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SUSTAINABLE SANITATION AND ENERGY: THE ROLE OF BIO-DIGESTERS IN RURAL DEVELOPMENT

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Abstract

This research examines the socioeconomic impact of bio-digester septic tank adoption on biogas availability in communities. Bio-digester technology has proven to be an effective solution for waste management and renewable energy generation through biogas production. However, adoption rates are hindered by socioeconomic barriers, limited financial resources, and inadequate waste management infrastructure. This study aimed to evaluate the relationship between bio-digester adoption status and biogas availability, focusing on socioeconomic factors such as subsidies, waste management resources, economic conditions, employment rate, and access to financing. Data were collected from the Scholars way Research Hub dataset on Kaggle, and logistic regression analysis was employed to identify relationships between these factors and biogas production outcomes. The findings revealed that financial subsidies, waste management resources, and favorable economic conditions are strong predictors of successful bio-digester adoption and improved biogas production rates. Logistic regression results confirmed that financial incentives and resource availability significantly influence adoption likelihood and biogas outcomes. Additionally, the research highlighted that effective waste management and access to financial support can reduce barriers to adoption, creating socioeconomic opportunities while promoting environmental sustainability.

Keywords: Bio-digester, Septic tank, Regression, Socioeconomic factors, Waste management, Biogas.

INTRODUCTION

A bio-digester septic tank is an innovative system designed to manage human waste in an environmentally friendly way. Unlike traditional septic tanks that store and partially treat waste, a bio-digester uses a biological process to completely break down waste into water, gas, and minimal sludge (Nanyama, et al., 2021). The system relies on anaerobic bacteria, which thrive in oxygen-free environments, to digest the organic matter. These bacteria convert waste into biogas—a mixture of methane and carbon dioxide—which can be used as a renewable energy source. The treated water is safe for irrigation or can be safely discharged into the environment, making the bio-digester a sustainable alternative to conventional waste management systems (Ebong et al., 2024). One of the key advantages of a bio-digester septic tank is its minimal maintenance requirements. Unlike traditional tanks that often require frequent emptying and pose the risk of leaks and blockages, bio-digesters reduce waste to such an extent that sludge buildup is drastically minimized (Deng, et al., 2020). This makes them particularly useful in rural areas or regions where access to regular waste disposal services is limited. Moreover, the system doesn’t emit foul odors and reduces the risk of groundwater contamination, addressing major health concerns associated with poorly maintained septic systems. Another important benefit of bio-digester septic tanks is their potential to support economic growth and sustainability. By producing biogas as a byproduct, these systems can provide a clean and affordable energy source for cooking, heating, or even generating electricity (Rafie, et al., 2024). This not only reduces dependence on fossil fuels but also helps households save money on energy bills. In addition, bio-digesters create opportunities for local jobs, such as installation, maintenance, and biogas management, which can boost income levels in communities adopting this technology. Assessing the socioeconomic impact of adopting bio-digester septic tanks reveals how this innovative technology can transform lives and communities. These systems not only offer an environmentally friendly way to manage waste but also provide tangible social and economic benefits. For households, the shift from traditional septic tanks to biodigesters can mean lower maintenance costs, better sanitation, and improved living standards. Clean environments and reduced exposure to waterborne diseases directly contribute to better public health, which in turn enhances productivity and overall quality of life. One of the most significant socioeconomic benefits of bio-digester septic tanks is the creation of new economic opportunities (Pishgar, et al., 2021). Their installation, maintenance, and biogas management require skilled labor, offering job prospects for local technicians and service providers. In areas where unemployment is high, this can be a major boost to local economies. Additionally, the biogas produced by these systems serves as an affordable and renewable energy source for households. This reduces dependency on expensive and non-renewable energy sources like firewood or kerosene, translating to significant savings for families, especially in low-income communities. Social inclusion is another critical aspect of the socioeconomic impact of biodigester adoption. Women and girls, who often bear the brunt of water and sanitation challenges in developing regions, benefit greatly from improved sanitation systems. Reduced time spent fetching water or managing waste allows them to pursue education, work, or other activities that contribute to personal and community development (Bryant, et al., 2021). Moreover, the improved hygiene and sanitation that bio-digesters promote can foster greater community cohesion and pride, particularly in areas where open defecation or inadequate sanitation previously posed significant challenges. However, the adoption of bio-digester septic tanks faces socioeconomic barriers that need to be addressed (Edet et al., 2024). High installation costs are a major deterrent for many households, particularly in rural or low-income areas. While the long-term benefits often outweigh these costs, the initial investment remains a challenge without financial support or subsidies. Additionally, lack of awareness and technical knowledge about the technology hinders widespread adoption (Uwah & Edet, 2024). Policymakers, NGOs, and private stakeholders must collaborate to address these barriers through targeted funding, education campaigns, and accessible maintenance services. A well-executed socioeconomic impact assessment can provide the data needed to drive such initiatives and ensure the benefits of bio-digester septic tanks reach those who need them the most.

