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Application of Predictive Model for Tractor Fuel Consumption in the Gezira Scheme, Sudan

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Abstract

Fuel scarcity and rising energy costs are major challenges for mechanized agriculture in large-scale irrigated schemes such as the Gezira scheme, Efficient planning and allocation of diesel fuel are therefore critical for sustaining mechanized farming operations and maintaining productivity. This study aimed to apply a previously developed and validated predictive power model for tractor fuel consumption to support fuel requirement estimation, operational planning and economic analysis under real field conditions in the Gezira scheme. The model was used to estimate specific volumetric fuel consumption (SVFC), specific volumetric fuel efficiency (SVFE), fuel consumption per unit area (L/ha), unproductive fuel losses associated with off-road tractor movement, and total fuel requirements at farm and scheme levels. The application covered major crops grown in the Gezira scheme, namely cotton, wheat, groundnut and sorghum, under three farming systems: traditional, semi-mechanized, and fully mechanized. Fuel consumption for individual tractor–implement combinations was estimated using predicted hourly fuel consumption and effective field capacity, while unproductive fuel consumption was quantified based on tractor travel distance, speed and off-road fuel use. The model was further applied to estimate total seasonal and annual fuel demand and to assess fuel-related economic costs and potential savings. Results showed stable tractor fuel performance, with an average SVFC and SVFE values were 0.19 L/kW·h and 5.36 kW·h/L, respectively, indicating stable tractor fuel-use performance. Fuel consumption per hectare varied widely among implements, with unproductive fuel losses representing a significant share in high-capacity operations. Total fuel demand increased substantially with mechanization intensity, reaching a maximum under fully mechanized systems. Economic analysis revealed that fuel costs constitute a major component of production expenses, while a 10% reduction in fuel consumption could result in substantial financial savings at both farm and scheme levels. The findings demonstrate the practical applicability of the developed power model as a reliable decision-support tool for fuel budgeting and mechanization planning in large-scale irrigated agricultural systems.

Keywords: Tractor fuel consumption, predictive modeling, agricultural mechanization, unproductivefuel loss; Gezira scheme, Sudan.

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تطبيق نموذج تنبؤي لاستهلاك وقود الجرارات في مشروع الجزيرة، السودان

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المستخلص

يُعدّ نقص الوقود وارتفاع تكاليف الطاقة من التحديات الرئيسية التي تواجه الزراعة الآلية في مشاريع الري واسعة النطاق، مثل مشروع الجزيرة. ولذلك، يُعدّ التخطيط الفعال وتوزيع وقود الديزل أمرًا بالغ الأهمية لاستدامة عمليات الزراعة الآلية والحفاظ على الإنتاجية. هدفت هذه الدراسة إلى تطبيق نموذج تنبؤي مُطوّر ومُدقّق سابقًا لاستهلاك وقود الجرارات، وذلك لدعم تقدير احتياجات الوقود، والتخطيط التشغيلي، والتحليل الاقتصادي في ظروف الحقل الفعلية في مشروع الجزيرة. استُخدم النموذج لتقدير استهلاك الوقود الحجمي النوعي(SVFC) ، وكفاءة استهلاك الوقود الحجمي النوعي(SVFE) ، واستهلاك الوقود لكل وحدة مساحة (لتر/هكتار)، وفقدان الوقود غير المُنتج المرتبط بحركة الجرارات على الطرق الوعرة، وإجمالي احتياجات الوقود على مستوى المزرعة والمشروع. شمل التطبيق المحاصيل الرئيسية المزروعة في مشروع الجزيرة، وهي القطن والقمح والفول السوداني والذرة الرفيعة، في ظل ثلاثة أنظمة زراعية: التقليدية، وشبه الآلية، والآلية بالكامل. تم تقدير استهلاك الوقود لمجموعات الجرارات والمعدات الزراعية الفردية باستخدام معدل استهلاك الوقود المتوقع بالساعة والقدرة الحقلية الفعالة، بينما تم تحديد كمية استهلاك الوقود غير المنتج بناءً على مسافة سير الجرار وسرعته واستخدامه للوقود على الطرق الوعرة. وطُبّق النموذج أيضًا لتقدير إجمالي الطلب الموسمي والسنوي على الوقود، ولتقييم التكاليف الاقتصادية المتعلقة بالوقود والوفورات المحتملة. أظهرت النتائج أداءً مستقرًا لاستهلاك وقود الجرارات، حيث بلغ متوسط قيمة استهلاك الوقود في الحقل (SVFC) وقيمة كفاءة استخدام الوقود في الحقل (SVFE) 0.19 لتر/كيلوواط ساعة و5.36 كيلوواط ساعة/لتر على التوالي، مما يشير إلى استقرار أداء استخدام وقود الجرارات. تفاوت استهلاك الوقود لكل هكتار بشكل كبير بين المعدات الزراعية، حيث مثّلت خسائر الوقود غير المنتجة نسبة كبيرة

