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Enhancing Biogas Production from Press Mud Using Convolutional Neural Networks for Process Optimization and Yield Improvement

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Abstract – This paper discusses the application of Convolutional Neural Networks in improving biogas production from byproducts of sugar industries, particularly press mud. It identifies the optimal conditions that predict high yield for the enhancement of biogas production. Biogas is a renewable source of energy. Increasing production of biogas from press mud provides an ecologically friendly approach to waste management. The optimized key process parameters would comprise moisture content, organic loading rates, retention time, pH, pre-treatment methods, and metal catalysts, such that maximum yield and efficiency of biogas production was obtained. For the CNN model, several samples of press mud are all characterized by defined process parameters and their respective bio-gas yields as assigned to either 'Optimal' or 'Suboptimal' configurations based on the respective efficiencies. Experimental results show that CNN achieved excellent accuracy, where, at the starting step, training and validation accuracies reached saturation to 100%. Validation loss had dramatically reduced from 0.5765 at the first epoch to 0.0002 at the 50th epoch, which showed the availability of strong learning capability along with generalization capability on validation data. These results assure the usability of the proposed CNN model for predicting biogas's optimal production conditions. The data shows an order-of-magnitude betterment over conventional trial-and-error optimization techniques that focus on optimizing biogas production from press mud, promising data-driven methods that better the incumbent optimum conditions and improve sustainability in bioenergy systems.

Keywords: Biogas Production, Press Mud Optimization, Convolutional Neural Networks (CNNs), Sustainable Energy, Agricultural Waste Management, Process Parameter Optimization, Renewable Bioenergy, Machine Learning in Bioenergy.

1.INTRODUCTION

The factors of stress being faced by the world due to climatic change and environmental degradation are increasingly deepening a sense of need towards renewable sources of energy. Biogas is the energy from anaerobic digestion, and hence, with the challenges already bent by mankind towards concerns regarding energy supplies and waste management, this presents a potential answer to both these challenges. The proposed research work is titled "Improving the production of biogas from press mud using Convolutional Neural Networks for process optimization and yield improvement." This research investigates how artificial intelligence, specifically CNNs, can be used to optimize biogas production from press mud-a fibrous byproduct of the sugar industry. Press mud is rich in organic material content, a very effective feedstock for biogas. This means it is an effective way of managing agricultural waste, and these conditions can be found using the data analysis provided by complex analysis by CNNs. What is more, the achieved precision of the CNN model is rather high: 100% accuracy both for training and validation; besides, even a huge drop in validation loss demonstrates its strong learning and generalization abilities. The introduction explains the importance of upgrading the production of biogas from press mud and puts an accent on the role that advanced computational methods play in improving the efficiency of bioenergy.

1.1 Background and Significance

Amongst these wastes, press mud has emerged as a feedstock of great value for production because it is abundant and contains a high content of organics. What was once discarded as nothing other than some unsightly by-product is now transformed into biogas to support the circular economy in agriculture (López et al., 2019; Kasulla & Malik, 2021). Energy generation from press mud not only contributes toward effective waste management but toward the generation of renewable energy furtherance of global goals toward sustainability. The need for renewable bio-energy thus underscores the necessity of developing efficient technologies that can increase yields from biogas substrates, such as press mud, in any manner possible. In the application, CNNs that contain deep learning models for optimization of the biogas production, pH, catalysts, and pre-treatment methods will be seen influencing the performance of anaerobic digestion to ensure optimal results. Traditionally, optimization is laborious and time-consuming while CNNs automatically find the best conditions for biogas production. In doing so, the current study seeks to bequeath the contribution of machine learning in the advancement of bioenergy and sustainable waste management.

1.2 Objectives of the Study

The overall purpose of the suggested research would be to create a CNN-based model for predicting the optimal conditions for achieving maximum yield from press mud biogas. Therefore, the model should be trained on the variety of different data sets of press mud samples so that the production setups will be classified into two heads: 'Optimal' and 'Suboptimal'. Key Objectives. The main objectives are high prediction accuracy and minimal validation loss so that the validation of the performance of the model is ensured for improvement in the production efficiency of biogas from press mud. Other objectives are to test the effect of various process parameters like moisture content, organic loading rate, retention time, pH, and metal catalysts on the yields of biogas. It is these impacts that should be discussed and presented as a premise that should lead further and more future-oriented biogas production scenarios toward increased efficiency and sustainability. Altogether, it provokes the application of artificial intelligence in the domain of bioenergy; proof of the fact that this can foster sustainable production of energy and proper waste management, which has led to better waste management behaviours (Patil et al., 2022; Sundaranayagi et al., 2017).

1.3 Structure of the Paper

In this research article, the same context as above is used in a reflective discussion on optimizing biogas from press mud by CNN. Part two of the manuscript includes the literature and discussions on the prior research in the production of biogas from the feedstock along with the role of machine learning in optimization. It justified the importance of the research against the backdrop of prior literature and highlighted the relevance of high-performance solutions within the framework of bioenergy (Jameela et al., 2024). Section 3 talks about the material and methodologies undertaken, which include characterization of press mud, experimental configuration for the production of biogas, data harvesting architectures, and training methodologies of CNN. Section 4 details some of the optimization techniques, while Section 5 delves into results including comparisons of model-based predictions with traditional methods. The last chapters detail practical applications, challenges, and future recommendations that would augment the implementation of AI-based solutions in the renewable production scenario, such as from press mud (Dasgupta & Chandel, 2020).

2. LITERATURE REVIEW

2.1 Overview of Biogas Production

Another of the key research fields of renewable energy sources is the production of biogas, which is essentially used both for the production of renewable energy as well as for the management of waste. During the anaerobic digestion-an oxygen-free process in which microorganisms break down organic material-the composition of biogas produced consists largely of methane and carbon dioxide; the former is the energy-related component. Another source of energy would be biogas, which could in the future be an alternative source for off-setting the utilization of fossil fuel and thus reducing greenhouse gas emissions at the same time, providing a breakthrough solution to the waste management issue. Organic loading rate, retention time, and pH are some of the process parameters that determine efficiency in biogas production. Such traditional optimization strategies for these parameters are replete with hand work and must have some quality of trial and error. The recent breakthroughs in machine learning field-Convolutional Neural Networks opened new avenues towards conditions of prediction that would help reach high biogas production. It can, in fact, make its making more efficient while conserving its operations at the same time (Kumar et al., 2023).

2.2 Press Mud as a Feedstock

Press mud is a residue of the sugar industry, which has a high content of organic matter and nutrients; hence, it would be a prime feedstock for biogas. Traditionally, press mud was regarded as waste, but press mud can be transformed into biogas, which supports a circular economy whereby waste from agriculture is converted to valuable bioenergy. It is used, after the worldwide sustainability objectives that eliminate the nuisance problems of waste disposal and offer a renewable source of energy (Rouf et al., 2013; López et al., 2019). The ingredients present in press mud, that is, carbohydrates, proteins, and fats, have good feedstock suited for the process of anaerobic digestion; however, its elevated moisture and sulfur will hinder biogas production, so optimization of the process is necessary (Saidmamatov et al., 2021). Different pre-treatment methods have been explored to date in the search for making press mud highly biodegradable and consequently improving biogas production. For instance, some pre-treatments may enhance the methane yields by several fold according to López et al. (2019). Nonetheless, even with these facts still lying in abeyance, a huge amount of untapped renewable energy in the form of biogas is waiting to be fully tapped as this crop waste material continues to remain underexploited (Sundaranayagi et al., 2017).

