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RESEARCH ARTICLE

RECENT TRENDS IN CONVERSION OF AGRICULTURAL WASTE INTO BIOENERGY USING ANAEROBIC DIGESTION WITH PERFORMANCE OPTIMIZATION

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Abstract

The present study investigated the conversion of agricultural waste into renewable bioenergy through anaerobic digestion with performance optimization. The study addressed the environmental problems associated with improper disposal of agricultural residues and examined their potential as substrates for biogas production. Agricultural residues including rice husk, sugarcane bagasse, corn stalks, vegetable waste, and cattle manure were considered for physicochemical characterization and anaerobic digestion. Feedstock characteristics including carbon-to-nitrogen ratio, volatile solids, pH, moisture content, total solids, and chemical oxygen demand were considered in evaluating digestion suitability. Pretreatment was applied to improve the accessibility of lignocellulosic biomass, including mechanical size reduction and alkaline treatment using sodium hydroxide. Anaerobic digestion was evaluated under mesophilic conditions, and process optimization was performed using Response Surface Methodology with Central Composite Design. The reported results showed that pretreatment reduced lignin content by 24.5%, increased biogas yield by 42%, and reduced digestion time by 15 days. Methane purity increased from 58% before optimization to 72% after optimization. The optimized operating conditions reported in the study were a temperature of 37°C, retention time of 25 days, and organic loading rate of 2.5 kg VS/m³/day. The calorific value of purified biogas was approximately 22.4 MJ/m³, with an estimated electricity generation potential of 1.85 kWh/m³. The study therefore demonstrates the technical potential of agricultural waste conversion into bioenergy through anaerobic digestion and process optimization.

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Introduction:-

The twenty-first century is witnessing increasing environmental, social, and economic challenges associated with energy demand and dependence on fossil fuels. The thesis identifies renewable energy as an important pathway toward reducing dependence on conventional energy resources. Bioenergy occupies a distinctive position among renewable energy technologies because organic materials can be converted into usable energy while waste streams can simultaneously be valorized. Agricultural production generates large quantities of organic residues and by-products, including crop straws and stalks, husks and shells, bagasse, animal manures, and processing effluents. India generates substantial quantities of agricultural residues, creating both an environmental management challenge and an opportunity for bioenergy production. Improper disposal through open burning, landfilling, and uncontrolled decomposition can contribute to air pollution, greenhouse gas emissions, nutrient losses, and other environmental impacts.

Anaerobic digestion is described in the thesis as a biological process in which complex organic matter is decomposed by microorganisms in the absence of molecular oxygen. The process produces biogas, consisting primarily of methane and carbon dioxide, together with a nutrient-rich digestate. The technology can accommodate diverse feedstocks and combinations of agricultural, municipal, and industrial organic waste streams. The anaerobic digestion process proceeds through hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolysis converts complex polymers into simpler compounds and is frequently a rate-limiting step for lignocellulosic materials. Acidogenesis converts hydrolysis products into volatile fatty acids and other intermediates. Acetogenesis produces acetate, carbon dioxide, and hydrogen, while methanogenesis converts these substrates into methane. The thesis identifies the recalcitrance of lignocellulosic agricultural residues as an important technical limitation. Pretreatment can improve accessibility of cellulose and hemicellulose to microbial degradation. Co-digestion can also improve nutrient balance and process stability by combining substrates with complementary characteristics. In addition, optimization approaches such as Response Surface Methodology, Artificial Neural Networks, and Genetic Algorithms provide approaches for evaluating interactions among process variables.

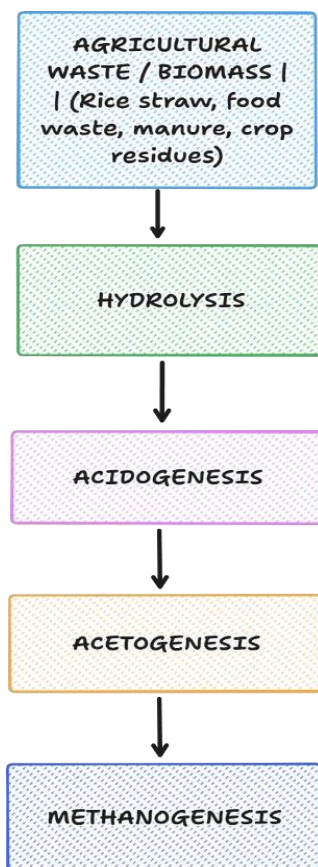


Figure 1. Anaerobic digestion process: hydrolysis, acidogenesis, acetogenesis and methanogenesis.