في العمليات ذات القدرة العالية. ازداد إجمالي الطلب على الوقود بشكل ملحوظ مع زيادة كثافة الميكنة، ليصل إلى أقصى حد له في ظل الأنظمة المميكنة بالكامل. كشف التحليل الاقتصادي أن تكاليف الوقود تُشكّل عنصرًا رئيسيًا من نفقات الإنتاج، في حين أن خفض استهلاك الوقود بنسبة 10% يمكن أن يؤدي إلى وفورات مالية كبيرة على مستوى المزرعة والمشروع. تُظهر النتائج التطبيق العملي لنموذج الطاقة المُطوَّر كأداة موثوقة لدعم اتخاذ القرارات في مجال ترشيد استهلاك الوقود وتخطيط الميكنة في النظم الزراعية المروية واسعة النطاق.

الكلمات المفتاحية: *استهلاك وقود الجرارات، النمذجة التنبؤية، الميكنة الزراعية، هدر الوقود غير المُنتِج؛ مشروع الجزيرة، السودان.*

Introduction

Agricultural mechanization is a fundamental component of modern farming systems, providing enhanced productivity, improved timeliness of operations and better resource-use efficiency (Grisso *et al.*, 2004; Mamkagh, 2019). Mechanization reduces dependence on manual labor, enables large-scale operations within critical crop calendars and supports efficient input use, particularly in irrigated systems where large areas must be managed within narrow operational windows.

In Sudan, the Gezira scheme represents the largest and most important irrigated agricultural system, playing a crucial role in national food security and cash crop production (Yousif *et al.*, 2025). The scheme supports year-round cultivation of major crops such as cotton, wheat, groundnut, and sorghum, necessitating extensive use of diesel-powered tractors for soil preparation, planting, cultivation, and harvesting. As a result, diesel fuel becomes an indispensable input for sustaining agricultural productivity in the scheme.

However, fuel scarcity and rising fuel prices have emerged as significant constraints to agricultural production in Sudan, particularly during peak cultivation seasons when demand for fuel surges. Limited fuel availability at critical times, inefficient fuel allocation and high variability in field-level tractor fuel consumption have increased production costs and disrupted farm operations. Highlighting the urgent need for reliable tools that support fuel estimation and energy management.

Tractor fuel consumption is influenced by multiple interacting technical and operational variables, including engine load, transmission type, implement characteristics, field conditions and operator behavior (Wei, 2024; Xiao *et al.*, 2018). Research has shown that optimizing engine load and operating conditions can significantly improve fuel economy, while advanced designs such as hydro-mechanical transmissions and adaptive systems further enhance efficiency (Xiao *et al.*, 2018). In addition, fuel consumption models increasingly incorporate multiple parameters to improve prediction accuracy and operational relevance (Al-Sager *et al.*, 2024).

While numerous predictive models have been developed internationally, many are calibrated under temperate climates or controlled experimental conditions and may not fully reflect the unique operational environments of large-scale irrigated schemes in tropical contexts. Dimensional analysis and machine learning approaches have recently been applied to tractor fuel consumption prediction, demonstrating improved modeling flexibility and predictive performance (Labad *et al.*, 2024; Al-Sager *et al.*, 2024).

However, there remains a gap in applying such models to actual field operating conditions in regions like Sudan.

In a preceding study, a predictive power-based model for tractor fuel consumption was developed and validated specifically under the field conditions of the Gezira scheme, showing strong statistical performance and practical relevance. Nonetheless, the utility of such models depends on translating their outputs into actionable decision-support tools for fuel planning and mechanization management.