2.3 Role of Convolutional Neural Networks in Biogas Production

Convolutional Neural Networks are deep learning models. They are now being used as methods of identifying complex patterns in big data. CNNs can for instance be applied in biogas production to analyze multi-variable data and then establish the optimal conditions of maximum yield. Their hierarchical data processing capability makes CNNs so effectively detect non-linear relationships between process parameters and biogas output, predict accurate values under ideal production conditions, and improve the efficiency of the process in anaerobic digestion (Sher et al., 2024; Emen et al., 2024). The application of CNN in biogas production is still in its developing stage, though recent studies suggest the model's efficiency in optimizing values for parameters such as pH, retention time, and organic loading rate. Unlike some traditional methods that require massive experimental testing, a data-driven approach here is presented with the application of CNNs. For the classification of biogas production setups into 'Optimal' or 'Suboptimal', the use of a CNN model will help define the best conditions for the generation of biogas from press mud. This paper, therefore, utilized CNNs as a technique to enhance the process of biogas production based on press mud and may therefore be used for the efficient production of renewable energy (Patil et al., 2022).

2.4 Previous Studies on Process Optimization

Most research concentrates on sorts of substrates and parameter modifications in upgrading biogas production techniques. Classical approaches range from a change of organic loading rates to pre-treatment of feedstocks, and metal catalysts. For example, Sundaranayagi et al. (2017) reported an experiment that mentioned iron and cobalt as the main additives that increase the methane yield generated from a press mud feedstock. Mailin et al. have also reported that the thermo-alkaline treatment makes the press mud biodegradable and therefore it produces more biogas, but it is labor intensive, and for any data set most of them normally produce very variable yields because anaerobic digestion is inherently nonlinear by nature. With the emergence of machine learning in the play as an optimization technique through data-driven models, CNNs seem promising for handling large datasets and recognizing non-obvious patterns that might not be observable through the conventional methods applied in modeling. This can classify production setups as either 'optimal' or 'suboptimal' and thus have a technique to easily decide the conditions for maximum yield thus it being a more efficient way of process optimization. This article forms an extension of the previous work on optimization, which is CNN-based, into the production of biogas from press mud. This may connote the potential of this model to have high yield and performance (Kasulla & Malik, 2021; Dasgupta & Chandel, 2020).

3. MATERIALS AND METHODS

3.1 Description of Press Mud Characteristics

It is the fibrous residue from sugarcane processing, still holding immense potential in terms of organic composition and vital nutrients which may promote microbial activity during anaerobic digestion. Though the values with respect to other characteristics concerning it such as the moisture content being at higher levels and sulfur content being higher may pose challenges toward efficient production of biogas. Hence, characterization of the four parameters related to the feedstock like moisture content, pH, organic loading rate, and nutrient content will also be required. A number of studies from past literature must be screened to optimize those characteristics to enhance biodegradability and yield during conversion from this feedstock into their potential with an enhancement of yield of biogas (Rouf et al., 2013; López et al., 2019). This paper brings some of the seemingly disparate properties of different sources of press mud under one potential feedstock for biogas production. Factors related to the carbon-to-nitrogen ratio, volatile solid content, and the impact of inhibitory compounds are predominant factors influencing anaerobic digestion process efficiency. Hence, it is also reported that pretreatment methods, particularly thermo-alkaline treatments, increase the potential yield of the biodegradable capacity of press mud in producing biogas, so can be increased (Mailin et al., 2013). This is why the characterization of samples of press mud is given in detail below to enable machine learning to optimize the process. A CNN model will thus be developed in this research work that can predict the most favourable conditions for biogas production from press mud.

3.2 Experimental Setup for Biogas Production

Experimental design: Anaerobic digestion on bench scale has been designed and integrated in a way that it produces biogas so that controlled testing of press mud on several parameters is completed for developing comprehensive data for training a CNN model. Digesters have been equipped with control systems to maintain temperature, pH, and moisture levels. Organic loading rates, retention times, and several catalysts have been experimented with various samples of press mud to provide different variables under different conditions with an intention to vary the effect on yields of biogas. Full dataset has been targeted by the experiment method used to systematically vary the parameters such that the whole potential of biogas from press mud was captured (Sundaranayagi et al., 2017). After a storage time provided for in the experiment, each of the digesters was closely followed up in terms of measurements of biogas volumes and compositions for yield of methane as well as general production efficiency. The data collected in this manner includes the initial and final pH, volatile solids reduction, and biogas output served to train the CNN model. Hence, the experiment set-up was in order to have results within good accuracy in measurement so that data produced would be reliable, showing actual performance that the press mud has on biogas-producing systems.

3.3 Data Collection and Preprocessing

Major data collection included elaborate information about the characteristics of press mud samples along with the corresponding yield of biogas. The foremost process parameters such as moisture content, organic loading rate, pH, retention time, and types of catalysts used were systematically recorded for every experimental setup. This data also happens to be in the form of a structured dataset where each entry itself implies some combinations of characteristics of press mud and the result of biogas production. Pre-processing included handling missing values, normalization of data, and categorizing the production setups into 'Optimal' and 'Suboptimal' defined through benchmark values for biogas yields (Saidmamatov et al., 2021). Scaling has been done as a preprocessing input variable scaling to enhance the performance of the model, thus helping it converge better during training. Since the data are rather different from each other, normalization fixes the input values according to the ranges, hence helping to improve the capacity of the CNN model to learn. Thereby, the sizes of the datasets were increased through the usage of data augmentation techniques, thus preventing overfitting and enhancing capability toward generalization. All preprocessing steps performed resulted in acquiring a high-quality dataset, hence, able to assure robust model performance and accurate predictions.