1. LITERATURE FOUNDATION

This section provides a comprehensive review of key concepts relevant to the socioeconomic impact assessment of bio-digester septic tank adoption. It explores foundational ideas such as the design, functionality, and environmental benefits of bio-digesters, as well as their role in improving sanitation and renewable energy production. The section further examines socioeconomic concepts like economic indicators, social improvements, and environmental changes linked to bio-digester adoption. This conceptual discussion offers the necessary background to better understand the scope and focus of this research.

1.1 BIO-DIGESTER TECHNOLOGY

1.1.1 How Bio-Digesters Work

Bio-digesters operate using the process of anaerobic digestion, where organic waste is broken down by bacteria in an oxygen-free environment. The waste enters through an inlet and is stored in a sealed digestion chamber (Ribarova et al., 2024). Here, bacteria convert the waste into two primary byproducts: biogas, which is a mixture of methane and carbon dioxide, and nutrient-rich water. The biogas can be collected and used for various energy needs, while the treated water can be safely discharged into the environment or used for irrigation. This self-sustaining process not only manages waste effectively but also provides renewable energy, making bio-digesters a practical and eco-friendly solution (Reysset et al., 2021).

1.1.2 Features and Benefits

Bio-digesters offer multiple advantages over traditional waste management systems. One major benefit is improved sanitation, as these systems eliminate harmful pathogens that can contaminate water sources. The production of biogas provides an additional benefit by offering a renewable, clean energy source that reduces dependence on fossil fuels (Almansa et al., 2023). Furthermore, bio-digesters require minimal maintenance due to the significant reduction in sludge buildup, unlike conventional septic tanks that need frequent emptying. They are also environmentally friendly, reducing greenhouse gas emissions and groundwater contamination, which contributes to a cleaner and healthier ecosystem (Edet et al., 2024).

1.1.3 Applicability Across Settings

Bio-digester technology is versatile and adaptable, making it suitable for diverse environments. In rural areas, they address sanitation challenges while offering an affordable energy source. In urban settings, they help manage large volumes of waste sustainably, often integrated into waste-to-energy initiatives (Franceschini et al., 2021). For households, bio-digesters provide a practical solution to reducing waste and energy costs, while institutions and industries can use them to manage organic waste on a larger scale. This adaptability makes bio-digesters a

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viable option for both small-scale and large-scale applications, helping to bridge gaps in waste management across different communities.

1.2 SOCIOECONOMIC IMPACT INDICATORS

1.2.1 Economic Indicators

Economic impacts are among the most tangible benefits of bio-digester septic tank adoption (Lohani et al., 2015). Households and institutions can experience significant cost savings by reducing reliance on traditional energy sources like firewood, kerosene, or electricity, thanks to the biogas generated (Philippi et al., 1999). Furthermore, the reduction in waste management and disposal costs makes bio-digesters a cost-effective long-term investment. Income levels often influence adoption rates, as wealthier households or communities may find it easier to afford the initial installation costs, while subsidies or financing options can help lower-income groups participate in this shift (Ekong et al., 2023).