Therefore, this study builds on the previously developed predictive model by applying it to estimate key fuel consumption indicators across different operations, quantify fuel requirements per unit area and assess fuel demand under traditional, semi-mechanized and fully mechanized farming systems. The research also evaluates the economic implications of fuel consumption and explores strategies to reduce unproductive fuel losses. The findings aim to support effective fuel budgeting, mechanization optimization and energy-efficient practices in large-scale irrigated agricultural systems.

Materials and Methods

Study area

The study was conducted in Gezira irrigated scheme, which is located between the Blue Nile and White Nile Rivers to the south of Khartoum. One of the largest irrigated scheme in the region, covering about 0.924 million hectares. The scheme is located in semi-arid region. The soil is Vertisols, with high clay content (50-60%) (Al-Naiem, 2009; Omer, 2011).

Crops and rotation

Crop diversity is a common characteristic in the Gezira scheme. Four main field crops are grown. These crops include cotton, groundnut and sorghum, as summer crop, besides wheat as winter crop. Since its establishment, a lot of crop rotations were applied (Mahgoub, 2014). Currently, a five-course rotation is applied. The summer and winter cultivated crops make the use of tractors and implements almost during the year.

Model application

The developed and validated power model (equation 1) predicts fuel consumption (L/h) based on tractor engine power. It was applied to estimate fuel consumption for different tractor-implement combination. The following procedures illustrates the application of the developed model and calculation methods.

$$\mathbf{Y = 0.0679\ X\char`\^{}\ ^{1.2203}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ (1)$$

Where:

Y = Diesel fuel consumption (L/h)
X = Tractor engine power (kW)

Specific volumetric fuel consumption (SVFC)

The SVFC in L/kW.h based on the tractor engine power, and was calculated as follows:

SVFC = Predicted fuel consumption (L/h)/ Tractor engine power (Kw)…………… (2)

Specific volumetric fuel efficiency (SVFE)

The SVFE in kW.h/L was calculated as follows:

SVFE = Tractor engine power (kW)/ Predicted fuel consumption (L/h)…………… (3)

Fuel consumption for tractor-implement combinations

For each specific farm operation, fuel consumption was computed by using engine power of the used tractor and effective field capacity of the attached implement as follows:

FC = PFC/EFC ……………………………… (4)

Where:

FC = Fuel consumption (L/ha)
PFC = Predicted fuel consumption (L/h)
EFC = Effective field capacity (ha/h)

This equation was used to compute fuel consumption for 17 implements usually used in the Gezira scheme.

Unproductive fuel consumption

The unproductive fuel consumption is that consumed for off road movement of the tractor and implement to and from farms. Fuel consumption measured in experiments and tests underestimates actual consumption because it does not include unproductive movements. The unproductive fuel consumption (L/ha) was calculated by the following equation:

UPFC = (D * ORFCR)/ (S * A) ……………………………… (5)

Where:

UPFC = Unproductive fuel (L/ha)
D = Distance to and from the farms (km)
ORFCR = Off-road fuel consumption rate (L/h)
S = Tractor speed for off-road movement (km/h)
A = Area covered per one trip of tractor (ha)

This unproductive fuel consumption was added to fuel consumption calculated by equation 4 to give the total fuel consumption for each specific farm operation.

Fuel requirement in Gezira scheme

Fuel consumption from land preparation to harvest for the main crops was computed by using three options of mechanization levels; fully mechanized, semi-mechanized and tradition farming system. The total fuel consumption (L/ha) for each crop is the summation of fuel consumption for the mechanized operations. The total fuel requirement (L) was computed by multiplying total area for each specific mechanized operation by its fuel consumption rate (L/ha) estimated including unproductive fuel consumption. The area for each crop was taken as 184.8 thousand hectares.

