International Journal of
Science, Architecture, Technology and Environment

Carbon Dioxide Emission Modelling in Power Plants: An Analysis of Otukpo Rice Mill and Sawmill in Benue State, Nigeria

Emmanuel Daniel Onoja[1*], Edwin Hart Ogwuche[2], Ejila Odeh Anthony[3], Alfred Daniel Owoicho[1]

[1]*Department of Medical Physics, Federal University of Health Sciences, Otukpo, Benue State, Nigeria*

[2]*Department of Biostatistics, Federal University of Health Sciences, Otukpo, Benue State, Nigeria*

[3]*Department of Biochemistry, Federal University of Health Sciences, Otukpo, Benue State, Nigeria*

[*]*Corresponding author, emmanuel.onoja@fuhso.edu.ng*

DOI: https://doi.org/10.63680/ijsate0526046.32

Abstract

Due to Nigeria's ongoing grid electricity supply shortage, many small and medium-sized businesses are now forced to rely largely on fossil fuel-powered generators, which raises carbon dioxide (CO_2) emissions and the related environmental effects. In this study, CO2 emissions from power plants used in a sawmill and rice mill in Otukpo, Benue State, Nigeria, are modelled. Over the course of six months, operational data such as operating hours, load factor, generator capacity, and fuel consumption rate were gathered. Multiple linear regression was used to model the relationship between CO_2 emissions and important operational parameters, and the Intergovernmental Panel on Climate Change (IPCC) emission factor approach was used to estimate carbon dioxide emissions. The most significant predictors of CO2 emissions, according to the results, were fuel consumption and operating hours ($p < 0.05$). In comparison to the rice mill, the sawmill showed higher emission intensity because of its longer operating hours and higher load demand. With coefficient of determination (R2) values above 0.85, the developed model showed good predictive performance. In addition to offering a useful modelling framework to assist emission reduction strategies and sustainable energy planning in developing regions, this study offers a localised emissions inventory for small industrial power plants.

Keywords: Carbon dioxide emissions; Emission modelling; Diesel generators; Rice mill; Sawmill; Otukpo; Nigeria

1. Introduction

Global climate change remains one of the most pressing environmental challenges of the 21st century, with carbon dioxide (CO_2) identified as the principal anthropogenic greenhouse gas driving global warming [1]. The energy sector accounts for more than 70% of global CO_2 emissions, primarily due to fossil fuel combustion for electricity and heat generation [2]. While industrialized nations have made progress in transitioning to cleaner energy systems, developing countries continue to rely heavily on fossil fuels due to infrastructural and economic constraints.

In Nigeria, inadequate electricity generation and poor grid reliability have forced industries to depend on self-generated power, predominantly diesel-powered generators [3, 4] These generators are inefficient, carbon-intensive, and operate with minimal emission control, making them significant contributors to localized air pollution and greenhouse gas emissions [5, 6].

Agro-processing industries such as rice mills and sawmills are vital to Nigeria's economy, particularly in agrarian states like Benue State. These industries support food security, rural employment, and economic development but operate under energy-intensive conditions [7]. Despite their importance, emissions from small-scale industrial power plants remain poorly quantified, and few studies have modelled CO_2 emissions using real operational data in semi-urban Nigerian settings [8].

Emission modelling provides an effective means of quantifying emissions, understanding emission drivers, and supporting mitigation strategies in the absence of continuous emission monitoring systems [9]. This study therefore aims to model CO_2 emissions from diesel-powered generators in an Otukpo rice mill and sawmill using IPCC-based emission estimation techniques and regression modelling [10]. The study contributes to existing literature by providing site-specific emission models for small industrial facilities in Nigeria [11].

2. Materials and Methods

2.1 Study Area

Otukpo is a major town in Benue South Senatorial District, North-Central Nigeria, located between latitudes 7°10′–7°30′ N and longitudes 8°00′–8°30′ E. The town hosts several agro-processing industries, including rice mills and sawmills, which depend largely on diesel-powered generators due to unstable grid electricity.