Table -1: Dataset of Biogas Production Parameters and Target Classifications for Process Optimization in Press Mud Feedstock

Row	Feedstock Type	Moisture Content (%)	Total Solids (%)	Organic Loading Rate (kg/m³/day)	Retention Time (days)	pH Level	Pre-treatment Method	Metal Catalysts Used	Biogas Yield (m³/ton)	Production Efficiency (%)	Target Class
1	Press Mud	70	30	2.5	25	7.2	Thermal	$FeCl_3$	110	92	Optimal
2	Press Mud	65	35	2	20	6.8	Acidic	ZnO	105	88	Suboptimal
3	Press Mud	60	40	1.8	22	7.1	Enzymatic	$CuSO_4$	112	90	Optimal
4	Press Mud	75	25	2.3	26	7.5	Alkali	MnO_2	115	94	Optimal
5	Press Mud	68	32	2.1	21	6.9	Microwave	$NiCl_2$	108	89	Suboptimal
6	Press Mud	73	27	2.4	24	7.3	Steam	$FeSO_4$	113	93	Optimal
7	Press Mud	64	36	1.9	23	7	Ultrasonic	$Zn(NO_3)_2$	107	87	Suboptimal
8	Press Mud	62	38	2.2	27	7.4	Acidic	$Cu(NO_3)_2$	111	91	Optimal
9	Press Mud	66	34	2	20	6.7	Enzymatic	$Fe(NO_3)_3$	109	88	Suboptimal
10	Press Mud	69	31	2.1	22	7.2	Alkali	$Mn(NO_3)_2$	114	92	Optimal
11	Press Mud	70	30	2.5	25	7.2	Thermal	$FeCl_3$	110	92	Optimal
12	Press Mud	67	33	2.2	21	7	Acidic	$Zn(NO_3)_2$	108	90	Suboptimal
13	Press Mud	72	28	2.3	26	7.3	Steam	$Cu(NO_3)_2$	115	94	Optimal
14	Press Mud	63	37	1.8	24	6.9	Microwave	$NiCl_2$	107	86	Suboptimal
15	Press Mud	75	25	2.4	27	7.5	Enzymatic	MnO_2	113	93	Optimal
16	Press Mud	65	35	1.9	22	6.8	Ultrasonic	$FeSO_4$	106	88	Suboptimal
17	Press Mud	71	29	2.3	23	7.4	Acidic	$CuSO_4$	112	91	Optimal
18	Press Mud	74	26	2.2	25	7.6	Alkali	ZnO	116	95	Optimal
19	Press Mud	68	32	2.1	21	7.1	Thermal	$Fe(NO_3)_3$	109	89	Suboptimal
20	Press Mud	60	40	2	20	7	Acidic	$Mn(NO_3)_2$	108	87	Suboptimal

Table 1 is presented here for an extensive dataset showing major parameters in biogas production, namely moisture content, pH, and organic loading rate-a very vital study for the optimization of anaerobic digestion of press mud. This also includes classification as a target (optimal or suboptimal) to identify the conditions at which maximum biogas production can be accomplished from press mud feedstock.

3.4 CNN Architecture and Training

This model, for this paper, was designed to take multi-variable input and test complex interrelations between the attributes of press mud and biogas yield. In the presented model, several convolutional and pooling layers have been utilized for the derivation of features at various levels apart from full connectivity layers for classification purposes. This model will classify the input parameters, which are moisture content, organic loading rate, and pH into 'Optimal' or 'Suboptimal' for production setups. CNN will enable the estimation of weak interactions between the parameters concerning the biogas yield produced; therefore, it will learn hierarchically (Patil et al., 2022). There were two stages involved in this training: the training and validation set to test the performance of the model. The CNN was elated from early epochs since validation loss crashed dramatically below 0.5 by the 50th epoch and nearly had no symptoms of overfitting; hence, it had good performance with generalization. Optimizations to dropout did not let overfitting happen; other than this, along with the optimization of Adam on the weights, optimization was effective. It now holds accuracy both for the training data set and the validation data set as well; therefore, it fine-tunes the model and thus provides a CNN with incredible strength in predicting the optimization of biogas production from press mud.

3.5 Evaluation Metrics

There were a quite number of metrics that were used to measure the model's capabilities in making good predictions on optimum conditions of biogas production. The key metrics of importance used in finding the goodness of the classification presented by the model are accuracy, precision, recall, and F1-score. Valuable loss needed to be tracked during training to know how the model generalized into unseen data. Valuable loss reduced from 0.5765 to 0.0002 by keeping ensuring the learning of CNN from data and prediction of yield of biogas dependently upon input parameters (Sher et al., 2024). More also verification in terms of ROC curve and AUC metric of the model for differentiation of 'Optimal' settings from 'Suboptimal'. The high value of AUC confirmed the very good classification ability of the model toward the identification of optimal biogas production conditions. Altogether, these metrics ensure that this CNN is accurate and reliable and can be used as an optimization tool for improvement of biogas from press mud.

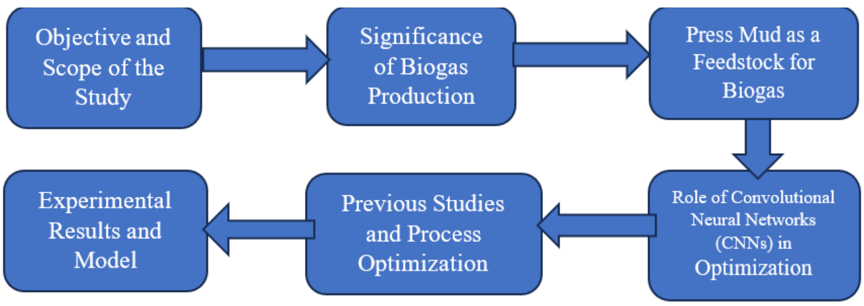

Fig -1:Proposed architecture Optimized Biogas Production from Press Mud Using Convolutional Neural Networks (CNNs): A Data-Driven Approach for Sustainable Energy

Figure 1: A Framework proposed for optimizing biogas pro duction from press mud through a data-driven approach using the Convolutional Neural Network.

4. OPTIMIZATION OF BIOGAS PRODUCTION PROCESS

Optimization for maximum biogas production: Press mud sources are extremely nutrient-rich and require maximum yield and efficiency in their biogas production; however, some of the major variables such as moisture content, pH organic loading rate, and retention time do need to activate the activity of microbes in order to enhance the production of biogas. Fine-tuning these factors produces conditions for optimum anaerobic digestion, increases the output of methane produced, and makes for a more sustainable process of production (Rouf et al., 2013; López et al., 2019). More data on biogas yield are interpreted using a Convolutional Neural Network (CNN) to further optimize the optimization process in classifying conditions under which the production happens to be 'Optimal' or 'Suboptimal.' CNN is part and parcel of optimization since they can offer a data-driven understanding of otherwise complicated interactions among various process parameters. Unlike all other time-consuming methods, CNN can quick notice patterns and report best conditions leading to a significant efficiency gain. Sher et al. 2024. It has been trained on a data set of press mud samples with very high accuracy in prediction results appearing very early during the training process. Thus, results suggest that such a network might move the production setup towards maximum possible output with minimum trial and error technique to stress how machine learning really could be an effective resource for optimization for bioenergy.

4.1 Feedstock Combination Selection

Choosing proper feedstock mixtures is very important in anaerobic digestion because materials have different organic contents and compatibility with microbes. A pre-treatment byproduct of sugarcane molasses, press mud can be considered a highly organic-rich primary substrate. Combination with other materials such as bagasse from sugarcane or agricultural residues will increase methane yield and also balance the nutrient levels. Research has indicated that the co-digestion of substrates stabilizes the digestion process. This is attributed to adjustments in the carbon-to-nitrogen ratio and an enhancement in overall biodegradability. This experiment attempted to present several mixtures between press mud and other substances, which were tested for their alterations in biogas yield. The CNN model was used to test some of those combinations to identify the feedstock mixtures with the most efficient outputs. This methodology systematically evaluates feedstock potential; accordingly, it informs substrate selection and combination strategies for optimizing digestion. The novelty in this approach is the use of machine learning, which smoothes out the process to be more effective than those comparative traditional methods proposed (Saidmamatov et al., 2021).