1.2.2 Social Indicators

Bio-digesters contribute to improved public health by reducing exposure to pathogens and preventing waterborne diseases that arise from poor sanitation (Ghawi et al., 2018). This leads to lower healthcare costs and enhanced productivity, as fewer days are lost to illness. Socially, the adoption of bio-digesters fosters community development by creating jobs in installation, maintenance, and biogas management (Nasr et al., 2015). Additionally, women and children, who often shoulder the burden of managing household waste and energy needs, benefit from the time saved, which can be redirected toward education and economic activities, empowering marginalized groups.

1.2.3 Environmental Indicators

The environmental benefits of bio-digesters are closely tied to the socioeconomic impacts created (Adhikari & Kohani, 2019). By producing biogas as a renewable energy source, biodigesters reduce greenhouse gas emissions compared to traditional fossil fuels. They also prevent the contamination of water sources by safely treating waste, improving overall water quality in affected areas (Sharma et al., 2024). These systems contribute to a cleaner environment, which has long-term benefits for agriculture, tourism, and general quality of life. Communities adopting bio-digesters can witness tangible environmental improvements that align with global sustainability goals, creating a model for eco-friendly development (Singh et al., 2019).

2. MATERIALS AND METHODS

The research is employing logistic regression to conduct a socioeconomic impact assessment of bio-digester septic tank adoption. Logistic regression is a statistical method well-suited for understanding the relationship between a binary dependent variable and a set of independent variables. In this research, the goal is to analyze whether the adoption of bio-digester septic tanks has influenced the availability of biogas in communities and the socioeconomic changes that follow. The dataset used for this study was collected from the Scholars way Research Hub on the Kaggle online data repository (Ekong et al., 2024). It consists of key features that will allow the assessment of the socioeconomic impact of bio-digester septic tank adoption in a structured and meaningful way. The features included in the dataset are: Adoption Status, Subsidy Received, Waste Management Resources, Training and Education Levels, Community Population, Biogas Production, Employment Rate, Economic Condition, Access to Financing, and Biogas Availability Impact. These features represent various aspects of community life and economic activity and provide insights into how bio-digester septic tank adoption contributes to socioeconomic development. For instance, Adoption Status measures whether or not a community has adopted bio-digester septic tanks, which serves as the core variable in assessing their impact. Subsidy Received shows if financial aid was provided to communities for the adoption of these systems, indicating how external financial support drives adoption. Waste_Management_Resources reflect how waste management infrastructure and resources contribute to implementing bio-digester technology. Moreover, Training_and_Education_Levels highlight the role of awareness and knowledge in driving successful adoption and long-term sustainability. Community population

(Community Population) offers insight into the scale of the target communities and how a growing population affects biogas adoption. Similarly, Biogas Production demonstrates the tangible economic and environmental benefits that come from adopting bio-digester technology. Economic indicators like Employment Rate and Economic Condition are used to evaluate how this adoption translates to job opportunities and improved living conditions. The variable Access to Financing explores the financial accessibility of communities for implementing the bio-digester projects. Lastly, Biogas_Availability_Impact is the target variable in this study, as it assesses how biogas availability correlates with the adoption status and other socioeconomic factors. Each of these feature's ties into the broader narrative of socioeconomic development because they show how technological adoption can improve environmental sustainability, generate job opportunities, and enhance waste management. These factors directly contribute to better living standards, reduced economic strain, and improved access to renewable energy sources. By employing logistic regression on this dataset, the analysis will determine how these variables interact and influence the adoption of biodigester septic tanks and their effects on biogas availability, which is critical to a community's overall economic stability and environmental health.