Cost and economic saving in fuel consumption

Fuel cost was calculated based on the predicted fuel consumption obtained from the developed power model. Official fuel price at petrol filling stations was used at 4331 Sudanese Pounds per liter (SDG/L). Fuel cost was calculated for annual consumption (L/yr) the following equation:

$$TFC_{fs} = TFC * P_f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (6)$$

Where:

TFC_{fs} = Total fuel cost for a farming system (SDG/yr)

TFC = Total fuel consumption per farming system (L/yr)

P_f = Diesel fuel price (SDG/L) = 4331

On the other hand, a ten percent (10%) reduction in total annual fuel consumption was used as saving factor. This reduction percentage may be achieved through better tractor-implement matching, reduction of unproductive fuel consumption, proper maintenance and operator training. The following equation was used to calculate monetary values of economic saving.

$$ES = (1- 0.9) * TFC * P_f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where:

ES = Economic saving (SDG/yr)

TFC = Total fuel consumption per farming system (L/yr)

P_f = Diesel fuel price (SDG/L) = 4331

Results and Discussion

Application of the developed fuel consumption power model

The developed power model was further applied to evaluate tractor fuel use performance through the estimation of specific volumetric fuel consumption (SVFC) and specific volumetric fuel efficiency (SVFE). These indicators provide a normalized measure of fuel use relative to engine power and offer practical insight into tractor energy performance and operational efficiency (Grisso *et al.*, 2004; Kim *et al.*, 2015).

Specific volumetric fuel consumption (SVFC) represents the volume of fuel consumed per unit of engine power output (L/kW·h), whereas specific volumetric fuel efficiency (SVFE) expresses the amount of engine power delivered per unit volume of fuel consumed (kW. L/h). The descriptive statistical characteristics of both indicators are presented in Table 1.

The results showed that the average SVFC value was 0.19 L/kW·h, with a maximum of 0.22 L/kW·h and a minimum of 0.16 L/kW·h. The relatively low standard deviation (0.02 L/kW·h) indicates limited variability in fuel consumption per unit of power, suggesting stable fuel use performance across the evaluated operating conditions.

In contrast, SVFE exhibited a mean value of 5.36 kW. L/h, with minimum and maximum values of 4.63 and 6.07 kW. L/h, respectively, and a standard deviation of

0.54 kW. L/h. Higher SVFE values indicate more efficient fuel utilization, reflecting improved conversion of fuel volume into useful engine power (Grisso *et al.,* 2010; Bowers, 2012).

The inverse relationship observed between SVFC and SVFE confirms the internal consistency of these performance indicators. Lower SVFC values corresponded to higher SVFE values, indicating improved operational efficiency. These results demonstrate that SVFC and SVFE can be effectively used for comparative evaluation of tractor performance, benchmarking energy efficiency and supporting fuel management and machinery selection decisions (Moitzi *et al.*, 2014; Kim *et al.*, 2015).

The application of the developed power model extends beyond fuel consumption prediction and provides a practical analytical framework for evaluating tractor energy efficiency and optimizing fuel use in agricultural mechanization systems.

Table 1. Specific volumetric fuel consumption and Specific volumetric fuel efficiency

Measure	Average	Max	Min	STD
Specific volumetric fuel consumption (L/kW. h)	0.19	0.22	0.16	0.02
Specific volumetric fuel efficiency (kW. L/h)	5.36	6.07	4.63	0.54

Predicted fuel consumption by implement type

Predicted fuel consumption rates (L/h) associated with different agricultural implements, corresponding tractor engine power and effective field capacity are summarized in Table 2. The results clearly demonstrated that fuel consumption is strongly influenced by the combined effect of tractor power demand and the operational characteristics of the attached implement (Grisso *et al.*, 2004; Bowers, 2012).

Heavy-duty, high-power implements such as the Abu Ishreen ditcher recorded the highest predicted fuel consumption, reaching 38.12 L/h. This high fuel demand reflects the substantial engine power requirement (179.04 kW) associated with deep soil excavation and sustained high draft resistance. Medium-power tillage implements, including the chisel plow, heavy-duty disk harrow and moldboard plow, exhibited moderate fuel consumption values ranging from 17.2 to 18.38 L/h, consistent with their intermediate power demands and intensive soil–tool interaction (Hunt, 2001; Moitzi *et al.,* 2014).

For lighter implements operating at lower power levels (approximately 55–60 kW), fuel consumption values clustered around 9 to 10 L/h. Despite similar hourly fuel use, these implements showed substantial variation in effective field capacity. High-capacity operations such as fertilizer spreading and spraying achieved effective field capacities of 11.6 and 8.0 ha/h, respectively, indicating superior fuel utilization per unit area. Conversely, operations such as stationary threshing, digger shaking and moldboard plowing recorded very low field capacities (<1 ha/h), resulting in relatively high fuel consumption per unit of productive output (ASABE, 2011; Kim *et al.*, 2015).