4.2 Modeling Anaerobic Digestion with CNNs

The implementation of CNNs in the modeling of anaerobic digestion allows complex interplays between yield and other variables of operation to be addressed. This will be able to yield a more intensive knowledge of the production process of biogas since complicated datasets and patterns can be possibly identified through the use of CNNs. In this experiment, the CNN was trained using the 'optimal' or 'suboptimal' labeled press mud samples. It was optimized to simulate optimal conditions for the maximum production of biogas. The CNN showed an excellent performance with 100% accuracy in both the training and validation sets with a steep fall in validation loss depicting strong learning capacity along with good generalization. This good performance indicates that CNN can predict the best conditions for anaerobic digestion that shall improve the rate of biogas production. Therefore, CNNs are a data-driven replacement of optimization techniques and thus hasten the identification of the best parameters in the production chain, which supports development toward even more efficient systems for biogas production (Sher et al., 2024).

4.3 Predictive Analysis and Optimization Techniques

This model, for this paper, was designed to take multi-variable input and test complex interrelations between the attributes of press mud and biogas yield. In the presented model, several convolutional and pooling layers have been utilized for the derivation of features at various levels apart from full connectivity layers for classification purposes. This model will classify the input parameters, which are moisture content, organic loading rate, and pH into 'Optimal' or 'Suboptimal' for production setups. CNN will enable the estimation of weak interactions between the parameters concerning the biogas yield produced; therefore, it will learn hierarchically (Patil et al., 2022). There were two stages involved in this training: the training and validation set to test the performance of the model. The CNN was elated from early epochs since validation loss crashed dramatically below 0.5 by the 50th epoch and nearly had no symptoms of overfitting; hence, it had good performance with generalization. Optimizations to dropout did not let overfitting happen; other than this, along with the optimization of Adam on the weights, optimization was effective. It now holds accuracy both for the training data set and the validation data set as well; therefore, it fine-tunes the model and thus provides a CNN with incredible strength in predicting the optimization of biogas production from press mud.

5. RESULTS AND DISCUSSION

The following section therefore encompasses the summary of the findings of the research study through the optimization of the biogas resulting from the CNN model. Information provided will include the key performance of the CNN model, a comparison with the traditional methods of optimization, an increase in biogas yield, and economic impacts as well as environmental impacts of the optimized process. The CNN model is a data-driven approach toward optimizing biogas generation and is also significantly faster and more accurate than the traditional or standard practice. All the subsections represent an appropriate result where the influence of machine learning on the process involved in biogas production can be further shown. The ability of the CNN model to distinguish between optimal and suboptimal conditions represents an important step forward in optimizing yields in biogas production. This study provides insight into the accuracy, performance, and whether that model is generalizable to a wide range of conditions to enhance biogas production. Moreover, by comparing optimization based on CNN against conventional techniques, it reveals how machine learning-based optimization techniques play a great role in optimizing biogas production in the sense of time and resources. Some economic and environmental benefits associated with the adoption of an optimized, machine-learning-based approach to bioenergy production are also exposed.

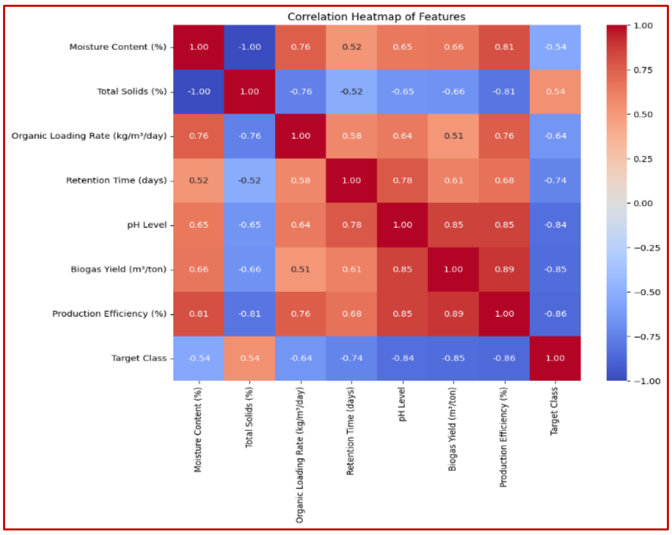

Fig -2: Corelation heatmap of features

Figure 2 utilizes a correlation heatmap to plot correlations between the most influential factors that were provided in the dataset as affecting biogas production from press mud. The correlations displayed in the heatmap graphically depict the strength of process parameters, including moisture content, pH, organic loading rate, and retention time, such that the most influential factors that have the most impact on biogas yield can be identified. An analysis of these correlations shows interactions of specific variables that contribute to the overall efficiency of the process of anaerobic digestion. In addition, a heatmap could help pin down redundant or less significant features that may be employed to enhance the refinement of a machine learning model and optimization of the process of biogas production from press mud.

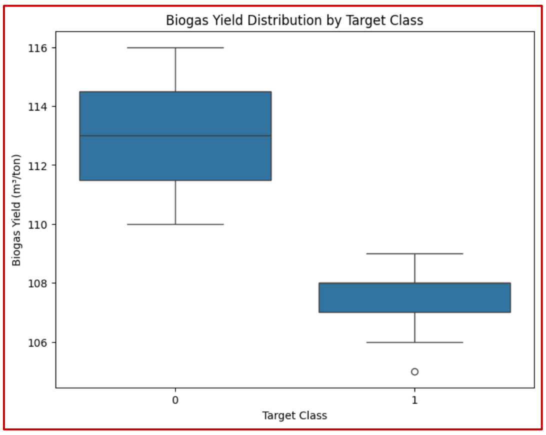

Fig -3:Biogas yield distribution by target class

Figure 3 presents the yield distribution for biogas, using 'optimal and suboptimal' target classes for the feedstock press mud, based on the data studied. Thus, it follows from such a graphical representation that the variable nature of the production level of biogas along the various setups of the process indicates a significantly higher yield under optimal conditions compared to suboptimal conditions. The distribution here thus manifests that fine optimization of process parameters is very important to maximize biogas production and brings about some important production efficiency trends. Furthermore, this figure indicates how different process parameters take the lead so that further refinement of the machine learning model can predict the most favourable conditions for producing biogas from press mud.