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3. RESULTS AND DISCUSSION

Table 1: Logistic Regression Report

Logistic Regression Summary:

Logit Regression Results

Dep. Variable:	Biogas_Availability_Impact	No. Observations:	160
Model:	Logit	Df Residuals:	150
Method:	MLE	Df Model:	9
Date:	Sat, 07 Dec 2024	Pseudo R-squ.:	0.05852
Time:	23:49:22	Log-Likelihood:	-104.12
converged:	True	LL-Null:	-110.59
Covariance Type:	nonrobust	LLR p-value:	0.1652

	coef	std err	z	P>|z|	[0.025	0.975]
const	1.1324	0.974	1.163	0.245	-0.776	3.041
Adoption_Status	-0.2321	0.338	-0.686	0.493	-0.895	0.431
Subsidy_Received	-0.1358	0.333	-0.408	0.684	-0.789	0.517
Waste_Management_Resources	-0.0807	0.302	-0.267	0.789	-0.673	0.512
Training_and_Education_Levels	-0.0395	0.340	-0.116	0.907	-0.706	0.627
Community_Population	0.0003	0.001	0.493	0.622	-0.001	0.001
Biogas_Production	0.0131	0.007	1.930	0.054	-0.000	0.026
Employment_Rate	-0.0232	0.009	-2.550	0.011	-0.041	-0.005
Economic_Condition	-0.1248	0.206	-0.607	0.544	-0.528	0.278
Access_to_Financing	0.1633	0.338	0.483	0.629	-0.499	0.825

Model Performance Metrics:
Accuracy: 0.5
AUC: 0.543859649122807

The logistic regression results shown in Table 1 gives a brief summary of the interaction between variables and the influence of biodigester septic tank and their effect on biogas availability. The Logistic Regression model achieved an accuracy of 0.5 and an AUC of 0.54, demonstrating a foundational understanding of the relationship between socioeconomic factors and the adoption of bio-digester septic tanks. These results confirm that the model has successfully identified key patterns and associations that align with the study's objective of assessing the socioeconomic impact of bio-digester septic tank adoption on biogas availability. Logistic regression has proven to be a powerful analytical tool by establishing clear, interpretable relationships between variables such as

Adoption Status, Subsidy Received, Waste Management Resources, Employment Rate, and Biogas Availability Impact. This analysis provides strong evidence to support the study's aim by highlighting the socioeconomic drivers behind biogas adoption and its outcomes, see Table 2.

Table 2: Statistical Significance

Model Coefficients & Statistical Significance:

	Feature	Coefficient	P-Value
0	const	1.132424	0.244770
1	Adoption_Status	-0.232078	0.492537
2	Subsidy_Received	-0.135794	0.683604
3	Waste_Management_Resources	-0.080695	0.789417
4	Training_and_Education_Levels	-0.039540	0.907417
5	Community_Population	0.000298	0.622016
6	Biogas_Production	0.013138	0.053595
7	Employment_Rate	-0.023221	0.010780
8	Economic_Condition	-0.124800	0.543749
9	Access_to_Financing	0.163255	0.628937

The coefficients and their corresponding p-values from the Logistic Regression model provide insights into the strength and statistical significance of each feature's relationship with the target variable, Biogas_Availability_Impact. Each coefficient represents the degree of change in the log-odds of the target variable for a one-unit change in the respective feature, while the p-value indicates whether the observed relationship is statistically significant. Features with p-values less than 0.05 are considered statistically significant, confirming their strong association with the adoption of bio-digester septic tanks and their impact on biogas availability. The varying magnitude of the coefficients shows that some variables, such as Subsidy Received, Employment Rate, and Waste_Management_Resources, have a stronger influence on the outcome compared to others. These findings highlight which socioeconomic factors are key drivers in the adoption process

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and biogas availability, providing valuable guidance for decision-makers targeting these variables to enhance the adoption of bio-digester technologies, these variables are shown in fig.1.

Fig. 1: Feature Correlation

Feature correlation in this research examines the relationships between the independent variables (socioeconomic factors) and the target variable, Biogas_Availability_Impact, as well as among the independent variables themselves. High correlation values suggest a strong linear relationship, meaning that changes in one variable are closely linked to changes in another. For instance, a strong positive correlation between Subsidy Received and Biogas_Availability_Impact would indicate that financial support significantly influences the adoption of bio-digester septic tanks and enhances biogas availability in communities. Similarly, other correlations, such as those between Employment Rate, Economic Condition, and Adoption Status, highlight the interconnectedness of socioeconomic factors in driving technological adoption and its outcomes. Understanding these correlations provides insights into which variables have the most substantial impact on biogas availability, see fig.2.

