



Development and Validation of Predictive Model for Tractor Fuel Consumption in the Gezira Scheme, Sudan

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Abstract

Accurate estimation of tractor fuel consumption is essential for effective machinery management, cost control, energy efficiency assessment and environmental impact evaluation in irrigated agricultural systems. The Gezira irrigated scheme in Sudan operates a heterogeneous tractor fleet characterized by wide variations in engine power, age and operational efficiency, resulting in highly variable fuel consumption rates. This study aimed to develop, verify, validate and compare a predictive model for tractor diesel fuel consumption under the specific operational and environmental conditions of the Gezira scheme. Field experiments were conducted using eight tractors with engine powers ranging from 56.0 to 190.3 kW coupled with different implements. Actual fuel consumption (L/h) was measured using an auxiliary fuel tank method. Five regression models; linear, logarithmic, exponential, polynomial and power were developed using tractor engine power as the independent variable. Model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE) and t-test analysis. Among the tested models, the power model ($Y = 0.0679 X^{1.2203}$) exhibited the best overall performance, combining high explanatory power (R^2), low RMSE, statistical robustness and physical interpretability. The model was successfully verified using experimental data and validated using independent datasets collected from Gezira, Al-Rahad, and El Suki irrigated schemes. Results showed no statistically significant differences were observed between predicted and measured fuel consumption values ($p > 0.05$). Comparative analysis demonstrated that the developed power model outperformed the commonly used linear PTO-based model

reported in the literature, particularly at medium and high engine power levels. Sensitivity analysis further confirmed the robustness of the model and highlighted the exponent coefficient as the most influential parameter. The developed model provides a reliable and practical tool for estimating tractor fuel consumption, supporting farm planning, and mechanization management in Sudanese irrigated agriculture.

Keywords: Tractor fuel consumption, Engine power, Predictive modeling, Agricultural mechanization, Gezira irrigated scheme.

تطوير نموذج تنبؤي لاستهلاك وقود الجرارات في مشروع الجزيرة، السودان، والتحقق من صحته

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المستخلص:

يُعدّ التقدير الدقيق لاستهلاك وقود الجرارات أمراً بالغ الأهمية للإدارة الفعّالة للآلات، والتحكم في التكاليف، وتقييم كفاءة الطاقة، وتقييم الأثر البيئي في النظم الزراعية المروية. يعتمد مشروع ري الجزيرة في السودان على أسطول جرارات متنوع يتميز باختلافات واسعة في قدرة المحرك وعمره وكفاءته التشغيلية، مما ينتج عنه معدلات استهلاك وقود متغيرة للغاية. هدفت هذه الدراسة إلى تطوير نموذج تنبؤي لاستهلاك وقود الديزل في الجرارات، والتحقق من صحته، ومقارنته، وذلك في ظل الظروف التشغيلية والبيئية الخاصة بمشروع الجزيرة. أُجريت تجارب ميدانية باستخدام ثمانية جرارات بقدرات محركات تتراوح بين 56.0 و190.3 كيلوواط، مزودة بمعدات زراعية مختلفة. تم قياس استهلاك الوقود الفعلي (لتر/ساعة) باستخدام طريقة خزان الوقود الإضافي. طُوّرت خمسة نماذج انحدار: خطي، لوغاريتمي، أسّي، متعدد الحدود، ونموذج القوة، باستخدام قدرة محرك الجرار كمتغير مستقل. قُيّم أداء النموذج باستخدام معامل التحديد (R^2)، وجذر متوسط مربع الخطأ (RMSE)، واختبار t من بين النماذج المختبرة، أظهر نموذج القدرة ($Y = 0.0679 X^{1.22^{03}}$) أفضل أداء شامل، إذ جمع بين قدرة تفسيرية عالية (R^2)، وانخفاض متوسط الجذر التربيعي للخطأ (RMSE)، ومثانة إحصائية، وقابلية تفسير فيزيائية. وقد تم التحقق من صحة النموذج بنجاح باستخدام بيانات تجريبية، وتم التحقق من صحته باستخدام مجموعات بيانات مستقلة جُمعت من مشاريع الري في الجزيرة والرهده والسوكي. وأظهرت النتائج عدم وجود فروق ذات دلالة إحصائية بين قيم استهلاك الوقود المتوقعة والمقاسة ($p > 0.05$) وأظهر التحليل المقارن أن نموذج القدرة المطور يتفوق على النموذج الخطي الشائع الاستخدام والقائم على مأخذ الطاقة (PTO) والمذكور في الأدبيات، لا سيما عند مستويات قدرة المحرك المتوسطة والعالية. كما أكد تحليل الحساسية مثانة النموذج، وأبرز معامل الأس باعتباره المعلمة الأكثر تأثيراً. يوفر النموذج المطور أداة موثوقة وعملية لتقدير استهلاك وقود الجرارات، مما يدعم تخطيط المزارع وإدارة الميكنة في الزراعة المروية السودانية.