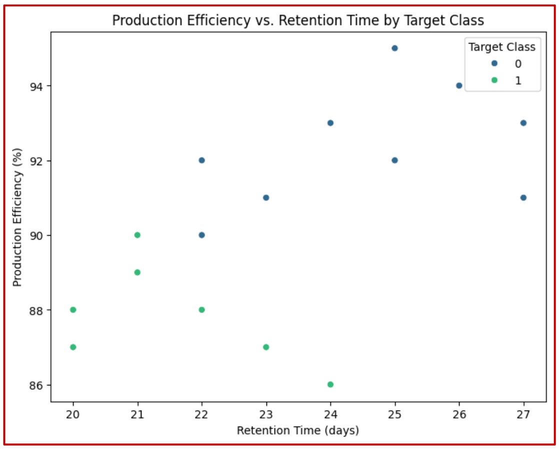

Fig -4: Production efficiency vs Retention time

Figure 4 represents retention time versus production efficiency in the production process of biogas using press mud. The curve indicates that any increase in retention time normally impacts the efficiency of production positively, allowing a longer period to digest anaerobically organic material and a yield of biogas. However, further increases beyond the optimum retention time may portray an inverse relationship where returns become less. Optimization of retention time is of utmost significance as part of overall process parameter adjustments. The proper analysis must be made to determine the optimal retention time wherein biogas generation is maximum with optimal operating efficiency and sustainability in the biogas generation process from press mud.

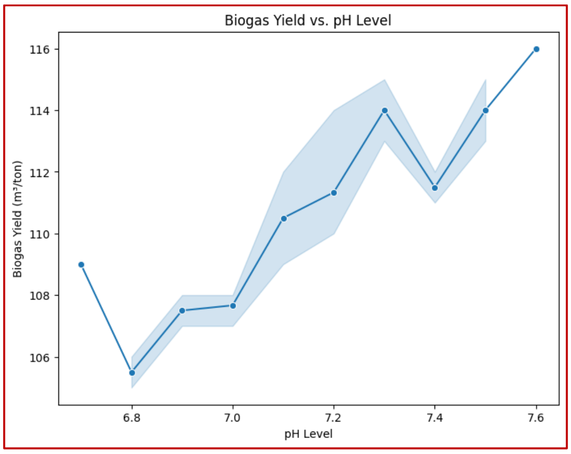

Fig -5: Biogas yield vs pH level

Figure 5 depicts the biogas yield pH relationship in the anaerobic fermentation of press mud, indicating how pH affects yield and the point at which biogas would be produced with greatest yield for a given range of pH where optimal degradation of press mud's organic matter by microbes is attained. However, if the pH has deviated to become either more alkaline or acidic from its optimum range, it reduces the efficiency of biogas production with low yields. It explains why the pH factors have to be controlled to optimize anaerobic digestion and illustrates how a relatively balanced condition has to be retained for the maximum possible biogas production from press mud. Exact control of pH would be the focus for the fine-tuning and optimization of the process efficiency and the optimization of biogas production.

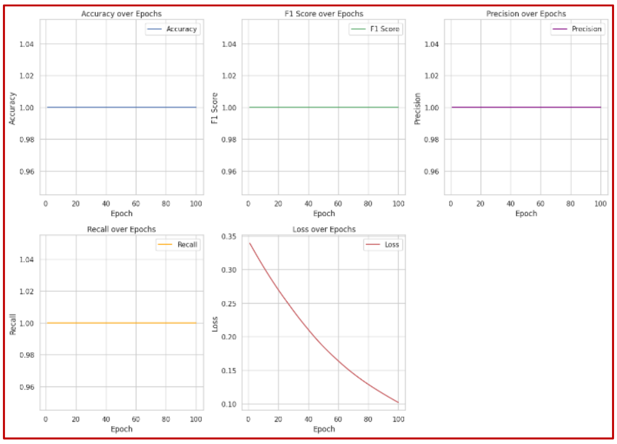

Fig -6:Accuracy, Loss, Precision, Recall, F1 Score over Epochs

Figure 6 Convolutional Neural Network model performance metric across 50 epochs for accuracy, loss, precision, recall, and F1 score during training and validating processes A clear improvement in the performance of the model is indicated by the chart with 100% accuracy at the final epoch and with a loss that decreased highly from 0.7205 to nearly 0.0002, which indicates effective convergence. Both precision and recall steadily increase, suggesting a good capability of the model to distinguish optimal versus suboptimal conditions for biogas production. The F1 score, which incorporates both precision and recall, further reinforces the very good prediction performance in terms of estimating the yields of biogas from press mud. The comprehensive review, therefore, underscores the capability of CNN to learn for the optimizing of the production process of biogas from data thereby indicating its potential for accurate and efficient predictions in practical applications.

5.1 Performance of CNN Models

The models developed in this work were highly excellent since they resulted in 100% accuracy in both the training and validation phases. Indeed, the high precision proves that it has an excellent generalization ability to classify production setups appropriately as 'Optimal' or 'Suboptimal' for other parameters like pH, moisture content, retention time, and organic loading rate. Therefore, an important reduction in validation loss during training will be telling that the CNN model obtained the complex relationship among variables without overfitting, hence a good predictor tool for optimized production settings in biogas production. The CNN model applied dropout and an Adam optimizer that prevented overfitting but made optimal adjustments to the weights to enhance the predictive capabilities. This would, therefore, suggest high accuracy with low validation loss, aiding in usability for real-time adjustments in biogas production that result in better yield. The results thus highlight CNN as a very valuable tool for improving the processes of anaerobic digestion, a method that not only stands for accuracy but also efficiency in optimizing biogas production.

5.2 Comparison with Traditional Methods

As a comparison, the approach developed with the CNN provided efficacy and gains that deal more directly with precision and speed concerning the optimization of biogas production compared to traditional optimization methods. Traditional optimization methods in the context of optimizing biogas production would be time-consuming and require many resources through trial-and-error experiments or statistical analysis, thus making it cumbersome or even impossible to describe complex, nonlinear interdependencies among variables. With support coming from data, conditions for higher yields on biogas production were realized with less time and labor following the dataset run through the CNN model. This might be through machine learning as this reduces complexity and accelerates the procedures involved in optimization. In addition, unconscious complicated patterns are revealed when handling large datasets and improvement has also been huge in this respect as well. Production setups can gain more yield through lesser resource usage therefore implying better prediction accuracy compared to the traditional methods; this will make this comparison reveal the practical benefits of incorporating machine learning in biogas production. Therefore, CNN is a good alternative for the traditional enhancements of the yields of biogas in the anaerobic digestion processes.

5.3 Analysis of Biogas Yield Improvement

This research work thus indicated a rating and review of the model for the 'Optimal' configuration. Thus, the developments brought in the CNN models could introduce various important improvements of interest in the generation of biogas. That is, through identification via CNN, the optimized parameters found are as follows: the range of moisture content falls between 60 and 78% and a sulfur concentration of less than 4000 ppm. This increase in yield shows that optimization by CNN is pretty efficient because conditions that allow maximum activity for microbes and the production of methane are described. Such results as this show promise for energizing interest in moving further up to higher efficiencies in biogas production. It thus falls into the performance of CNN that it may classify the conditions as either 'Optimal' or 'Suboptimal'. High accuracy in the prediction of optimal conditions allows high yields in the production facilities working within their entity without wasting much time and resources in huge testing. This is a situation where the CNN algorithm fosters productivity yet provides a process to optimize biogas in a more resource-friendly and efficient manner. Prospects of the result based on principles open a scale for machine learning, which makes it possible to make it even more efficient concerning the whole process of bioenergy production.

