation time were spent turning and reversing, respectively;
- The highest contributor of energy expenditure in tillage operations was fuel energy expenditure, which represented 90.99% of the total energy. The contributions of machine utilization and human labor expenditure were 9.0% and 0.01%, respectively;
- The distribution of the energy used in the first, second, and third tillage passes were 37%, 33%, and 30% of the total energy, respectively;
- In performing the tillage operations, a total of 70 kg CO_2eq/ha of GHG emissions were emitted. GHG emissions resulting from fuel and machinery totaled to 62.4 and 7.6 kg CO_2eq/ha, respectively. Hence, fuel is the highest contributor to total GHG emissions: 89% of the total GHG emissions. The contribution of machinery was 11%.

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