

Transforming Organic Waste into Valuable Bio-Products: An Integrated Approach to Ecological Resource Management

Dr Shashank Dattatray Kulkarni¹, Dr Biju Sidharthan²

¹Department of Political Science and Public Administration, Central University of Jharkhand, Email: agroneershashank@gmail.com

Department of Plant Breeding and Genetics, University name with full address (city, pin code): College of Agriculture, Vellanikkara, Thrissur 680656, Kerala Agricultural University, Email Id: biju.s@kau.in, ORCID ID: 0009-0008-9775-7670

 <https://doi.org/>

Abstract

The sustainable transformation of organic waste into renewable bio-products is an important strategy for advancing ecological resource management and supporting circular bioeconomy. This study evaluated the performance of farm-scale biodigesters in converting organic waste into biogas while identifying the operational and environmental factors influencing production. Secondary operational data comprising 1,063 observations collected from four biodigesters between January 2024 and January 2025 were analysed. Data preprocessing, descriptive statistics, multiple linear regression, and Random Forest regression were employed to investigate predictor–response relationships and model biogas production. The regression analysis demonstrated that reactor-specific characteristics significantly influenced biogas production, whereas biodigester type was not a significant predictor. Water input exhibited a modest negative association with biogas output, while air temperature and seasonal variation showed significant positive effects. Multicollinearity was negligible, with all variance inflation factor values below two. The Random Forest model achieved satisfactory training performance but exhibited limited temporal generalization, indicating that additional operational and biochemical variables are necessary for reliable future prediction. Overall, the findings demonstrate that effective organic waste valorization depends on optimized reactor management, environmental conditions, and continuous process monitoring rather than biodigester technology alone. The study provides practical evidence supporting biodigester-based renewable energy production and offers insights for developing data-driven decision-support frameworks that enhance sustainable bio-product recovery and ecological resource management.

Keywords: Organic waste valorization, Biodigester, Biogas production, Circular bioeconomy, Ecological resource management

1. INTRODUCTION

Global population growth, urbanization and intensification of agriculture have contributed to the tremendous amount of organic waste generated, which poses serious environmental and resource management problems. The disposal of large amounts of food waste, animal waste, crop residues and other organic waste materials through uncontrolled decomposition, open dumping and landfilling creates emissions of GHGs, nutrient losses and environmental pollution. The waste management practices that are followed traditionally are not only wasting valuable land resources but also fail to recognize that there is a significant economic and environmental value in the organic waste streams. Increasingly, the focus is shifting from the traditional waste management system to sustainable resource recovery systems that acknowledge organic waste as a valuable feedstock and a source for renewable bio-products, instead of a problem for the environment (Mahjoub & Domscheit, 2020).

The idea of circular bioeconomy has been developed as a successful solution to meet these challenges, encouraging the efficient use of biological resources and reducing waste. In this context, the use of organic waste is increasingly shifting toward considering it as a renewable source that can be used to produce bioenergy, organic fertilizers, soil amendments and other valuable products that increase environmental sustainability and economic resilience. In recent years, several developments in waste valorization technologies have shown that combining biological conversion technologies with resource recovery can lead to high material efficiency by decreasing the use of fossil fuels. The conversion of food waste and agricultural residues to renewable sources helps to create sustainable production systems and to meet wider environmental and climate goals (Pal et al., 2024).

In the range of waste valorization technologies available, anaerobic digestion has attracted a great deal of interest due to its capacity to manage biodegradable waste while at the same time producing renewable energy. The microorganisms during anaerobic digestion will transform the organic matter into biogas, which is a mixture of methane and carbon dioxide, and generate nutritive rich digestate, which can be used as an organic fertilizer. Combined with other technologies like microalgae production and waste biorefineries, anaerobic digestion maximizes the recovery of the resources by additionally creating energy. These integrated systems help to decrease waste disposals and enhance agricultural and industrial ecosystems sustainability (Chen et al., 2018).