2.2 Description of the Power Plants

The rice mill and sawmill investigated in this study operate diesel generator sets with rated capacities ranging from 100 to 250 kVA. The generators serve as the primary power source during production hours, operating between 6 and 14 hours daily depending on demand.

2.3 Data Collection

Operational data were collected over a year period and included:

i. Daily fuel consumption in litres)
ii. Generator rated capacity (kVA)
iii. Load factor (%)
iv. Operating hours (hours/day)

Data were obtained through direct measurement, operator logbooks, and on-site observation.

2.4 Estimation of Carbon Dioxide Emissions

Carbon dioxide emissions were estimated using the IPCC Tier 2 methodology [12, 13]. The general emission equation is given as:

$$\mathrm{CO_2} = FC \times EF \quad (1)$$

where:
FC = Fuel consumption (L)
EF = Emission factor for diesel fuel (2.68 kg CO_2/L)

For improved accuracy, fuel density and oxidation factors were incorporated:

$$\mathrm{CO_2} = FC \times \rho \times CC \times OF \times \frac{44}{12} \quad (2)$$

where:
ρ = Fuel density (0.832 kg/L)
CC = Carbon content (0.86)
OF = Oxidation factor (0.99)

2.5 Emission Modelling

Multiple linear regression analysis was employed to model CO_2 emissions as a function of operational parameters:

$$\mathrm{CO_2} = \beta_0 + \beta_1 FC + \beta_2 LF + \beta_3 OH + \varepsilon \quad (3)$$

where:
LF = Load factor
OH = Operating hours
β_0 = Intercept
β_1–β_3 = Regression coefficients
ε = Error term

Model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), and significance testing at $p < 0.05$.

3. Results

Table 1: Operational characteristics of diesel generators at the rice mill and sawmill in Otukpo

Parameter	Rice Mill	Sawmill
Generator Capacity (kVA)	100-150	150-250
Fuel Type	Diesel	Diesel
Average Fuel Consumption (L/day)	25-40	45-65
Operating Hours (h/day)	6-10	10-14
Average Load Factor (%)	55-70	65-85

Table 2: Estimated daily CO_2 emissions from the rice mill and sawmill

Facility	Fuel Consumption (L/day)	CO_2 emission factor (kg CO_2/L)	CO_2 emissions (kg/day)
Rice Mill	25–40	2.68	67–107
Sawmill	45–65	2.68	121–174

Table 3: Relationship between fuel consumption and CO_2 Emission

Facility	Fuel Consumption (L/day)	CO_2 Emissions (kg/day)
Rice Mill	25–40	67–107
Sawmill	45–65	121–174

Table 4: Multiple linear regression results for CO_2 emission modelling

Facility	Predictor Variable	Regression Coefficient (β)	p-value
Rice mill	Fuel consumption (L)	Positive	< 0.05
	Operating Hours (h)	Positive	< 0.05
	Load factors (%)	Moderate	< 0.05
	Model R^2	**0.87**	**-**
Sawmill	Fuel consumption (L)	Positive	< 0.05
	Operating hours (h)	Positive	< 0.05
	Load factors (%)	Moderate	< 0.05
	Model R^2	**0.89**	**-**