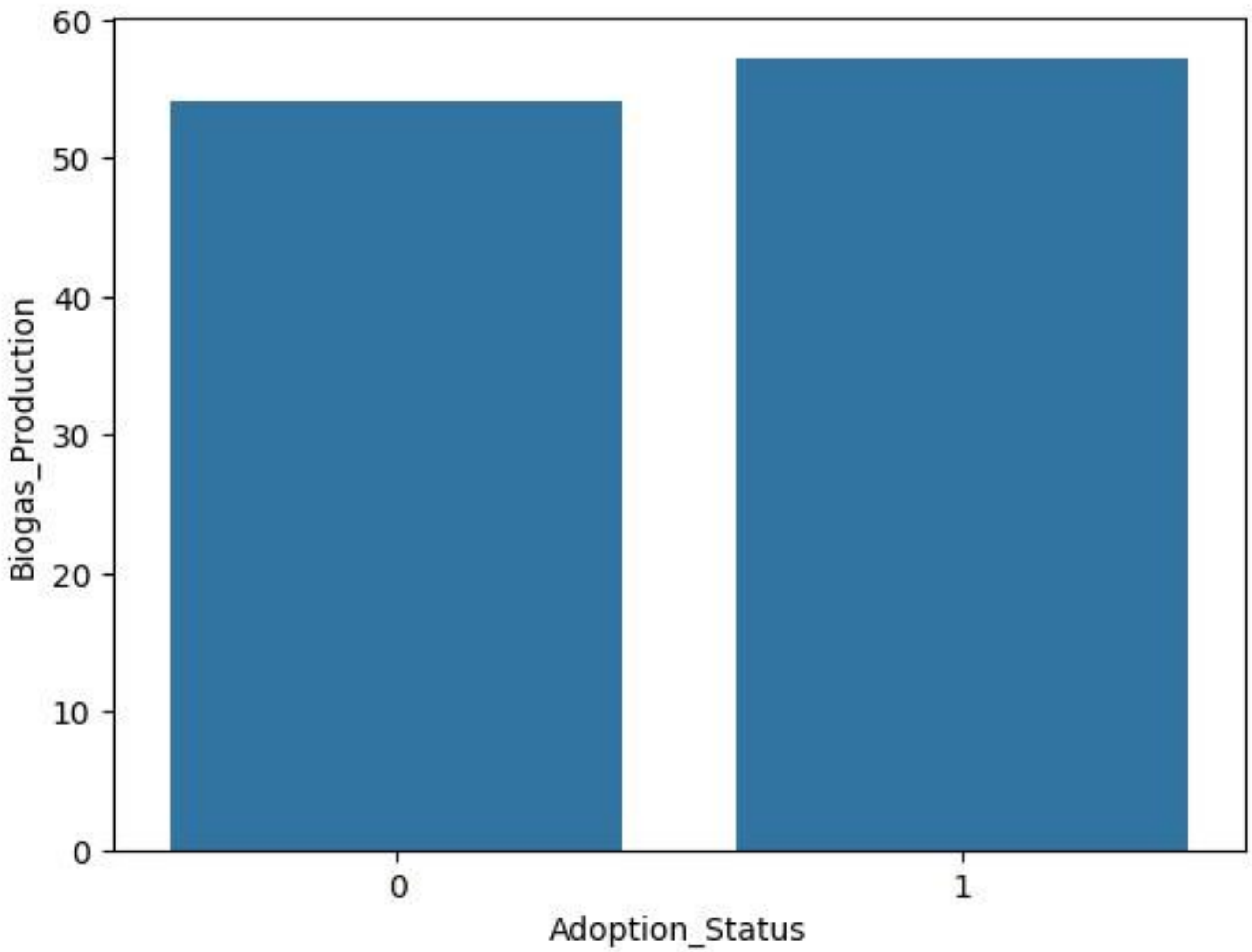

Fig. 2: Bio Septic Tank Adoption and Biogas Production Rate

The relationship between Bio Septic Tank Adoption Status and Biogas Production Rate provides valuable insights into the impact of adopting bio-digester septic tank technologies on communities' biogas availability. A higher adoption rate of bio-digester septic tanks typically leads to increased biogas production because these systems effectively capture organic waste and convert it into biogas through anaerobic digestion. This implies that communities with a higher percentage of adoption are likely to experience better biogas production rates, improving their access to renewable energy sources. Conversely, low adoption status can limit the production of biogas, highlighting the importance of understanding barriers to adoption such as financial constraints, lack of awareness, or insufficient waste management resources. Fig.3 explains the regression plot of such other different features.