In addition to generating renewable energy, composting and other biological methods for the production of organic fertilizers have come to the fore as a valuable alternative to improve soil health and reduce the environmental impact of synthetic fertilizers. The composting process is a transformation of biodegradable waste into stable organic amendments, that enhance the fertility, water holding capacity and stimulate beneficial microbial activity of the soil. Though it has environmental benefits, composting has some operational hurdles such as optimization of composting processes, variability of feedstocks, management of composting odors, compost quality control, etc. To achieve the best compost quality, and to facilitate general use of compost as an environmentally friendly bio-product (Ayilara et al., 2020), these challenges must be addressed. Similarly, biomass conversion technologies have shown high potential in the production of sustainable and organic fertilizers from agricultural residues and other organic materials that are biodegradable, which can enable nutrient recycling and sustainable agricultural production (Chew et al., 2019).

In addition, the transition of organic waste to valuable bio-products will need to be approached with a more comprehensive and integrated perspective of ecological resource management, not only from a technological innovation perspective, but also from an environmental governance and sustainable policy perspective. The efficient management of resources involves maximizing energy productivity, reducing environmental damage and encouraging responsible use of natural resources, from raw materials to waste. Governance quality, institutional effectiveness and resource management policies are of critical importance for the implementation of sustainable waste valorization projects and for moving towards a low-carbon and circular economy (Chen et al., 2023). Moreover, policies promoting sustainable development for carbon emissions reduction in resource-endowed areas have shown to produce significant impacts by promoting cleaner technologies and the overall environmental performance (Zheng & Ge, 2022).

Significant advances have been made in OW utilization technologies, but the previous studies have mainly investigated individual technologies like composting, anaerobic digestion, or fertilizer production separately. Few studies have taken a combined approach that considers operational performance, bio-product generation from renewables and ecological resource management in a single framework. Furthermore, there are only a few empirical studies related to the combined effects of operational conditions and environmental parameters on the efficiency of bio-product recovery in farm-scale bio digestion systems. To address these knowledge gaps, evidence-based strategies need to be developed that can maximize recovery of resources while enabling sustainable environmental management.

Research Objectives

1. To evaluate the efficiency of farm-scale biodigesters in transforming organic waste into valuable bio-products under varying operational conditions.
2. To examine the influence of operational and environmental factors on biogas and methane production during the anaerobic digestion of organic waste.
3. To identify the key determinants of sustainable organic waste valorization for enhancing ecological resource management and renewable bio-product recovery.

2. MATERIALS AND METHODS

2.1 Research Design

This research was quantitative research and secondary data which was used to explore the process of utilizing organic waste for producing useful bio-products in farm-scale anaerobic digestion systems as discussed in Mulat, 2025. The performance of the Biodigester was assessed by conducting an analytical study using a data driven method to understand the performance of the Biodigester under various operational and environmental conditions. The study highlighted the identification of the factors that influence the production of bio-products from renewable sources and implications on sustainable management of ecological resources.

2.2 Data Source and Study Variables

The analysis was done by processing publicly available secondary data, which included operational data from 4 farm scale biodigesters, and a weather monitoring database. The following variables were included in the operational data set: manure input, water input, type of biodigester used, ambient temperature, biodigester temperature, gas temperature, daily biogas production, daily methane production, and standardized gas yields. Weather data was provided as supplementary environmental data such as solar radiation, rainfall, wind speed, air pressure and air temperature, which was very useful for a thorough evaluation of the performance of the biodigester was carried out.

2.3 Data Pre-processing

The datasets were pre-processed for consistency and analysis in order to increase analytical reliability. Some observations were missing and some duplicate, and all data sets were checked for consistency of units, date format, etc. Outliers were statistically screened and operational and environmental datasets were joined by the common observation dates. The processed data was subsequently ready for descriptive, inferential and predictive analysis.