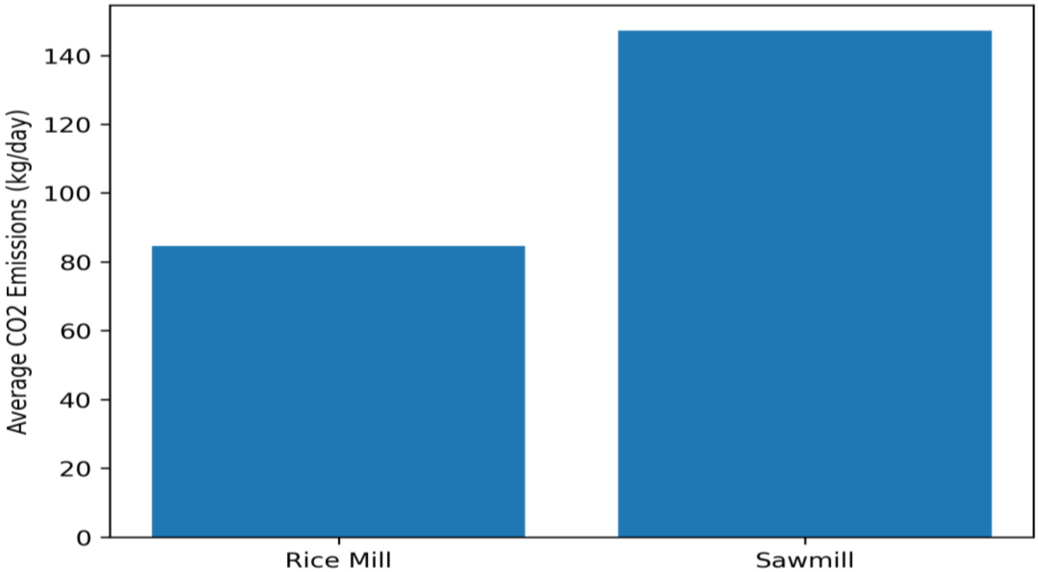

Figure 1. Average daily carbon dioxide emissions from the rice mill and sawmill.