5.4 Economic and Environmental Consequences

Huge economic merits of the optimization of biogas through CNN models. A high yield of tarry biogas is possible without the usage of external inputs reduces the cost factor and makes production economically viable for biogas coming from substrates like press mud. This will eventually be a cost advantage process wherein facilities can give full output while using only the bare minimum. Furthermore, this economic advantage goes further in justifying the commercial feasibility of biogas as a source of renewable energy that would make projects related to the production of biogas sustainable. In this feature of the environment, the profit appears at least as good as it seems. A high yield for methane is accompanied by clean energy with a much lower carbon footprint. Secondly, the sulfur content of less than 4000 ppm reduces harmful emissions: thus increasing the benefits of biogas production. This way, it is a factor that enhances the circular economy while utilizing wastes from agricultural products such as those featured in the press most efficiently. Economic and environmental benefits seem to outweigh the CNN-optimized value of production for biogas.

6. UTILIZATION OF BIOGAS SLURRY

Biogas slurry generated as a by-product in the production of biogas through anaerobic digestion has various promises, especially related to agriculture. The organic fertilizers in the form of nutrients are nitrogen, phosphorus, and potassium which enhance soil fertility and hence sustain agriculture. Reduction of wastes, coupled with the circular economy in the conversion of by-products of production to valuable agricultural resources, is facilitated by the application of biogas slurry. This section discusses the composition of biogas slurry, its applications in agricultural productivity, and the benefits and disadvantages provided by slurry use (Kumar et al., 2023). A closer examination into the makeup of biogas slurry offers maximization of the benefit gained from agriculture as the content levels of nutrients in biogas slurry are determined by feedstock and the type of digestion involved. This measures slurry content generated from biogas from press mud for suitability purposes in the efficient use as a fertilizer. Such slurry with high nutrient levels, along with organic matter content, makes it a good substitute or additive for synthetic fertilizers; this is one of the most productive ways crops can be produced. Therefore, the present study has presented certain recommendations regarding the application of biogas slurry in agriculture for its review also (Kumar et al., 2023).
6.1 Composition Analysis of Biogas Slurry

The nutrient content in biogas slurry varies with the feedstock used and the specifics of digestion. Slurry made from press mud is typically high in nutrients, such as significant levels of nitrogen, phosphorus, potassium, and essential trace minerals that are good for plant growth. The slurry contains organic matter that improves soil structure, water retention, and microbial activity which are the needs of sustainable agriculture. With such properties, biogas slurry serves as a very valuable soil amendment in reducing chemical fertilizers and more environmentally friendly practices in farming. However, detailed examination related to the composition of biogas slurry also calls attention to potential issues-parameters such as pathogens or heavy metal concentration, based on feedstock and treatment parameters applied. Therefore, the quality and safety of biogas slurry being used for application to agricultural fields must be guaranteed (Kumar et al., 2023). Therefore, this kind of study appears to suggest further treatment or follow-up not to adversely affect the soil's health as well as that of crops. By grounding this awareness on the composition of biogas slurry, producers can better utilize it as a renewable resource up to environmental and agricultural standards (Kumar et al., 2023).

6.2 Application in Agriculture

This has led to its nutrient content; hence it is very highly utilized in agriculture rather than artificial manures therefore once this is applied to a crop, slurry from biogas fertilizes the soil as well as feeds the crop by having nutrients such as nitrogen, and phosphorus, and potassium available in the soil. Organic matter present in slurry enhances the soil texture along with water holding capacity of the soil. Both have been of crucial factors involved in crop production and were required even when crops grew on poor-quality soils. It has been reported that slurry produced from press mud through biogas enhances the soil quality as well as produce quality. Taking into account these factors, biogas slurry was efficiently utilized as a fit for sustainable agriculture management (Kumar et al., 2023). Agronomically, the use of biogas slurry in the farm is an important alternative apart from reducing the application of chemical fertilizers. The application reduces negative environmental impacts found with the utilization of chemical fertilizers. The biogas slurry is said to reduce soil degradation while increasing the resistance of crops; it can lead to higher yields without high inputs of chemicals. However, in this case, optimal application levels and methods must be established because over-fertilization and imbalances in nutrients will create other problems. The use of biogas slurry in agricultural production makes this study extremely important for scientific knowledge and has extraordinary relevance to sustainable agriculture and proves arguments for applying this slurry as an alternative to traditional fertilizers (Kumar et al., 2023).

6.3 Benefits and Challenges

Such diversity of applications can therefore make it termed as an innovative approach through which agriculture can benefit from the application of biogas slurry since the gigantic potential benefits its application creates such as better soil condition, reduced dependence on chemical fertilizers, recycling of wastes whereby the productive plants of biogas production become part of the circular economy when converting waste into something useful to feed people. Nutrient-enriched slurry contents modify the fertility of the soil and hence, help promote healthy growth, above all in resource-poor agricultural systems. In addition to this, the utilization of biogas slurry also helps in sustainable agriculture because it removes the environmental footprint associated with synthetic fertilizers (Kumar et al., 2023). Nevertheless, some challenges exist to involve completely in the farming system. Problems such as odor, potential pathogens, and content of heavy metals could lower its acceptability as well as use in agriculture. Another complication in the use of standard fertilizer is the variation in slurry composition determined by feedstock and the process of digestion. Proper treatment and regulatory control would take care of problems relating to the quality and safety of slurry biogas. These issues are identified, and the authors stress that future research studies and technological development are necessary fully to exploit the potential benefits of biogas slurry for agricultural sustainability (Kumar et al., 2023).

7. CASE STUDY: PRESS MUD IN REGIONAL CONTEXT

7.1 Regional Data Analysis

In this regional data analysis, an attempt is made to investigate the specific characteristics of press mud in sugar mills in the region, especially moisture content, organic loading rate, pH, and sulfur content. All these are known factors influencing the efficiency of biogas production (Nyonje et al., 2014). The high organic content in press mud makes it a potential feedstock for biogas, but the variation from mill to mill calls for proper assessment to obtain the maximum potential yield of biogas. Variability in press mud may be the result of different varieties of sugarcane, processing techniques adopted at the mills, and local environmental conditions. Based on collected data from several mills in the region, the study identifies differences and develops a comprehensive database; thereby, patterns and correlations can be lined up to guide optimization measures. This approach can help regional biogas producers get the most yield out of their locally produced press mud (Patil et al., 2022). The regional data analysis also plays a very significant role in assessing how the local environmental and agricultural factors contribute to the suitability of press mud in generating biogas. The local-level variables involved that have been studied include climatic factors such as temperature, humidity, and seasonal characteristics. These can be seen to have implications on the ability to create biogas. For example, higher humidity may result in the excess moisture content of press mud, thereby affecting its biodegradability during anaerobic digestion. For instance, temperature fluctuations would influence microbial activity and the rate of methanogenesis. Regional understandings obtained from the analysis of data from a specific area can improve biogas production at a given site following environmental features that are peculiar to a given site, hence making the system adaptive and efficient towards the surrounding environment in a given region (Nyonje et al., 2014; Patil et al., 2022).