These findings highlight that operations characterized by low field productivity tend to consume fuel without proportional gains in output, thereby reducing overall energy efficiency. The results emphasize the importance of appropriate tractor–implement matching and effective operational planning to minimize fuel losses and improve mechanization efficiency (Grisso *et al.*, 2010; Bowers, 2012).

Table 2. Predicted fuel consumption (L/h) and effective field capacity (ha/h) for different tractor and attached implements

Implement	Matched tractor power (kW)	Fuel consumption (L/h)	Effective field capacity (ha/h)
Abu Ishreen ditcher	179.04	38.12	59.2
Chisel plow	93.25	17.2	1.5
Heavy duty disk harrow	98.5	18.38	1.4
Moldboard plow	98.5	18.38	0.7
Disk plow	55.5	9.13	0.7
Disk harrow	55.5	9.13	1.3
Ridger	55.5	9.13	2.0
Abu Sita ditcher	59.68	9.98	2.5
Planter	55.5	9.13	2.0
Fertilizer spreader	55.5	9.13	11.6
Sprayer	55.5	9.13	8.0
Leveler	59.68	9.98	2.5
Seed drill	59.68	9.98	1.3
Wide level disk	59.68	9.98	2.9
Digger shaker	55.5	9.13	0.6
Stationary thresher	55.5	9.13	0.5
Combine harvester	56.7	9.37	2.1

Fuel consumption per unit area and unproductive fuel losses

Fuel consumption expressed on an area basis (L/ha), including productive, unproductive and total fuel consumption for different tractor–implement combinations, is presented in Table 3. Expressing fuel use per hectare provides a more realistic indicator of operational efficiency, as it integrates both fuel consumption rate and effective field capacity (Grisso *et al.*, 2004; Bowers, 2012).

Substantial variation in fuel consumption per hectare was observed among implements. Operations such as moldboard plowing, stationary threshing and digger shaking recorded the highest total fuel consumption values, reaching 25.43, 17.43, and 15.80 L/ha, respectively. These elevated values are attributable to high draft requirements combined with low effective field capacities, which amplify fuel consumption per unit area (Hunt, 2001; Moitzi *et al.*, 2014).

In contrast, high-capacity operations including the Abu Ishreen ditcher, fertilizer spreader and sprayer exhibited very low total fuel consumption per hectare, ranging from 1.36 to 1.86 L/ha. Although some of these operations involved moderate to high hourly fuel consumption, their large field capacities substantially reduced fuel use per unit area, demonstrating superior energy efficiency (Kim *et al.*, 2015; ASABE, 2011).

A constant unproductive fuel consumption value of 0.71 L/ha was observed across all operations, representing fuel used during non-productive activities such as tractor movement to and from fields. This unproductive component constituted a significant proportion of total fuel consumption in high-capacity operations. For example, unproductive fuel accounted for more than 50% of total fuel use in fertilizer spreading and spraying activities.

These results underscore that total fuel consumption per hectare is governed not only by implement draft and tractor power but also by operational efficiency and field capacity. Reducing unproductive fuel losses through improved field layout, appropriate implement selection and optimized tractor–implement matching is therefore critical for enhancing energy efficiency. The findings further confirm the practical applicability of the developed power model under real field conditions (Moitzi *et al.,* 2014; Kim *et al.*, 2015).

Table 3. Predicted fuel consumption, unproductive fuel consumption and total fuel consumption for different tractor-implement combinations

Implement	Fuel consumption (L/ha)	Unproductive fuel consumption (L/ha)	Total fuel consumption (L/ha)
Abu Ishreen ditcher	0.64	0.71	1.36
Chisel plow	11.53	0.71	12.24
Heavy duty disk harrow	13.43	0.71	14.14
Moldboard plow	24.73	0.71	25.43
Disk plow	13.59	0.71	14.29
Disk harrow	7.25	0.71	7.96
Ridger	4.60	0.71	5.31
Abu Sita ditcher	3.96	0.71	4.67
Planter	4.65	0.71	5.37
Fertilizer spreader	0.79	0.71	1.50
Sprayer	1.14	0.71	1.86
Leveler	3.96	0.71	4.67
Seed drill	7.42	0.71	8.13
Wide level disk	3.44	0.71	4.15
Digger shaker	15.09	0.71	15.80
Stationary thresher	16.72	0.71	17.43
Combine harvester	4.46	0.71	5.17