2.4 Statistical and Predictive Analysis

Harmonizing all the characteristics of the study variables with descriptive statistics was first carried out. Pearson correlation analysis was used to analyze the relationships among the operational factors, environmental factors and bio-product production. Multiple linear regression was used to find significant predictors of biogas and methane production and Random Forest regression was used to assess the nonlinear relationship and determine the relative importance of influential variables. The coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE) were used to evaluate the model performance.

2.5 Software and Ethical Considerations

Initial data organization and visualization was done in Microsoft Excel, and all data management, statistical analyses and predictive modelling was performed in Python. The study used only secondary public data which did not include any personal or confidential information. Thus, no ethical approval and informed consent were needed. The analyses conducted were done with respect to accepted scientific standards and practices of scientific rigor, repeatability, and responsible data practices.

3. RESULTS

3.1 Descriptive Characteristics of the Study Dataset

After data preprocessing and quality assessment, 1,063 observations were taken for final statistical analysis after conducting the sensitivity analysis. The operational data from four farm-scale biodigesters were collected from January 2024 to January 2025, which included daily biogas production, water input, air temperature, bioset of the biodigester, type of biodigester and temporal variables. Inconsistencies in the data were improved due to the removal of incomplete records and influential outliers, while retaining the data variability needed for modelling.

The inferential analysis and the predictive analysis were both based on the processed data set. The descriptive characteristics and number of observations included in the final analysis is summarized in Table 1.

Table 1. Descriptive characteristics of the analysed biodigester dataset

Variable	Description
Total observations	1,063
Study period	January 2024 – January 2025
Biodigester systems	Flexible and Fixed Dome
Number of reactors	4 (R1–R4)
Response variable	Daily biogas production (mL)
Environmental variable	Air temperature (°C)
Operational variable	Water input (kg)
Temporal variables	Month and day of year

3.2 Multiple Linear Regression Analysis

The effects of operational, environmental and temporal variables on daily production of biogas were evaluated by multiple linear regression with log transformation of the dependent variable. Two regression models have been created. Model 1 was used to assess the effects of the type of biodigester, while model 2 added reactor-specific effects to consider the variability in operating conditions across different digesters.

The daily biogas production did not significantly differ by biodigester type in Model 1 ($\beta = -0.022$, $p = 0.769$) as shown in Table 2. Water input, on the other hand, had a significant negative correlation with biogas production ($\beta = -0.029$, $p = 0.036$), whereas air temperature ($\beta = 0.043$, $p < 0.001$) and month ($\beta = 0.040$, $p = 0.001$) had significant positive correlation.

The model was more successful in explaining more variation with the reactor specific model. Reactor R2 generated significantly less biogas than Reactor R1 ($\beta = -0.292$, $p = 0.003$); Reactor R3 significantly more biogas than Reactor R1 ($\beta = 0.464$, $p < 0.001$); and Reactor R4 significantly less biogas than Reactor R1 ($\beta = -0.704$, $p < 0.001$). Air temperature and month had positive effects while water input continued to be negatively associated with production.

Table 2. Multiple linear regression analysis of factors influencing daily biogas production

Predictor	Model 1 β (p-value)	Model 2 β (p-value)
Biodigester type (Flexible)	-0.022 (0.769)	—
Reactor R2	—	-0.292 (0.003)
Reactor R3	—	0.464 (<0.001)
Reactor R4	—	-0.704 (<0.001)
Water input (kg)	-0.029 (0.036)	-0.028 (0.031)
Air temperature (°C)	0.043 (<0.001)	0.045 (<0.001)
Month	0.040 (0.001)	0.041 (<0.001)
Adjusted R ²	0.041	0.152

3.3 Multicollinearity and Model Diagnostics

Multicollinearity assessment and diagnostic testing of the regression models were performed to check the validity of the models. From Table 3, all the predictor variables had low variance inflation factors ranging from 1.01 to 1.96, which meant there was no presence of multicollinearity.