الكلمات المفتاحية: استهلاك وقود الجرارات، قوة المحرك، النمذجة التنبؤية، الميكنة الزراعية، مشروع ري الجزيرة

Introduction

The Gezira irrigated scheme is the largest and most important irrigated agricultural system in Sudan, covering vast areas cultivated mainly with cotton, sorghum, wheat, and other strategic crops. Due to its central role in national agricultural production and food security, improving the efficiency and sustainability of farming operations within the scheme has become a critical priority (FAO and UNIDO, 2008). Agricultural mechanization plays a key role in this process by enhancing productivity, reducing labor intensity and optimizing the use of production inputs.

Mechanization in the Gezira scheme represents a major transition from traditional labor-based farming toward machine-based agricultural operations. However, the level and effectiveness of mechanization vary considerably across crop types, field operations and management practices (Yousif *et al.*, 2025). The tractor fleet operating within the scheme is highly heterogeneous, with differences in engine power, age, maintenance status and operational efficiency. This variability often results in excessive and inconsistent fuel consumption, leading to increased production costs and reduced economic efficiency for farmers and mechanization service providers (Eltom *et al.*, 2014).

Accurate estimation of tractor fuel consumption is essential for effective farm planning, machinery management, fuel budgeting, and cost analysis (Grisso *et al.*, 2014). Moreover, reliable fuel consumption models form a fundamental basis for evaluating energy use efficiency and estimating greenhouse gas emissions associated with agricultural mechanization (Lal, 2004; FAO, 2016). Therefore, fuel consumption prediction has gained increasing importance in the context of sustainable agricultural production systems.

Tractor fuel consumption is influenced by a complex interaction of technical, operational and environmental factors. Tractor-related factors include engine power, engine efficiency, transmission type, drivetrain configuration, tractor mass and maintenance condition (Kutzbach, 2000; Grisso *et al.*, 2014). Operational factors involve forward speed, working depth, implement type and width, drawbar load, wheel slip, field efficiency and operator behavior (ASABE, 2015). Environmental and field-related factors include soil texture, soil moisture content, bulk density, surface roughness and field slope (Al-Suhaibani *et al.*, 2010; Keller *et al.*, 2019).

Despite the central role of tractors in the Gezira irrigated scheme, tractor fuel consumption remains inadequately quantified under local operating conditions. Fuel use varies widely among operations due to differences in tractor characteristics, implement combinations and field practices. Furthermore, locally calibrated fuel consumption prediction models are limited. Most existing models have been developed under temperate climatic conditions or controlled experimental environments and may not adequately capture the unique soil properties, irrigation practices and tractor fleet characteristics of the Gezira scheme (Babiker, 2011; Ahmed and Mustafa, 2018). This study addresses this critical knowledge gap by developing a locally calibrated and field-validated predictive model for tractor diesel fuel consumption under the specific biophysical and operational conditions of Sudanese irrigated agriculture.