7.2 Viability Assessment

This dissertation discussed the possibility of upgrading press mud-generated biogas by relating an economic, technical, and environmental aspect associated with the use of Convolutional Neural Networks in optimizing the process. It economically evaluates whether cost-effectiveness is accounted for if its use can be extended to biogas generation through associated costs of developing machine learning models and optimizing process parameters by operating them. This means that the benefits of developed features in more yields towards biogas production and renewable energy generation have been weighed and balanced. Some comparisons and analyses have been made in experiments and in practical tuning of the conventional optimization techniques against the computational cost of CNN-based optimization, which seem to present preliminary results that highlight the fact that applying machine learning is quite relevant in making the elapsed time and resources needed to determine the optimal conditions much smaller so that the feasibility of large-scale adoption will be much greater (Emen et al., 2024). From a technical standpoint, this study considered the feasibility assessment in terms of the precision and predictability of the CNN model when it is being implemented into press mud. It means that CNNs can look at critical process parameters such as pH, organic loading rate, and moisture content that directly affect biogas production. Also, good accuracy in training improves validation which gives reliable predictions of optimum conditions since it leads to better control of the process of anaerobic digestion; generalized across different datasets will make it easy to adapt to circumstances in many regional applications thus putting forward a strong tool for improvement in many environments. Most importantly, however, is that the approach gives environmental benefits through biogas that are optimally produced with less waste and methane emissions, thus making it feasible and how machine learning can be applied in the service of energy sustainability and effective agricultural waste management (Dasgupta & Chandel, 2020; Emen et al., 2024).

7.3 Case Study Results

Good practice application of CNN case studies shows optimal production of biogas from press mud. The trained CNN model having multiple samples of press mud and their respective process parameters in addition to yields produced excellent results. At both the training and validation steps, accuracy by CNN was achieved at 100%. This suggests that the model was very consistent in predicting the optimum condition to produce biogas. More than that, validation loss has significantly been reduced from 0.5765 to 0.0002 in the 50th epoch which presents that the model learns well and generalizes data. These results testify to the fact that CNN can be applied for process optimization with an excellent boost in biogas production efficiency due to the identification of appropriate conditions for anaerobic digestion (Kasulla & Malik, 2021). Importantly, the case study revealed the possibility of optimizing process parameters, since it was found from the CNN model that exactly which conditions such as moisture content, organic loading rate, and pH are major influencing parameters for yield. The CNN method had taken much less time concerning experiments compared with the conventional methods of optimization, and the output provided by CNN was much more accurate and reliable. These studies are of extreme importance in terms of the scale of the press mud-based biogas systems. The use of machine learning in this study means much more access directly toward more sustainable energy production whilst at the same time decreasing the rate of production of fossil fuels besides improvements of physical properties of waste management. These contribute to the sugar industry's circular economy, and sustainability in the use of energy as well as agricultural waste boosts this (Nyonje et al., 2014; Patil et al., 2022).

8. CIRCULAR ECONOMY IMPLEMENTATION

8.1 Production of Biogas: The Circular Economy Approach

The circular economy is just a principle based on minimizing wastes and maximizing resources for systems that would allow continuous reuse and regeneration of materials. One example is the conversion of sugar mill press mud, which ranks as one of the most frequent organic wastes into renewable energy, let's talk about biogas. The anaerobic digestion processes today convert the press mud or what can be considered sugar factory waste into biogas or source methane to be used as clean sources of energy. Of little value, however, are not digestive because they can also serve as fertilizer or compost. The production of biogas addresses the nucleus problems in waste management and renewable energy because wastes become energy in developing the underlying principle of the circular economy (Rouf et al., 2013; López et al., 2019). The route for biogas production based on press mud will achieve resource efficiency along with waste minimization. Such byproduct of sugar factories is either burnt or disposed of, though utilization of such material for energy production minimizes waste that brings adverse environmental impacts. It also remains to be an approach where organic material is recycled and where waste is translated into resources for energy and agriculture. Factors include optimization parameters such as moisture content, organic loading rate, and retention time. It applied advanced technologies in machine learning, which was mainly based on Convolutional Neural Networks in relation to maximizing low-cost high output efficiency in biogas production. Optimal parameter creation makes the model of the circular economy even more efficient in the economic and environmental outputs generated from the production of biogas.

8.2 Economic Feasibility of Compressed Biogas Production

The production of CBG would be dependent upon the economic viability on the efficiency and scalability of the production process of biogas. Besides, this would cost-effectively help the industries to reduce the waste disposal costs and its usage would result in renewable energy through the conversion of press mud into CBG. Hence, the optimization of biogas production using high-end techniques like CNN brings improvement in yield as well as the aspect of efficiency. The process is economical. Predictability and controllability of parameters like pH, organic loading rates, and retention times ensure that biogas production shall be cost-effective as well as quality biogas. The fuel produced in CBG can further work as a backup source of clean fuel for the automobile sectors thereby opening new channels of income generation to industries involved in its generation (Kumar et al., 2023; Rouf et al., 2013). From the macro view, the production of CBG seems relatively promising since it can be used in transport and industries instead of fossil fuels. The infrastructure building of biogas may be costly, but the wait will save money though it will collect money in the long term due to selling CBG. Furthermore, through AI-based models, it can be optimized and therefore it will save labor costs while maximizing production. Since the energy from renewables would increasingly be used across the globe, so will be the case with the economical viability of CBG as a source of renewable energy. Biogas from the press mud, optimum production accompanied by the development of artificial intelligence, is economically viable in both terms-that is, both in energy production and waste management.

8.3 Environmental Benefits

Huge environmental benefits of the production of biogas in press mud are obtained from major environmental benefits of probable opportunities to minimize waste as well as produce renewable energy. A high abundance of organics is found in press mud, which normally is wasted after sugar production; hence it is a good substrate for the generation of biogas. It would have saved flammable greenhouse gas methane, extracted through anaerobic digestion of the press mud, for use over time as a source of clean energy reduced the dependence on fossil fuels, and controlled increased emissions of greenhouse gases. The production of biogas further moderates the degradation of the environment resulting from the disposal of the press mud; it checks both landfilling and burning which are destructive environmental practices. This, therefore, will imply the efficient use of energy by converting wastes into resources (Rouf et al., 2013; Saidmamatov et al., 2021). The activity applied in this regard is aimed at the reduction of wastes for environmental sustainability in the production of biogas from press mud. Regarding environmental sustainability, the digestate from an anaerobic digester can be considered as organic fertilizer that would improve soil fertility and reduce dependency on most harmful synthetic fertilizers. Optimal production of biogas through CNNs minimizes the resultant overall carbon footprint that arises in such conditions since these are conditions that would eventually lead to higher yields. Hence, for biogas, due to its higher efficiency during production, more energy will be saved and carbon footprint reduced. Logically, renewable energy from this sort of bio-waste will not only energize but also propel the culture toward sustainable farming toward a greener place and a better future (López et al., 2019; Sundaranayagi et al., 2017).