Residual diagnostics revealed violations of classic assumptions of linear regression. The Shapiro–Wilk and Jarque–Bera tests were statistically significant and indicated that the residual distributions were not normal ($p < 0.001$). Similarly, the Breusch–Pagan test showed that there was a significant heteroscedasticity ($p < 0.001$). Thus, heteroscedasticity-consistent (HC3) robust standard errors were used in obtaining statistical inferences.

Model 2 was a better model as evidenced by lower AIC and BIC values than Model 1. Similarly, Model 2 produced lower prediction errors (MAE = 341.32 mL; RMSE = 466.44 mL) than Model 1 (MAE = 368.22 mL; RMSE = 498.80 mL).

Table 3. Multicollinearity assessment and regression diagnostics

Parameter	Model 1	Model 2
Observations	1,063	1,063
Adjusted R ²	0.041	0.152
AIC	3402.52	3273.86
BIC	3427.36	3308.64
RMSE (log scale)	1.193	1.121
MAE (original scale, mL)	368.22	341.32
RMSE (original scale, mL)	498.80	466.44
Durbin–Watson	0.970	1.101
VIF range	1.01–1.96	1.01–1.96
Shapiro–Wilk p	<0.001	<0.001
Jarque–Bera p	<0.001	<0.001
Breusch–Pagan p	<0.001	<0.001

3.4 Random Forest Regression Performance

A Random Forest regression model was developed to detect the possibility of nonlinear relationships between the operational variables, based on the chronological temporal validation. The number of observations in the dataset was split into 816 training observations and 247 testing observations to ensure that model evaluation was under future operational conditions.

The overall performance of the Random Forest model during training is good as evidenced by the R² value obtained, which is 0.598 on the logarithmic scale and 0.559 on the original scale (see Table 4). The errors in the prediction of the training samples were relatively small (MAE = 188.72 mL; RMSE = 297.10 mL).

However, predictive performance decreased significantly when it was tested independently on the temporal testing dataset. The testing results gave R² of −1.458 on the logarithmic scale and −0.916 on the original scale with the higher prediction error (MAE = 479.37 mL; RMSE = 622.25 mL). These results show that the model has poorer generalisation accuracy when predicting the data outside of the training period.

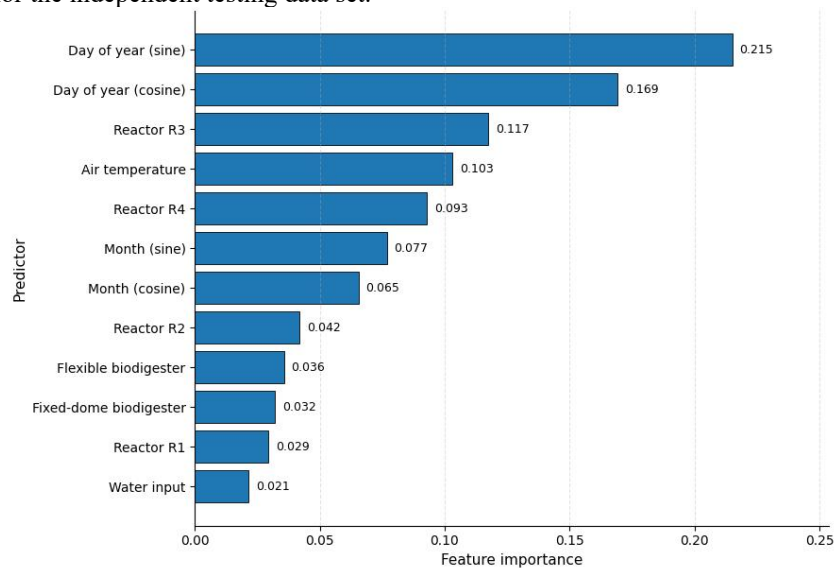
Table 4. Random Forest temporal validation performance