The proposed model is based on extensive field measurements that reflect actual tractor–implement combinations, Vertisol soil conditions and real farm operating practices within the Gezira scheme. The novelty of this research lies in its use of tractor engine power as a practical and readily available predictor. The developed model provides a simple yet robust decision-support tool that can be readily adopted by farmers, mechanization service providers, engineers and policymakers for fuel budgeting, machinery selection and operational planning.

Therefore, this study aims to develop a locally applicable predictive model for tractor diesel fuel consumption based on engine power, to verify and validate the model using field data and to compare its performance with established fuel consumption models reported in the literature.

Materials and Methods

Study area

The study was conducted in the Gezira irrigated scheme, which is located between the Blue Nile and White Nile rivers south of Khartoum, Sudan. The scheme is one of the largest irrigated agricultural systems in the region, covering approximately 2.2 million feddans (1 feddan = 0.42 ha). The area lies within a semi-arid climatic zone, receiving annual rainfall ranging from 150 to 300 mm, which is concentrated mainly between July and September. The dominant soils in this area have a high holding capacity and exhibit pronounced shrink–swell behavior (Al-Naiem, 2009; Omer, 2011). These soil properties have significant impact on tractor traction performance and fuel consumption under field conditions.

Measurement of actual fuel consumption

Field tests were conducted using eight agricultural tractors of different makes, models and engine power ratings (56.0, 61.9, 74.9, 82.1, 113.4, 134.3, 166.4, and 190.3 kW), each coupled with representative agricultural implements. Experiments were carried out over a test area of 0.84 ha under typical field operating conditions.

Tractor diesel fuel consumption (L/h) and effective field capacity (ha/h) were measured using an auxiliary fuel tank system. For each tractor–implement combination, the time required to complete the operation and the volume of fuel consumed were recorded. Each test was replicated five times and average values were used for analysis. Fuel consumption and effective field capacity were calculated using the following equations:

$$K = F \times 60 / T \dots\dots\dots (1)$$

$$EFC = A \times 60 / T \dots\dots\dots (2)$$

Where:

- K = Fuel consumption (L/h)
- F = Fuel consumed during operation (L)
- T = Time required (min)
- EFC = Effective field capacity (ha/h)
- A = Area covered (feddan)
- 60 = Conversion factor from minutes to hours

Model development

Five regression models were developed to predict tractor diesel fuel consumption (L/h) are classified as Vertisols, which characterized by high clay content (50–60%), high water-h), with tractor engine power (kW) used as the independent variable. The tested functional forms included linear, logarithmic, exponential, polynomial and power models. Regression analyses were performed using Microsoft Excel and model parameters were estimated based on the experimental dataset obtained from the eight tested tractors.

The developed models were evaluated based on their ability to explain the relationship between tractor engine power and fuel consumption and to provide reliable predictions within the studied power range.

Additional data collection

To strengthen model verification and validation, secondary field data were collected from farmers, tractor operators, and agricultural engineers operating in the Gezira scheme. These data included tractor engine power ratings, implement types, effective field capacity, and corresponding fuel consumption rates. The independent dataset was used to evaluate the predictive reliability and generalizability of the developed model under real farm conditions.

Statistical analysis

Descriptive statistical methods, including mean values and correlation analysis, were used to explore relationships between engine power and fuel consumption. A paired t-test was applied to evaluate the statistical significance of differences between measured and predicted fuel consumption values at a 5% probability level.

Model predictive performance was further assessed using the root mean square error (RMSE), calculated as:

$$RMSE = \sqrt{1/n \sum_{i=1}^n (K - L)^2} \dots\dots\dots (3)$$

Where:

- RMSE = Root mean square error (L/h)
- K = Observed fuel consumption (L/h)
- L = Model-predicted fuel consumption (L/h)
- n = Number of observations (n = 8)

Lower RMSE values indicate stronger agreement between predicted and observed fuel consumption and higher model accuracy (Montgomery *et al.*, 2021; Kutner *et al.*, 2005).