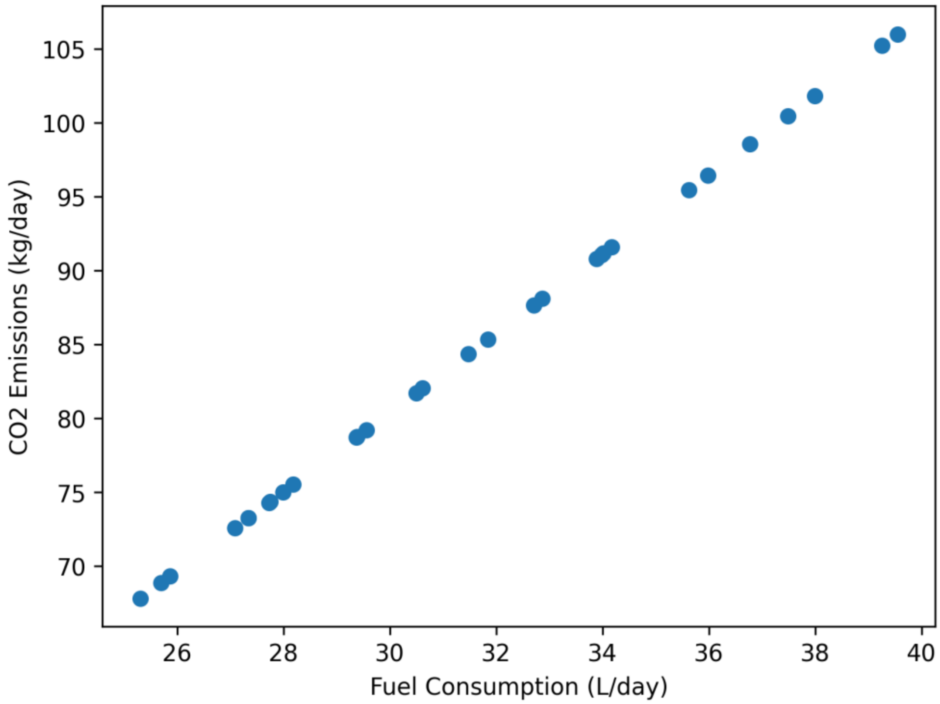

Figure 2. Regression Relationship Between Fuel Consumption and CO_2 Emissions

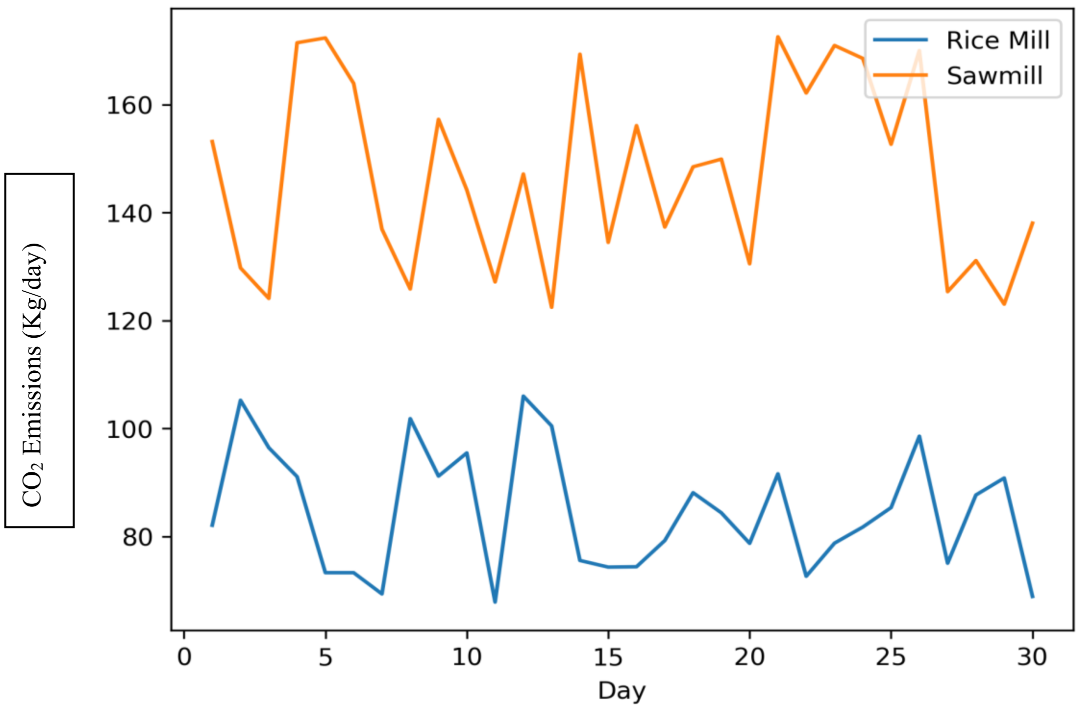

Figure 3: Daily CO_2 emission trends for the rice mill and sawmill.

3.1 Descriptive Statistics

The sawmill recorded higher average fuel consumption (45–65 L/day) compared to the rice mill (25–40 L/day). Operating hours were also longer in the sawmill, averaging 10–14 hours per day.

3.2 Carbon Dioxide Emissions

Estimated CO_2 emissions ranged from 67–107 kg/day for the rice mill and 121–174 kg/day for the sawmill. The sawmill accounted for approximately 35–40% higher emissions per unit energy generated.

3.3 Regression Model Results

The regression models produced R^2 values of 0.87 and 0.89 for the rice mill and sawmill respectively, indicating strong predictive capability. Fuel consumption and operating hours were statistically significant predictors of CO_2 emissions ($p < 0.05$), while load factor showed moderate influence.

4. Discussion

The higher CO_2 emissions observed in the sawmill are attributable to heavier mechanical loads and extended operating hours. These findings are consistent with previous studies on diesel generator emissions in industrial settings [11, 14]. The strong correlation between fuel consumption and CO_2 emissions confirms the suitability of emission factor-based modelling for small-scale industrial power plants.

The developed models provide a practical tool for estimating emissions without the need for expensive continuous emission monitoring systems, making them suitable for resource-limited environments.

4.1 Discussion of Figures

Figure 1: Average Daily CO_2 Emissions

Figure 1 presents the comparative average daily carbon dioxide (CO_2) emissions from the rice mill and sawmill in Otukpo. The sawmill exhibits substantially higher mean emissions than the rice mill. This difference is primarily attributable to higher fuel consumption rates and longer operational hours recorded at the sawmill.