Performance metric	Training	Testing
Observations	816	247
MAE (log scale)	0.467	0.729
RMSE (log scale)	0.836	0.900
R ² (log scale)	0.598	−1.458
MAE (original scale, mL)	188.72	479.37
RMSE (original scale, mL)	297.10	622.25
R ² (original scale)	0.559	−0.916

3.5 Variable Importance Analysis

The temporal variables were the most important variables in the Random Forest feature importance analysis. The cyclical day-of-year variables had the highest importance, with day_sine (0.215) and day_cosine (0.169) the most significant for model performance (as shown in Figure 1). The characteristics of the reactors also had a significant influence, especially Reactor R3 (0.117) and Reactor R4 (0.093), and next air temperature (0.103).

Temporal validation was confirmed by the reactor identity and air temperature, the latter showing the highest influence on the variables, while the water input showed a relatively low predictive importance, as confirmed by the permutation importance analysis. The performance of the model in terms of prediction of daily biogas production was compared against the observed biogas production as shown in Figure 2 for the independent testing data set.

**Figure 1. Random Forest feature importance for predicting daily biogas production**

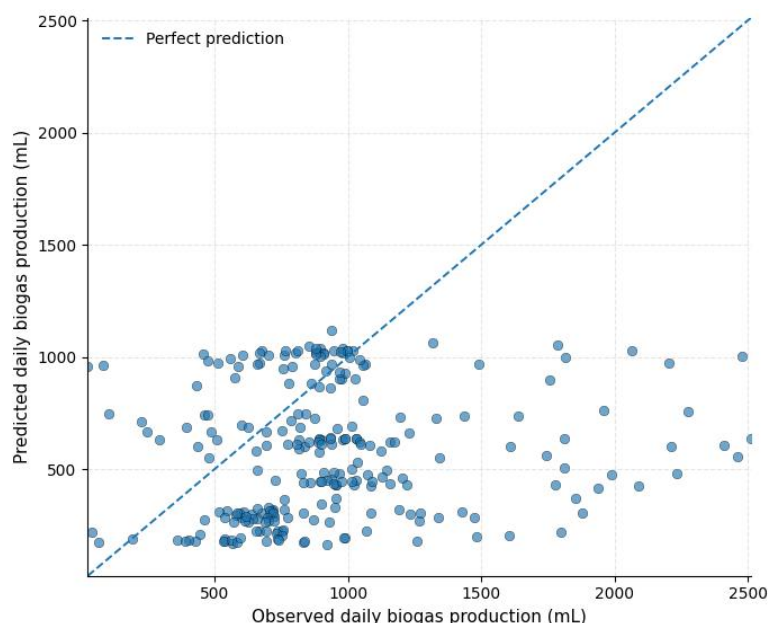


Figure 2. Observed versus predicted daily biogas production during temporal validation

4. DISCUSSION

In the present study, the conversion of organic waste into useful bio-products using farm scale-based biogas digester and the various operational, environmental, reactor specific and temporal factors associated with the daily production of biogas has been explored. The results confirm the principle of the circular bioeconomy of using organic waste as a renewable resource. It aligns with Pal et al. (2024) who pointed out the importance of using food waste as a source for obtaining renewable products, and Lee et al. (2022) who described biological conversion routes for obtaining bio-based materials from food wastes and residues.

There was no significant association of the type of biodigester with the produced biogas, suggesting that flexible or fixed dome would not be the sole indicator of the performance of a biogas system. However, marked variations could be detected between different reactors. The amount of biogas generated by reactor R3 was much more than the reference reactor, while R2 and R4 generated less. The results indicate that the reactor type is not as important as the reactor operating practice, maintenance conditions, management of feed, and internal process stability. Hence, site specific management is required instead of a generic assumption about the efficiency of the biodigester as stated by Ng et al., 2019.