Research Gap and Objective:-

The literature review identifies several research gaps. Integrated optimization frameworks that simultaneously consider feedstock pretreatment, co-digestion ratios, and operating parameters remain limited. The applicability of optimization models under tropical and subtropical conditions also requires further validation. In addition, economic evaluation of optimized anaerobic digestion systems has been insufficiently addressed. The study therefore develops an integrated framework progressing from feedstock characterization through pretreatment optimization, co-digestion studies, process parameter optimization, and techno-economic evaluation. The intended framework combines experimental design, statistical analysis, and computational modelling to evaluate agricultural waste conversion into bioenergy.



Figure 2. Integrated research methodology framework described in the thesis.

Materials and Methods:-**Feedstock Collection and Characterization:-**

The methodology describes rice straw from the Cauvery delta region of Tamil Nadu, sugarcane press mud from a sugar processing mill in Vellore or Salem district, banana pseudo-stem from plantations in Trichy or Thanjavur districts, fresh cattle dung from an organized dairy farm, and dairy effluent from the wastewater treatment inlet of the same facility. Samples were described as being collected in triplicate from multiple sampling points, homogenized, and preserved for analysis. The characterization program included total solids, volatile solids, moisture, ash, carbon, hydrogen, nitrogen, sulfur and oxygen, chemical oxygen demand, total Kjeldahl nitrogen, total phosphorus, cellulose, hemicellulose, lignin, and carbon-to-nitrogen ratio.

Pretreatment:-

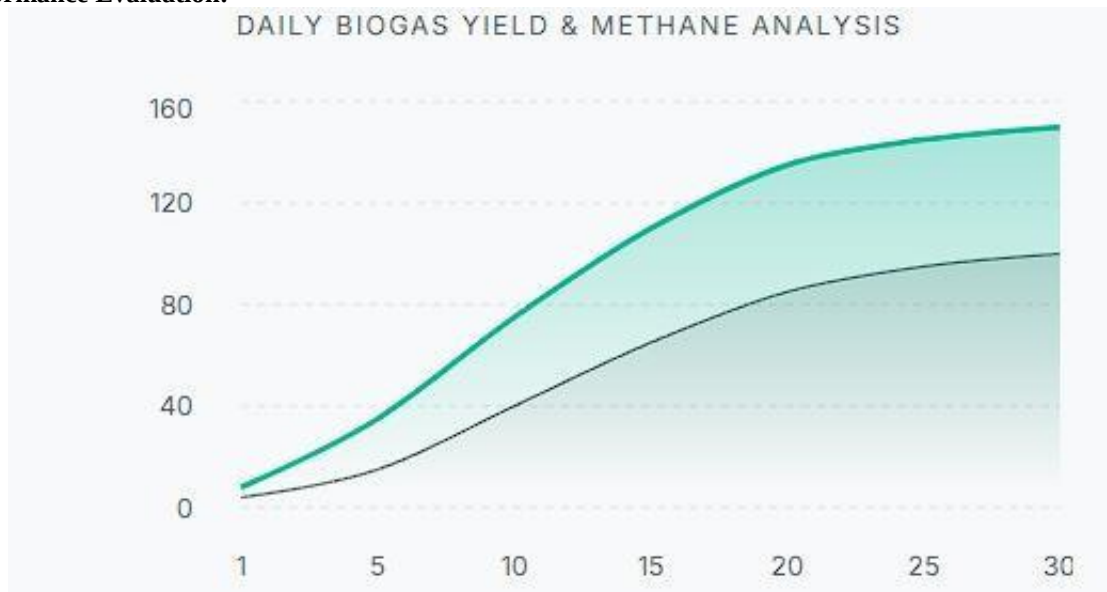
Physical pretreatment was described using a laboratory hammer mill for lignocellulosic feedstocks, with target particle size ranges of 1–2 mm and 2–5 mm. Mechanical grinding using a laboratory blender was described for softer substrates including banana pseudo-stem and press mud. Energy consumption was to be measured using a calibrated power meter and particle size distribution characterized by sieve analysis. Alkaline pretreatment was described using sodium hydroxide concentrations of 1%, 2%, 4%, and 6% at temperatures of 50°C, 70°C, and 90°C for contact durations of 30, 60, and 90 minutes. Pretreated biomass was to be neutralized to pH 7.0 ± 0.2 before digestion. Changes in cellulose, hemicellulose, lignin, and cellulose crystallinity were identified as evaluation parameters, with furfural and hydroxymethylfurfural measured to assess fermentation inhibitors. Biological pretreatment was described using *Pleurotus ostreatus* and *Trametes versicolor* cultures. Rice straw and wheat straw were to be inoculated at an inoculum-to-substrate ratio of 10% and incubated for 7, 14, 21, and 30 days under controlled conditions.