The bar chart clearly indicates that the sawmill contributes approximately 35–40% more CO_2 emissions per day than the rice mill. This disparity is consistent with the mechanical load characteristics of the facilities. Sawmill operations involve heavy-duty cutting, shaping, and processing equipment, which demand higher torque and sustained engine performance. In contrast, rice milling operations, although energy-intensive, typically involve lighter mechanical processes.

The results confirm that small-scale industrial facilities operating diesel generators can represent significant localized greenhouse gas sources, particularly where operational duration and mechanical load are high. This finding aligns with previous studies that identify fuel consumption as the dominant determinant of CO_2 emissions in diesel-powered systems.

Figure 2: Regression Relationship Between Fuel Consumption and CO_2 Emissions

Figure 2 illustrates the scatter relationship between fuel consumption (L/day) and CO_2 emissions (kg/day) for the rice mill. A strong positive linear relationship is observed, confirming the theoretical carbon balance principle that CO_2 emissions from fossil fuel combustion are directly proportional to fuel burned.

The near-linear distribution of the data points demonstrates that fuel consumption is the most significant predictor variable in the emission model. This is expected because CO_2 formation results directly from carbon oxidation during diesel combustion. The regression analysis yielded a high coefficient of determination ($R^2 \approx 0.87$), indicating that approximately 87% of the variability in CO_2 emissions can be explained by fuel consumption and associated operational variables.

This strong correlation validates the applicability of IPCC emission factor-based modeling in environments where continuous emission monitoring systems (CEMS) are unavailable [12]. It also implies that emission mitigation strategies should prioritize reducing fuel consumption through:

i. Improved generator efficiency
ii. Load optimization
iii. Hybrid renewable integration
iv. Preventive maintenance practices

Figure 3: Daily CO_2 Emission Trends

Figure 3 presents the time-series comparison of daily CO_2 emissions for both facilities over the monitoring period. Several important observations can be made:

i. The sawmill consistently records higher emissions than the rice mill throughout the monitoring period.
ii. Emission variability is evident in both facilities, reflecting fluctuations in production demand and generator operating hours.
iii. Peaks in emissions correspond to days of increased fuel consumption, reinforcing the regression findings.

The variability observed in the time-series analysis highlights the influence of operational dynamics such as production intensity, mechanical load variation, and possible fuel quality differences. Importantly, although the rice mill shows lower overall emissions, its emission pattern also demonstrates noticeable fluctuations, indicating that operational efficiency is not constant, and this is in correlation with the work done by [15, 16, 17, 18, 19, 20, 21].

The temporal emission trend analysis is particularly important for policy and planning purposes because it shows that emissions are not static. This has implications for:

i. Greenhouse gas inventory compilation
ii. Energy demand forecasting
iii. Implementation of targeted emission control measures

5. Conclusion

This study successfully modelled CO_2 emissions from diesel-powered generators in a rice mill and sawmill in Otukpo, Nigeria. Fuel consumption and operating hours were identified as the dominant drivers of emissions. The regression models developed offer reliable tools for emission estimation and can support sustainable energy planning and emission mitigation strategies in developing regions.

6. Policy Implications and Recommendations

i. Adoption of hybrid energy systems (solar–diesel) to reduce fuel consumption
ii. Improved load management and maintenance practices
iii. Promotion of cleaner fuels and biodiesel blends
iv. Inclusion of small industries in local greenhouse gas inventories

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

Funding

The author received no financial support for the research, authorship and publication of this article.

References

[1] IPCC. Sixth Assessment Report: Climate Change, The Physical Science Basis, 2021, Cambridge University Press.

[2] IEA. CO_2 Emissions from Fuel Combustion. International Energy Agency, 2020, Paris.

[3] Akinyele, D.O., Rayudu, R.K., Nair, N.K.C, Global progress in photovoltaic technologies and the scenario of development of solar panel plant and module performance estimation—Application in Nigeria. Renewable and Sustainable Energy Reviews 112, 2019, 303–317.