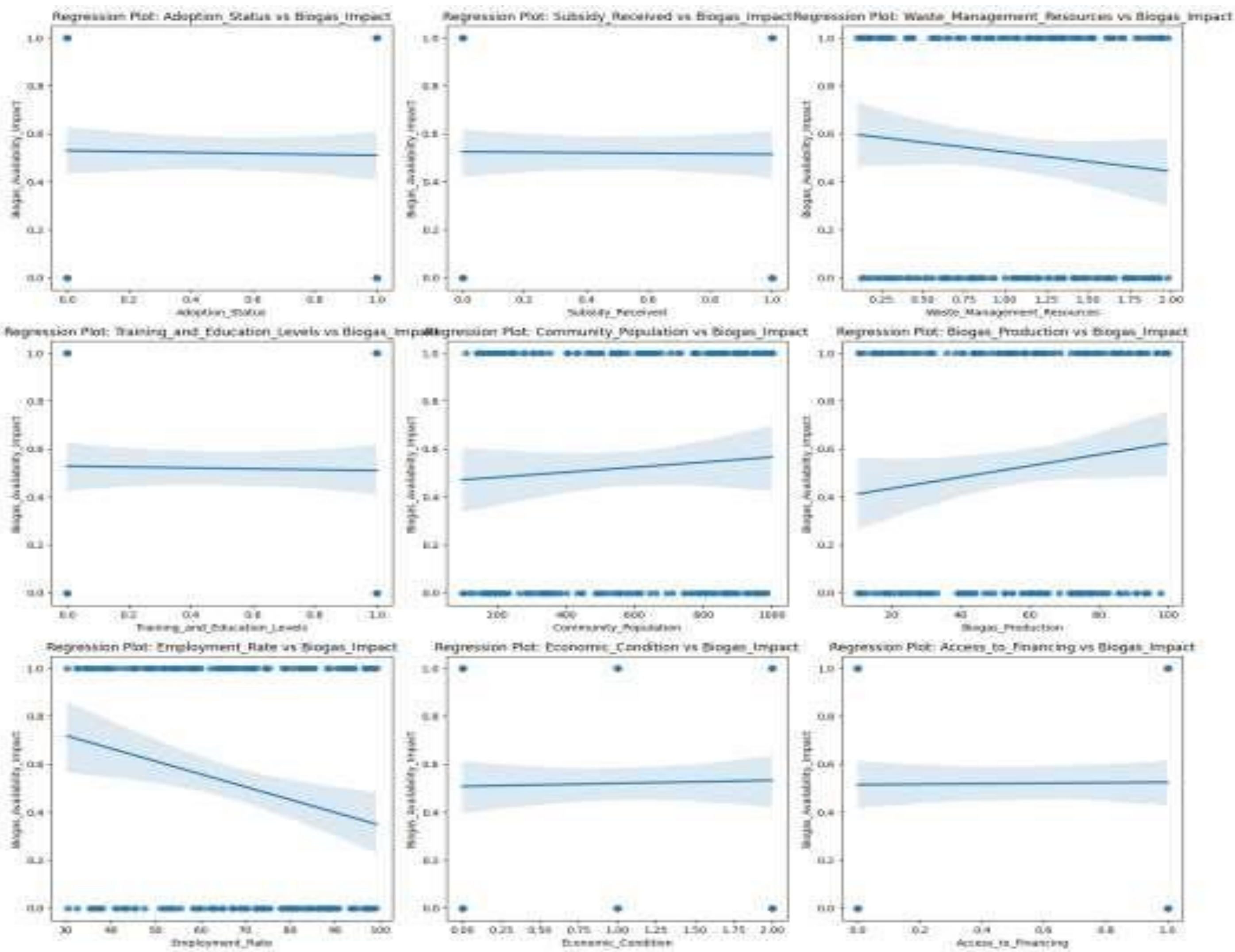

Fig.3: Regression plot of features

The regression plot of different features against the target variable Biogas_Availability_Impact visually illustrates the relationships between socioeconomic factors and the adoption of biodigester septic tanks. These plots help identify trends, patterns, and the strength of association between each feature and biogas availability. For instance, a positive trend between Subsidy Received and Biogas_Availability_Impact helps confirm that financial support positively influences biogas availability by encouraging adoption. Similarly, patterns observed with other features like Employment Rate or Waste_Management_Resources reveal their role in shaping biogas production and availability.

Fig. 4: Waste management and Resources and Benefit of Recycling

Figure 4 showed that Waste Management and Resources play a critical role in the successful adoption and efficiency of bio-digester septic tanks, as they rely on organic waste for biogas production. Proper waste management ensures a steady and consistent supply of organic material that can be processed in bio-digesters to generate biogas. Communities with effective waste management systems are better equipped to implement bio-digester technologies, as they can provide the necessary raw materials for biogas generation. Additionally, access to sufficient waste management resources, such as collection infrastructure and community education on waste segregation, enhances the sustainability and productivity of biogas systems. Without proper waste management, the availability of raw materials for biogas production is limited, reducing the effectiveness of bio-digester systems and their intended socioeconomic benefits. The Benefit of Recycling and Production of Biogas lies in its ability to transform waste into a renewable and sustainable energy source. Recycling organic waste through biodigesters minimizes waste in landfills, reduces pollution, and generates biogas that can be used for cooking, electricity, or heating purposes. This process not only provides communities with an affordable and clean energy source but also fosters environmental sustainability by reducing reliance on