Experimental Setup:-

The thesis describes laboratory-scale batch and semi-continuous anaerobic digestion using 1 L batch digesters and 5 L semi-continuous reactors. Temperature control was specified at $35 \pm 0.5^\circ\text{C}$ for mesophilic operation and $55 \pm 0.5^\circ\text{C}$ for thermophilic operation. The experimental program comprised BMP assays, batch digestion experiments evaluating pretreatment and co-digestion effects, and semi-continuous experiments evaluating organic loading rate and hydraulic retention time.

Optimization:-

Response Surface Methodology with Central Composite Design was described for simultaneous evaluation of temperature, pH, organic loading rate, and co-digestion ratio on biogas yield and methane content. The design comprised 30 experimental runs, including factorial, axial, and center points. A second-order polynomial model was to be evaluated using analysis of variance, lack-of-fit testing, and the coefficient of determination. Numerical optimization was described using a desirability function. The thesis also describes Artificial Neural Network modelling using a Multi-Layer Perceptron architecture and subsequent Genetic Algorithm optimization. The ANN was intended to predict biogas yield and methane content, while the Genetic Algorithm was intended to identify process conditions maximizing predicted biogas yield.

Performance Evaluation:-**Figure 3. Daily biogas yield and methane analysis under the digestion process.**

Biogas volume was described as being measured daily in batch experiments and using calibrated gas flow meters in semi-continuous experiments. Biogas composition was to be evaluated for methane, carbon dioxide, hydrogen sulfide, and hydrogen. Performance indicators included specific biogas yield, specific methane yield, methane content, COD removal efficiency, volatile solids reduction, and overall energy efficiency.

Table 1. Results of Pretreatment, Biogas Production, Optimization, and Energy Potential

Parameter	Result
Lignin reduction	24.5%
Increase in biogas yield	42%
Reduction in digestion time	15 days
Days 1–5	Low gas production
Days 5–20	Rapid biogas generation
Peak biogas production	Day 20
Cumulative biogas yield	140–150 m ³
Methane concentration before optimization	58%
Methane concentration after optimization	72%
Temperature	37°C
Retention time	25 days
Organic loading rate	2.5 kg VS/m ³ /day
Calorific value of purified biogas	22.4 MJ/m ³
Electricity generation potential	1.85 kWh/m ³
Annual large-scale implementation potential	145,000 kWh/year
Capital investment	\$45,000
Annual operational cost	\$2,200/year
Return on investment (ROI)	31.5%

Parameter	Result
Payback period	3.2 years
Annual carbon reduction	125 tons/year
Digestate utilization	Organic fertilizer

Conclusion:-

The study demonstrates the technical feasibility of converting agricultural waste into renewable bioenergy through anaerobic digestion with performance optimization. The reported feedstock characterization results indicate that agricultural residues differ substantially in C/N ratio, volatile solids, moisture, pH, and biodegradability, and that combining feedstocks can improve nutrient balance and digestion performance. Pretreatment was reported to improve conversion efficiency, with mechanical shredding and alkaline treatment contributing to reduced lignin content, increased biogas yield, and shorter digestion time. Mesophilic anaerobic digestion produced substantial biogas, with peak production reported around Day 20. Optimization using RSM and CCD increased methane purity from 58% to 72% under the reported optimized conditions of 37°C, 25 days retention time, and 2.5 kg VS/m³/day organic loading rate. The reported energy, economic, and environmental assessments indicate potential for agricultural-waste-based anaerobic digestion to provide renewable energy while reducing waste-management impacts. The thesis therefore presents anaerobic digestion, combined with pretreatment and process optimization, as an integrated approach for agricultural waste valorization.

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