Model selection criteria

The coefficient of determination (R²) was used as the primary criterion for selecting the most appropriate predictive model. The model yielding the highest R² value and acceptable RMSE was selected as the best representation of the relationship between tractor engine power and fuel consumption.

Model verification and validation

Model verification was performed by comparing predicted fuel consumption values generated by the selected model with experimental measurements obtained from field tests. Statistical consistency between predicted and observed values was assessed using paired t-tests and descriptive statistical measures.

Model validation was conducted using independent datasets collected from Gezira, Al-Rahad, and El Suki irrigated agricultural schemes. Predicted and measured fuel consumption values were statistically compared to evaluate the robustness and external applicability of the developed model across different irrigated production environments.

Model comparison

The predictive performance of the selected model was compared with the linear fuel consumption model proposed by Bowers (2001), which is based on tractor power take-off (PTO) power. PTO power was estimated as 0.83 of engine power, following ASAE (2003) recommendations. Model comparison was conducted using R^2 , RMSE, paired t-test results, and graphical trend analysis to evaluate differences in prediction behavior and model accuracy.

$$Y = 0.223 x \dots\dots\dots (Bower, 2001) \dots\dots\dots (4)$$

Where: Y is tractor diesel fuel consumption (L/h) and X is tractor PTO power (kW).

Sensitivity Analysis

Sensitivity analysis was conducted to assess the robustness of the selected model and to determine the influence of model parameters on predicted fuel consumption. Tractor engine power was varied by $\pm 5\%$, $\pm 10\%$, and $\pm 15\%$ while holding model coefficients constant, and corresponding changes in predicted fuel consumption were computed. Similarly, model coefficients (a and b) were varied within the same percentage ranges while keeping engine power constant. The resulting responses were analyzed to identify the most influential parameters and to evaluate the stability of the model across low- and high-power tractor categories (56.0 and 190.3 kW).

Results and Discussion

Model development and statistical analysis

Tractor diesel fuel consumption (L/h) was modeled as a function of tractor engine power (kW), treating fuel consumption as the dependent variable and engine power as the independent variable. Five regression models; linear, logarithmic, exponential, polynomial, and power, were developed to describe the relationship between engine power and fuel consumption. The regression equations and their corresponding coefficients of determination (R^2) are presented in Table 1.

The results revealed a strong positive relationship between tractor engine power and fuel consumption across all tested models, as indicated by relatively high R^2 values. This finding is consistent with previous studies that reported engine power as a key determinant of fuel consumption under agricultural field conditions (Grisso *et al.*, 2004; Moitzi *et al.*, 2014). However, noticeable differences in predictive performance were

Development and Validation of Predictive Model for Tractor Fuel Consumption

observed among the models, emphasizing the importance of selecting an appropriate functional form to accurately represent fuel consumption behavior.

Table 1. Models developed for predicting tractor fuel consumption (L/h) by using tractor engine power (kW)

Model type	Equation	R ²
Exponential	$Y = 5.5406 e^{0.0111x}$	0.9637
Linear	$Y = 0.2443x - 5.2001$	0.9512
Logarithmic	$Y = 26.032 \ln(x) - 98.316$	0.9053
Polynomial	$Y = 0.0006 x^2 + 0.0945 x + 2.4278$	0.9588
Power	$Y = 0.0679 x^{1.2203}$	0.9740

The statistical adequacy of the developed models was further evaluated using paired t-test analysis (Table 2). For all models, the calculated t-values were lower than the critical tabulated value at the 5% significance level ($t_{0.05} = 2.3646$), indicating that differences between predicted and measured fuel consumption values were not statistically significant. These results confirm the statistical reliability of the developed models within the tested engine power range.

Model accuracy was also assessed using the root mean square error (RMSE). Lower RMSE values reflected stronger agreement between predicted and observed fuel consumption. Although all models demonstrated acceptable predictive accuracy, variations in RMSE highlighted differences in their practical suitability for field applications (Kutner *et al.*, 2005; Montgomery *et al.*, 2021).