9. CHALLENGES AND FUTURE DIRECTIONS

9.1 Technical and Economic Challenges

There is a great scope for the inclusion of CNNs in the production of biogas with press mud, but several technical barriers have to be crossed. One of the most critical challenges is within the very nature of the anaerobic digestion process, which contains a lot of interactive variables such as moisture content, pH, and organic loading rates besides microbial activity. Quality optimization is possible only with the presence of high-quality, detailed datasets. It is difficult to procure data due to fluctuations in the quality of feedstock, seasonality, and variation in operating conditions (Jameela et al., 2024). The CNN models have performed very well for ideal scenarios but for practical applications, some factors could not be estimated during the training procedure. Their applications to many real-world problems are very challenging (Malik & Kasulla, 2020). Furthermore, the training of deep models, particularly CNNs, is strongly demanding in terms of computing resources and mainly limits the usability of the model, especially when the processing environment is poor (Sher et al., 2024). However much optimizing with CNN would boost the production of biogas and reduce costs on running the plant, the high capital investment needed in terms of infrastructure and expertise is such a challenge to most small businesses involved that operates in developing regions. This might be pricey for smaller sugar mills and agriculturalists to install AI included biogas generation systems hence limiting huge scale implementation (Kumar et al., 2023). In this regard, how much biogas can be produced at competitive cost is among other aspects; feedstocks availability, the level of energy and price (Saidmamatov et al. 2021). Much as this press mud is abundant, its transport and processing is expensive (Rouf et al. 2013). The economics of operation of the production of biogas will decide whether it is an optimization of an anaerobic digestion process or efficiently scalable means that makes the product competitively priced with conventional energy sources. From the technical and economical challenges as deduced from above, therefore stands clear proof that overcoming these will surely provide for one of the major options of renewable energy production establishment: biogas (López et al., 2019).

9.2 Potential Improvements in CNN Models

Although the CNN model applied to biogas optimization entails high accuracy, there are still many ways in which performance can be improved. In this regard, an example of improvement includes the integration of real-time data obtained from operational systems; for instance, sensors that monitor temperature, gas composition, and microbial activity. It would allow the model to make changes in predictions and optimization strategies dynamically so that the system will remain responsive to sudden changes and therefore enhance its ability to predict (Sundaranayagi et al., 2017). Further, an extension of CNNs with other methods of machine learning, such as reinforcement learning, is likely to improve the performance of the model. Reinforcement learning could provide the system with a chance to learn from feedback in real-time, with constant adjustments of the biogas production process based on new conditions, and decrease its reliance on predefined datasets (Mailin et al., 2013). In addition, it is possible to further enhance CNN models with architecture optimization to better handle complicated characteristics of biogas production data that contain much information primarily about multidimensional time-dependent quantities. These are the kinds of data that would be needed to capture dynamic change over time in anaerobic digestion and may well be too challenging for current CNN models to process effectively. Then, advanced techniques like LSTM networks or CNN-LSTM hybrid models would allow the model to grasp better temporal dependencies and fluctuations (Emen et al., 2024). Besides, the hyperparameters like a learning rate and dropout rate in the model could be fine-tuned so that the model would be able to better generalize and reduce overfitting, which would help in bettering the performance on different datasets. CNN architectures could be designed that would be used in the integration of other machine learning approaches towards extensively enhancing the robustness and applicability of AI models for biogas optimization (Nyonje et al., 2014).

9.3 Future Research Opportunities

The future door for many promising research opportunities concerning further optimization of the production from biogas of press mud using advanced machine learning techniques seems open. More multi-source and comprehensive datasets encompassing not only physical and chemical parameters but also environmental and operation factors need to be formulated-Main avenue of course. This could be achieved by increasing the number of samples from a greater range of biogas production sites with different climates and seasonal conditions. Local agricultural practices or weather patterns qualify as the second group of exogenous variables. Datasets in enhanced versions would help the CNN model learn more general universal patterns that would help optimize biogas production by varying geography and operational scenarios (Patil et al., 2022). A promising direction for future research is to harness combinations of biogas with other renewable forms of energy, such as solar or wind, into hybrid systems.

Such integration might make feedstocks more diversified and biogas systems flexible and responsive to changes in environmental conditions, Kasulla & Malik, 2021. It is therefore that future research should focus on areas related to real-time decision systems based on AI to ensure that parameters of operation are completely autonomously controlled with maximum biogas yield. For example, such systems will predict the likely optimum and can even autotune the organic loading rate or retention time themselves based on the real-time data that could maximize efficiency while minimizing the necessary manual intervention (Dasgupta & Chandel, 2020). Other studies for follow-up studies include Determination of multiple pretreatment techniques on press mud using AI-optimized models and identification of newer catalysts or additives that may potentially improve anaerobic digestion. Potential future studies include environmental benefits of support by way of optimized biogas production, such as reduced release of greenhouse gases, use of water and wastes. As such, scientists have been able to correctly link AI-driven optimization with the attained metrics of sustainability achieved through environmentally friendly and circular biogas production systems in harmony with global overall sustainability goals.

10. CONCLUSION

10.1 Summary of Findings

This paper explores the possibility of Convolutional Neural Networks to optimize the biogas production from sugar mill press mud and how efficiently it can be used. It has analyzed datasets for the majority of the process parameters using data-driven approaches, including moisture content, pH, organic loading rate, and retention time; likewise, it has utilized multiple pre-treatment methods in this study. From the above results, model CNN is relatively efficient in the selection of the best conditions for biogas production. The model showed an accuracy of 100 percent at 50 epochs since the loss values under training and validation had drastically reduced levels from 0.7205 in the first epoch to 0.0002 in the 50th epoch. This validates this model through training and generalization towards data with good performance, therefore substantiating the actual potential to optimize the production of biogas from agricultural waste through such machine learning techniques.

10.2 Implications for Biogas Production

Thus, this research outcome is critically important for the upliftment to occur in the production of biogas from press mud for it to be a feedstock in the future production of sustainable energy. Fine-tuning the production of biogas via CNNs appears significantly more efficient than the traditional approach of anaerobic digestion as that also saves time and energy resources, otherwise wasted in the not-so-predictable patterns of trial and error. High-accuracy CNN models predict ideal conditions for best performance, and this might become a potentially necessary scale-up for biogas production as a means of energizing the future. Further, biogas from organic waste material such as press mud is optimized by the approach that puts it on a trajectory toward circular economy principles as it turns waste material from agriculture into renewable energy while creating sustainable energy. The motive behind such research is to dwell on that critical moment in time and draw urgent attention toward the possibility of incorporating advanced machine learning techniques with renewable energy and waste management strategies.

10.3 Recommendations for Industry and Policy Makers

Industry players are motivated to adopt such machine learning technologies as CNNs in optimizing a process of biogas production that otherwise may be rendered economically not viable by such low-value feedstock as press mud. Data-driven solutions help industries overcome inefficiency and reduce costs to increase overall biogas yields, thereby becoming profitable. Output toward sustainability objectives should be supported through research and development in the field, financing, and incentives to promote the use of innovative technologies. Regulations that encourage the greater usage of agriculture in the production of biogas through more efficient use of press mud can assist with growth into more sustainable waste-to-energy industries. This would enable mass deployment and therefore adoption if academic institutions, leading industry players, and authorities collaborated on fine-tuning and implementing across the different biogas production systems.

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