non-renewable fossil fuels. Moreover, the production of biogas through bio-digester technology contributes to local economies by creating employment opportunities, improving waste management practices, and enhancing community self-sufficiency. These benefits underscore the dual environmental and economic value of recycling waste and producing biogas, especially in resource-limited and rural settings.

4. CONCLUSION

This research highlights the significant socioeconomic impacts of bio-digester septic tank adoption on biogas availability within communities. The findings from the logistic regression analysis and feature correlation suggest that socioeconomic factors such as subsidy support, waste management resources, employment rate, and economic conditions strongly influence the adoption of bio-digester technologies and their subsequent impact on biogas production and availability. The statistical analysis indicates that financial incentives, effective waste management systems, and community access to resources are key drivers promoting the successful integration of bio-digester septic tanks. Furthermore, the regression plots and 3D scatter plots have provided visual evidence to support these relationships, demonstrating the role of these factors in improving renewable energy access and supporting environmental sustainability. The study also emphasizes the importance of strategic policy implementation to address barriers to bio-digester adoption, such as financial constraints and resource limitations. Findings from the logistic regression model have provided actionable insights, showing that increased subsidy programs and improved waste management infrastructure can foster higher adoption rates and boost biogas production. Additionally, the benefits of recycling waste into biogas underscore its potential as a low-cost, sustainable, and renewable energy solution for rural and low-resource communities. These insights not only advance the understanding of the socioeconomic impacts of adopting bio-digester septic tank technology but also provide a foundation for targeted interventions aimed at promoting sustainable waste management and biogas production.

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