The biogas production was found to be slightly negatively correlated with water input. The higher the concentration of biodegradable organic matter available for microbial conversion may be, the less water that needs to be diluted. However, this correlation must be interpreted with caution since it did not have the benefit of total solids, volatile solids and organic loading rates. However, the discovery suggests that adding water should be optimized to prevent waste of resources and difficulty in the process. The same concept is applied to sustainable waste management strategies that focus on the maximisation of resources and minimisation of unnecessary operational inputs (Ng et al., 2019; Zhang et al., 2021).

Biogas production was positively correlated with air temperature and month, and cyclical day-of-year variables were significant temporal predictors. The results show that environmental and seasonal factors are affecting the performance of farm scale biodigesters. Gas production can vary due to changes in weather, feedstock characteristics, water availability and day-to-day operations. It is in line with the overall environmental context for renewable energy generation systems (Gielen et al., 2019; Hassan et al., 2024).

The model trained with Random Forest showed moderate training performance, but poor temporal generalization with negative testing R^2 values. This means that model learned the concept during training but was unable to reliably predict the conditions it was used for later. The result indicates that the data distribution over time has changed, and that the set of predictors available is not sufficiently comprehensive to explain the result. This indicates that the distribution over time of the data has changed, not that there was a computation error. Other parameters that could be added to future models are pH, hydraulic retention time, organic loading rate, volatile solids, substrate composition, internal digester temperature, and maintenance events.

The results are applicable to management of ecological resources. The benefits of anaerobic digestion range from reducing reliance on organic waste disposal to landfill diversion, to producing decentralised renewable energy. Benefits are like those of sustainable waste recovery strategies proposed by Nanda and Berruti (2021); Zhang et al. (2021). However, continuous monitoring, reactor specific optimization and improved data collection of processes will help to implement it successfully. From the environmental point of view, the valorisation of organic waste using biodigesters is a promising technology, but a reliable recovery of the bio-products needs to be complemented with the implementation of technology and good environmental and operational management.

5. CONCLUSION

The feasibility of implementing a farm scale biodigester was demonstrated as it can create useful bio-products, manage ecological resources and generate renewable energy as well. The results showed that the daily biogas production strongly depends on the operational characteristic of the reactor more than on the type of biodigester, thereby highlighting the importance of biogas production in terms of the operation of the system and not only technology. The results indicated that water input had a slight negative correlation with biogas production, while air temperature and seasonal variation had a positive correlation, suggesting that environmental and operational conditions need to be optimized for better process performance. The multiple linear regression model could successfully explain the biogas production at statistical significance, but the model could not explain the production of biogas at a high level of accuracy, suggesting that other operational and biochemical factors need to be considered to explain anaerobic digestion dynamics better. Likewise, the Random Forest model had good training performance and poor temporal generalization, meaning that the ability to predict future biogas production will require the inclusion of more extensive data sets, including details of the digester's operating conditions, such as organic loading rate, substrate composition, hydraulic retention time, pH and digester temperature. The overall findings of this study support the valorisation of organic waste by establishing a sustain the operations, and explainable machine learning methods to optimize the efficiency of the biodigester and sustainable resource recovery.