Table 2. Statistical analysis for models developed to predict tractor fuel consumption

Model type	RMSE	T- calculated
Exponential	2.62	0.963575
Linear	2.59	0.997768
Logarithmic	3.60	0.999371
Polynomial	2.40	0.764329
Power	2.50	0.888702
T- tabulated	2.364624	

Model selection

Based on the combined evaluation of R², RMSE, statistical significance and practical applicability, the power model was selected as the most appropriate predictive model for tractor diesel fuel consumption. The selected model is expressed as:

$$Y = 0.0679 X^{1.2203} \dots\dots\dots (5)$$

Where: Y is tractor diesel fuel consumption (L/h) and X is tractor engine power (kW).

The power model achieved superior explanatory power and a relatively low RMSE value (2.5 L/h) compared with the other tested models. Although the polynomial model yielded a marginally lower RMSE, the power model was preferred due to its simpler structure, reduced risk of overfitting and stronger physical interpretability. Similar observations favoring power-type relationships between engine power and fuel

consumption have been reported in earlier mechanization studies (Grisso *et al.*, 2010; Kim *et al.*, 2015; Bowers, 2012).

From a theoretical standpoint, the selected power model effectively captures the nonlinear nature of fuel consumption behavior. The exponent value (>1) indicates that fuel consumption increases at a rate greater than proportional with increasing engine power, reflecting higher engine loads, increased internal friction losses and variations in engine efficiency at higher operating capacities (Hunt, 2001; ASABE, 2011; Moitzi *et al.*, 2014). This behavior is consistent with established engine performance principles under field operating conditions.

Model verification

Model verification was conducted by comparing predicted fuel consumption values obtained from the selected power model with experimentally measured values from tractors of different engine power classes (Table 3). The comparison demonstrated strong agreement between predicted and observed fuel consumption across the evaluated power range. The percentage agreement ranged from 90% to 116%, indicating that the model provides reasonable estimates under diverse operating conditions.

Minor deviations were observed at higher engine power levels, particularly at 166.4 kW and 190.3 kW, where the model slightly overestimated and underestimated fuel consumption, respectively. These discrepancies can be attributed to variations in field load, engine operating efficiency, implement characteristics and soil conditions, which are not explicitly included in the single-variable model (Bowers, 2012; Kim *et al.*, 2015).

Table 3. Verification of the power model for fuel consumption prediction with actual data

Tractor engine power (kW)	Actual	Predicted	Comparative (%)
56.0	9.78	9.22	94
61.9	10.85	10.44	96
74.9	12.00	13.17	110
82.1	13.70	14.72	107
113.4	23.18	21.84	94
134.3	28.33	26.85	95
166.4	29.97	34.87	116
190.3	45.45	41.06	90
RMSE	2.50		

Statistical analysis further confirmed the verification results (Table 4). The paired t-test showed no statistically significant difference between measured and predicted fuel consumption values at the 5% probability level. The calculated t-value (0.8887) was substantially lower than the critical value (2.3646). Moreover, the mean values of actual and predicted fuel consumption were nearly identical (21.658 and 21.521 L/h, respectively). These results confirm the reliability and internal consistency of the developed power model.

Development and Validation of Predictive Model for Tractor Fuel Consumption

Table 4. T-test for paired two sample for means of the predicted and actual data

Statistical Parameters	Values
Mean for actual fuel consumption	21.658
Mean for predicted fuel consumption	21.521
Variance for actual fuel consumption	156.641
Variance for predicted fuel consumption	139.800
Number of observations for each	8
Degree of freedom for each	7
T-calculated	0.8887
T-tabulated	2.3646

Model validation

The external validity of the developed power model was evaluated using independent datasets collected from three major irrigated agricultural schemes in Sudan: Gezira, Al-Rahad and El Suki. A paired two-sample t-test was applied to compare predicted and actual fuel consumption values for each scheme (Table 5).