Fuel consumption requirements for different crops and farming systems

Estimated fuel consumption requirements per unit area (L/ha) for selected crops under different farming systems are presented in Table 4. The results demonstrated that fuel consumption varies considerably with crop type and mechanization level (Hunt, 2001; Grisso *et al.*, 2004), reflecting differences in operation intensity, machinery use and production practices.

Under the traditional farming system, fuel consumption was relatively low for cotton and groundnut, at 22.0 and 11.4 L/ha, respectively. Whereas, sorghum recorded a higher value of 28.8 L/ha, likely due to land preparation and additional field operations. Wheat was not included under this system, as it is predominantly cultivated using mechanized practices.

Fuel consumption increased markedly under the semi-mechanized farming system for all crops. Cotton, groundnut, sorghum and wheat recorded fuel requirements of 25.4, 30.9, 36.1, and 31.9 L/ha, respectively. However, the increase use of mechanical operations such improve productivity but require higher energy inputs (Moitzi *et al.*, 2014; Kim *et al.*, 2015).

As expected, the fully mechanized farming system exhibited the highest fuel consumption levels, with values ranging from 44.4 to 47.4 L/ha across all crops. This suggests that under full mechanization, fuel consumption is driven more by the number and intensity of field operations than by crop-specific characteristics (Grisso *et al.*, 2010; Bowers, 2012).

The results reveal a clear relationship between mechanization level and fuel consumption. While higher mechanization substantially increases fuel consumption per hectare, it is typically associated with improved timeliness and reduced labor dependency. These findings highlight the need to optimize mechanization strategies to balance fuel requirements and productivity gains in irrigated agricultural systems (Hunt, 2001; Kim *et al.*, 2015).

Table 4. Fuel consumption (L/ha) requirement for different crops and farming system

Farming system	Cotton	Groundnut	Sorghum	Wheat
Tradition	22.0	11.4	28.8	-
Semi-mechanized	25.4	30.9	36.1	31.9
Fully-mechanized	44.4	46.7	45.3	47.4

Total fuel consumption requirements

Total fuel consumption requirements (L) for selected crops under different farming systems are summarized in Table 5. Unlike area-based fuel consumption, total fuel use reflects the combined effect of fuel intensity per hectare and total cultivated area, providing a comprehensive assessment of energy demand at the system level (Hunt, 2001; Grisso *et al.*, 2004).

Under the option of traditional farming system, total fuel consumption was lowest for groundnut (approximately 2.11 million L), followed by cotton (4.07 million L), while sorghum recorded the highest value (5.32 million L). These differences reflect both crop-specific fuel requirements and cultivated area. Wheat was not included due to its limited presence under traditional practices.

A substantial increase in total fuel consumption was observed under the option of semi-mechanized system, with fuel requirements of 4.70, 5.71, 6.67, and 5.90 million L for cotton, groundnut, sorghum and wheat, respectively.

The option of fully mechanized farming system recorded the highest total fuel consumption, exceeding 8 million L for all crops. Cotton, groundnut, sorghum and wheat recorded total fuel requirements of 8.21, 8.63, 8.37, and 8.76 million L, respectively. The relatively narrow variation among crops indicates that under full mechanization, total fuel demand is largely governed by the scale of mechanized operations rather than crop-specific differences (Grisso *et al.*, 2010; Bowers, 2012).

These results demonstrate that increasing mechanization intensity leads to a pronounced rise in total fuel consumption at the system level. While mechanization enhances productivity and operational efficiency, it also imposes higher energy demands, underscoring the importance of optimizing fuel use and machinery efficiency.