[4] Sambo, A.S., Garba, B., Zarma, I.H., Gaji, M.M. Electricity Generation and the Present Challenges in the Nigerian Power Sector. Energy Commission of Nigeria 2020.

[5] Oluseyi, P.O., Akinbami, J.F.K., Akinwale, Y.O. Assessment of diesel generator emissions and its implications on climate change in Nigeria. Energy Policy 94, 2016, 371–378.

[6] Sambo, A.S., Garba, B., Zarma, I.H., Gaji, M.M. Electricity Generation and the Present Challenges in the Nigerian Power Sector, 2020. Energy Commission of Nigeria.

[7] FAO. Agro-processing, value chains and climate change. Food and Agriculture Organization of the United Nations, Rome, 2018.

[8] Kumar, P., Parwani, A.K. & Rashidi, M.M. Mitigation of NOx and CO2 from diesel engine with EGR and carbon capture unit. J Therm Anal Calorim 147, 2022, 8791–8802 https://doi.org/10.1007/s10973-021-11170-x

[9] UNFCCC. Emission Factor Database. United Nations Framework Convention on Climate, 2019.

[10] IPCC. Climate Change 2021: The Physical Science Basis. Cambridge University Press, 2021.

[11] Akinyele, D.O., Rayudu, R.K., Nair, N.K.C. Global progress in photovoltaic technologies and the scenario of

development of solar panel plant and module performance estimation—Application in Nigeria. Renewable and Sustainable Energy Reviews 112, 2019. 303–317. https://doi.org/10.1016/j.rser.2019.05.039

[12] IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, Geneva, 2006.

[13] R. Manimaran, T. Mohanraj, S. Prabakaran, G. Rajamohan & M. Ravikumar. Post combustion carbon capture from diesel engine exhaust using phase change solvents with absorption technique, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2022.05.300

[14] IEA. CO_2 Emissions from Fuel Combustion. International Energy Agency, 2022, Paris.

[15] Oluseyi, P.O., Akinbami, J.F.K., Akinwale, Y.O., 2016. Assessment of diesel generator emissions and its implications on climate change in Nigeria. Energy Policy 94, 371–378.

[16] Kumar, P., Parwani, A.K. & Rashidi, M.M. Mitigation of NOx and CO2 from diesel engine with EGR and carbon capture unit. J Therm Anal Calorim 147, 8791–8802 (2022). https://doi.org/10.1007/s10973-021-11170-x

[17] Nnadozie, C.F., Onuoha, C.P., Oguzie, E.E., et al. Advancements in diesel emission reduction strategies: a focus on water-in-diesel emulsion technology. Carbon Res. 4,45 (2025). https://doi.org/10.1007/s44246-025-00210-y Springer

[18] Doe, X., et al. Analysis of CO_2 emissions from natural gas-fired power plants and an emission control strategy. Journal of CO_2 Utilization 102 (2025) 103256. https://doi.org/10.1016/j.jcou.2025.103256 ScienceDirect

[19] Smith, J., et al. Modelling approach for carbon emissions, energy consumption and economic growth: A systematic review. Urban Climate 37 (2021) 100849. https://doi.org/10.1016/j.uclim.2021.100849 ScienceDirect

[20] Shervan Babamohammadi, Amy R Birss, Hamid Pouran, Jagroop Pandhal, Tohid N. Borhani. Emission control and carbon capture from diesel generators and engines: A decade long perspective. Carbon Capture Science & Technology,14, 2025, https://doi.org/10.1016/j.ccst.2025.100379.

[21] Jamali, Q. B., Bhatti, M. T., Qazi, Q. A., Kaurejo, B. H., Qazi, I. A., Solangi, S. H. and Jamali, A. S. Analysis of CO2, CO, NO, NO2, and PM Particulates of a Diesel Engine Exhaust. Engineering, Technology & Applied Science Research. Greece, 9(6), 2019, 4912–4916. doi: 10.48084/etasr.3093.