REFERENCES

1. Mahjoub, B., & Domscheit, E. (2020). Chances and challenges of an organic waste-based bioeconomy. *Current Opinion in Green and Sustainable Chemistry*, 25, 100388.
2. Ayilara, M. S., Olanrewaju, O. S., Babalola, O. O., & Odeyemi, O. (2020). Waste management through composting: Challenges and potentials. *Sustainability*, 12(11), 4456.
3. Chew, K. W., Chia, S. R., Yen, H. W., Nomanbhay, S., Ho, Y. C., & Show, P. L. (2019). Transformation of biomass waste into sustainable organic fertilizers. *Sustainability*, 11(8), 2266.
4. Pal, P., Singh, A. K., Srivastava, R. K., Rathore, S. S., Sahoo, U. K., Subudhi, S., ... & Prus, P. (2024). Circular bioeconomy in action: Transforming food wastes into renewable food resources. *Foods*, 13(18), 3007.
5. Chen, Y. D., Ho, S. H., Nagarajan, D., Ren, N. Q., & Chang, J. S. (2018). Waste biorefineries—integrating anaerobic digestion and microalgae cultivation for bioenergy production. *Current opinion in biotechnology*, 50, 101-110.
6. Chen, F. F., Wang, Q. S., Umar, M., & Zheng, L. (2023). Towards sustainable resource management: The role of governance, natural resource rent and energy productivity. *Resources Policy*, 85, 104026.
7. Zheng, H., & Ge, L. (2022). Carbon emissions reduction effects of sustainable development policy in resource-based cities from the perspective of resource dependence: Theory and Chinese experience. *Resources Policy*, 78, 102799.
8. Pal, P., Singh, A. K., Srivastava, R. K., Rathore, S. S., Sahoo, U. K., Subudhi, S., ... & Prus, P. (2024). Circular bioeconomy in action: Transforming food wastes into renewable food resources. *Foods*, 13(18), 3007.
9. Ng, K. S., Yang, A., & Yakovleva, N. (2019). Sustainable waste management through synergistic utilisation of commercial and domestic organic waste for efficient resource recovery and valorisation in the UK. *Journal of Cleaner Production*, 227, 248-262.
10. Pari, L., Bergonzoli, S., Cozzolino, L., Baldi, G. M., Falce, M., & Alexopoulou, E. (2024). Mechanical Harvesting of Marginal Land and Agroforestry Field: New Insights from Safflower for Bio-Product Production. *Agronomy*, 14(10), 2268.
11. Xue, Y. N., Luan, W. X., Wang, H., & Yang, Y. J. (2019). Environmental and economic benefits of carbon emission reduction in animal husbandry via the circular economy: case study of pig farming in Liaoning, China. *Journal of Cleaner Production*, 238, 117968.
12. Singh, A. (2019). Remote sensing and GIS applications for municipal waste

- management. *Journal of environmental management*, 243, 22-29.
13. Nanda, S., & Berruti, F. (2021). Municipal solid waste management and landfilling technologies: a review. *Environmental chemistry letters*, 19(2), 1433-1456.
 14. Zhang, J., Qin, Q., Li, G., & Tseng, C. H. (2021). Sustainable municipal waste management strategies through life cycle assessment method: A review. *Journal of environmental management*, 287, 112238.
 15. Hassan, Q., Viktor, P., Al-Musawi, T. J., Ali, B. M., Algburi, S., Alzoubi, H. M., ... & Jaszczur, M. (2024). The renewable energy role in the global energy Transformations. *Renewable Energy Focus*, 48, 100545.
 16. Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy strategy reviews*, 24, 38-50.
 17. Tong, N., Domingo Dr, N., & Le, A. (2025). Landfill waste diversion in residential projects in New Zealand. In *CIB Conferences* (Vol. 1, No. 1, p. 304).
 18. Mondal, K., Jana, K., Saha, P., Paramanik, B., Mondal, R., Agrawal, R. K., ... & Kundu, A. (2025). Effect of nitrogen fertilization integrated with bio-product on productivity, profitability, and resource use efficiency of dual-purpose oats-residual green gram system. *Journal of Plant Nutrition*, 48(8), 1383-1396.
 19. Pal, P., Singh, A. K., Srivastava, R. K., Rathore, S. S., Sahoo, U. K., Subudhi, S., ... & Prus, P. (2024). Circular bioeconomy in action: Transforming food wastes into renewable food resources. *Foods*, 13(18), 3007.
 20. Lee, J. Y., Lee, S. E., & Lee, D. W. (2022). Current status and future prospects of biological routes to bio-based products using raw materials, wastes, and residues as renewable resources. *Critical Reviews in Environmental Science and Technology*, 52(14), 2453-2509.
 21. Mulat, Daniel (2025), "Process monitoring and weather datasets on farm-scale biogas digesters", Mendeley Data, V1, doi: 10.17632/gk3f363sfg.1