Table 5. Fuel consumption (L) requirement for different crops and farming system

Farming system	Cotton	Groundnut	Sorghum	Wheat
Tradition	4067227	2107563	5324370	-
Semi-mechanized	4695798	5712605	6673950	5897479
Fully-mechanized	8208403	8633613	8374790	8763025

Seasonal fuel requirements in the Gezira scheme

Total diesel fuel requirements for summer and winter crops under different options of farming systems, expressed in metric tons, are presented in Table 6. Fuel quantities were converted from volume to mass using a diesel fuel density of 0.84 kg/L to allow standardized comparison across seasons and systems.

Under the option of traditional farming system, fuel consumption was limited to summer crops, with a total requirement of 9659 tons. The absence of winter fuel demand reflects limited mechanization and lower cropping intensity under traditional practices (ASABE, 2011; Grisso *et al.,* 2004).

Fuel demand increased substantially under the option of semi-mechanized system, with 14349 tons required for summer crops and an additional 4954 tons for winter crops, resulting in a combined total of 19303 tons. This increase reflects expanded mechanization and multi-season cropping (Moitzi *et al.,* 2014; Kim *et al.,* 2015).

The fully mechanized system option recorded the highest fuel demand, with summer crops consuming 21182 tons and winter crops 7361 tons, bringing total annual fuel requirements to 28543 tons. Compared to the traditional system option, full mechanization resulted in nearly a threefold increase in fuel demand. This highlights the substantial energy implications of intensive mechanized agriculture (Grisso *et al.,* 2010; Bowers, 2012).

These findings demonstrate that mechanization level and cropping intensity are major determinants of fuel demand in large-scale irrigated schemes, emphasizing the need for energy-efficient machinery and strategic planning.

Table 6. Total fuel requirement (ton) for summer and winter crops in the Gezira scheme

Farming system	Summer crops	Winter crop	Total
Tradition	9659	-	9659
Semi-mechanized	14349	4954	19303
Fully-mechanized	21182	7361	28543

* Diesel fuel density = 0.84 kg/L

Economic implications of fuel consumption

Fuel consumption expenses and potential economic savings across different farming systems are presented in Table 7. Fuel cost represents a major component of mechanized agricultural production expenses, and its impact increases sharply with higher mechanization levels (Hunt, 2001; Grisso *et al.,* 2010).

The results show that annual fuel expenditure under the fully mechanized system was approximately three times higher than under the traditional system, exceeding 147 billion SDG at the scheme level. To assess potential economic benefits, a fuel-saving scenario assuming a 10% reduction in fuel consumption through improved machinery management was evaluated.

The analysis indicates that a 10% reduction in fuel use could generate annual savings of approximately 5, 10, and 14.7 billion SDG for traditional, semi-mechanized, and fully mechanized systems, respectively. These results highlight that even modest improvements in fuel efficiency can yield substantial economic benefits, particularly at large system scales.

Improved fuel efficiency through optimized tractor–implement matching, reduced unproductive fuel consumption, and better operational management could allow savings to be redirected toward machinery maintenance, farmer support services, or investment in energy-efficient technologies (Moitzi *et al.,* 2014; Grisso *et al.,* 2004). The findings confirm that fuel efficiency is a critical driver of economic sustainability in irrigated agricultural systems and that the developed power model provides a valuable tool for fuel budgeting and cost control.

Table 7. Economic saving of 10% reduction in fuel consumption (L/yr) across farming systems

Farming system	Fuel consumption (L/yr)	Fuel expense (SDG/yr)	10% reduction in fuel consumption (L/yr)	Economic saving (Billion SDG/yr)
Tradition	11499160	49802861960	10349244	5.0
Semi-mechanized	22979832	99525652392	20681848.8	10.0
Fully-mechanized	33979831	147166648061	30581847.9	14.7

Conclusion

This study demonstrated the practical applicability of a predictive power-based model for estimating tractor fuel consumption under real operating conditions in the Gezira scheme, Sudan. The model was successfully applied to quantify specific fuel consumption indicators, fuel use per unit area, unproductive fuel losses and total fuel requirements across different crops and mechanization levels. The results confirmed that fuel consumption is strongly influenced by mechanization level, implement type and operational efficiency, with unproductive fuel losses constituting a significant share of total fuel use in several operations. Higher mechanization increases total fuel demand and economic costs, but even modest improvements in efficiency can generate substantial savings. Proper tractor–implement matching, operational planning and reduction of unproductive fuel use are critical for sustainable mechanized agriculture.

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