For all three schemes, the calculated t-values were markedly lower than the corresponding critical values at the 5% significance level, indicating no statistically significant differences between predicted and measured fuel consumption. RMSE values ranged from 3.154 to 3.773 L/h, reflecting acceptable prediction accuracy under diverse field conditions. These results demonstrate that the developed power model is robust and applicable across different irrigated agricultural systems with varying operational characteristics.

The successful validation across multiple schemes highlights the potential of the model as a generalized predictive tool for tractor fuel consumption in Sudanese irrigated agriculture, beyond the specific conditions of the Gezira scheme.

Model comparison

Figure 1 presents a comparison between the developed power model and the linear PTO-based fuel consumption model proposed by Bowers (2001). The linear model assumes a constant proportional relationship between PTO power and fuel consumption, resulting in a uniform linear trend. While this approach provides reasonable estimates at lower power levels, increasing deviations were observed at medium and high engine power ranges.

Table 5. T-test for paired two sample for means of the predicted and actual fuel consumption in three irrigated schemes

Statistical Parameters	Gezira	Al-Rahad	El-Suki
Mean for actual fuel consumption	6.82	6.98	7.17
Mean for predicted fuel consumption	10.20	9.30	9.65
Variance for actual fuel consumption	2.594	5.657	5.15
Variance for predicted fuel consumption	1.810	0.055	0.183
Number of observations for each	13	12	13
Degree of freedom for each	12	11	12
T-calculated	0.00002	0.0041	0.0018
T-tabulated	2.1788	2.2010	2.1788
RMSE	3.773	3.154	3.293

In contrast, the engine power-based power model developed in this study exhibited greater flexibility in capturing the nonlinear behavior of fuel consumption under practical field conditions. Engine power inherently accounts for total energy demand, including drivetrain and auxiliary losses, which are not fully represented in PTO-based models. Consequently, the developed model provides a more realistic representation of actual tractor fuel consumption behavior.

Both statistical indicators and graphical analysis confirm the superior predictive performance of the developed power model, particularly across a wide range of tractor power and operational conditions (Bowers, 2001; Grisso *et al.*, 2010).

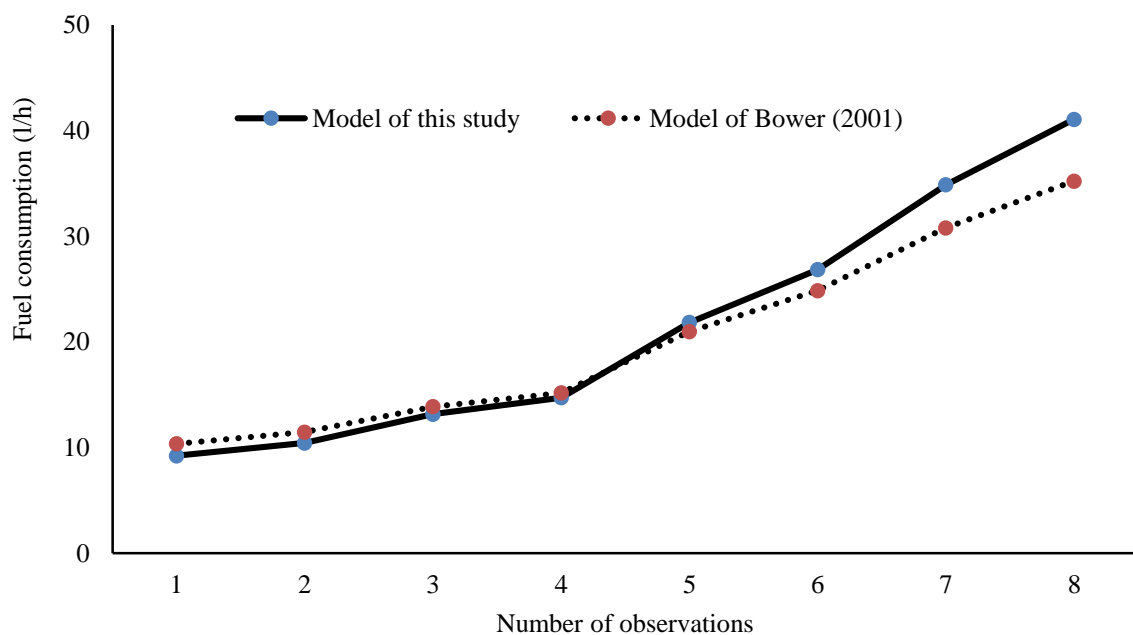


Fig. 1. Comparison between results from this model and Bower (2001) model for fuel consumption (l/h)

Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the robustness of the selected power model and to identify the relative influence of its parameters. Variations in tractor engine power ($\pm 5\%$, $\pm 10\%$, and $\pm 15\%$), while keeping model coefficients constant, resulted in proportional changes in predicted fuel consumption at both low (56.0 kW) and high (190.3 kW) power levels (Table 6). This consistent response indicates stable and predictable model behavior across the evaluated power range. This confirms the internal consistency of the power model and its suitability for analyzing the impact of power variation on fuel consumption (ASABE, 2011).

Development and Validation of Predictive Model for Tractor Fuel Consumption

Table 6. Effect of changing engine power in fuel consumption (l/h) at constant coefficients (a) and (b)

Change %	56.0 kW	190.3 kW
+5%	6.13	6.13
+10%	12.33	12.33
+15%	18.60	18.60
-5%	-6.07	-6.07
-10%	-12.06	-12.06
-15%	-17.99	-17.99

Changes in coefficient a, with engine power and exponent b held constant, produced equivalent proportional changes in predicted fuel consumption, confirming the role of coefficient a as a scaling factor. Percentage increases or decreases in a led to identical percentage changes in predicted fuel consumption at both engine power levels (Table 7).

Table 7. Effect of changing coefficient (a) in fuel consumption (l/h) at constant engine power and coefficient (b)

Change %	56.0 kW	190.3 kW
+5%	5	5
+10%	10	10
+15%	15	15
-5%	-5	-5
-10%	-10	-10
-15%	-15	-15

In contrast, variations in exponent b resulted in nonlinear and increasingly pronounced effects at higher engine power levels (Table 8). An increase in b led to a substantial rise in predicted fuel consumption, with the effect being more pronounced at 190.3 kW than at 56.0 kW. Conversely, reductions in b produced significant decreases, again with larger impacts observed at higher power levels. This behavior indicates that coefficient b is the most sensitive parameter in the model and plays a critical role in defining the curvature of the fuel consumption–power relationship (Bowers, 2012; Kim *et al.*, 2015).

Table 8. Effect of changing coefficient (b) in fuel consumption (l/h) at constant engine power and coefficient (a)

Engine power	56.0 kW	190.3 kW
+5%	27.84	37.75
+10%	63.42	89.74
+15%	32.56	44.42
-5%	-21.77	-27.40
-10%	-38.81	-47.30
-15%	-52.13	-61.74

The sensitivity analysis confirms the robustness of the developed power model and provides valuable insight into its structural behavior under varying conditions. These

findings further support the suitability of the model for strategic fuel consumption assessment, machinery management and operational planning in agricultural mechanization systems (Hunt, 2001; Grisso *et al.*, 2004; ASABE, 2011).

Conclusion

1. A predictive power model was developed for tractor diesel fuel consumption based on engine power in the Gezira scheme, Sudan.
2. Model validation across multiple irrigated schemes confirmed its reliability and robustness under diverse field conditions.
3. The power model outperformed PTO-based linear models, accurately capturing the nonlinear relationship between engine power and fuel use.
4. Sensitivity analysis identified the exponent coefficient as the most influential factor, ensuring stable predictions across tractor power ranges.
5. The model provides a practical tool for fuel budgeting and machinery management in irrigated agriculture.
6. Future studies may further enhance model accuracy by incorporating additional operational and soil parameters and extending validation to rainfed agricultural systems.

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