HYDROTHERMAL PRETREATMENT OF SUGARCANE BAGASSE PITH FOR BIOGAS PRODUCTION AND DIGESTATE VALORIZATION

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by

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submitted

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DEDICATED TO MY LOVING PAPA

DECLARATION

I hereby declare that:

1. The work presented in this thesis is original and has been carried out by me as a student of IIT Delhi.
2. To the best of my knowledge, the work presented in this thesis has not been submitted, either in whole or in part, to any other institution for the award of any degree or diploma.
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5. I take full responsibility for all data presented in this thesis and confirm that no data has been collected without appropriate permission. Where required, ethical approval has been obtained for the research, and all relevant approvals and documentation have been included as part of the thesis submission.
6. All sources of information, including data, ideas, and text, have been duly acknowledged and appropriately cited in the thesis.
7. The use of artificial intelligence (AI) tools (if any), including large language models, has been appropriately disclosed. All analysis interpretations, and conclusions presented in this thesis are my own. Alternatively, I declare that no AI tools, including large language models, have been used in the preparation of this thesis.
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CERTIFICATE

This is to certify that the thesis entitled "**Hydrothermal Pretreatment of Sugarcane Bagasse Pith for biogas production and digestate Valorization**", being submitted by Mr. Nitin Kumar Agarwal to the Indian Institute of Technology Delhi for the award of "Doctor of Philosophy" is a record of bonafide research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis. To the best of our knowledge, the results contained in this thesis have not been submitted in part or full to any other university or institute for the award of any degree or diploma.

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ABSTRACT

The study explores the hydrothermal pretreatment of sugarcane bagasse pith for biogas production and digestate valorization, addressing key concerns associated with the underutilization of bagasse pith and its potential for bioenergy applications. The research is framed within the broader context of the Indian government's initiatives to reduce fossil fuel dependency by leveraging renewable energy sources such as agricultural residues. The study is particularly relevant given India's significant agricultural output and the resulting substantial generation of lignocellulosic biomass waste, estimated at approximately 620 Megatonne (Mt) annually, of which around 50% remains underutilized.

Bagasse pith, a byproduct of the sugar industry, constitutes approximately 30-38% of the total bagasse. During the paper production from the sugarcane bagasse, a short-fiber substance called pith is separated from the sugarcane bagasse. Despite its similar chemical composition to bagasse, it has historically been used as a low-value fuel in boilers, contributing to approximately 95% of greenhouse gas emissions from the sugar industry. This study proposes an alternative pathway that converts bagasse pith into biogas via anaerobic digestion (AD) following hydrothermal pretreatment, thereby enhancing its biodegradability. The study further explores the valorization of the anaerobic digestate to maximize resource utilization and promote a circular bioeconomy.

To achieve the first objective, anaerobic digestion of sugarcane bagasse pith was attempted, and the pretreatment process was optimized. The study employed Response Surface Methodology (RSM) using a Box-Behnken design to optimize the pretreatment conditions for maximizing biogas yield. For pith pretreatment, hydrothermal pretreatment was considered, as it is environmentally friendly and produces fewer inhibitors. Hydrothermal pretreatment was conducted under various conditions of solid loading (5-15 wt.%), temperature (160-220 °C), and time (10-30 min). The pretreatment aimed to break down the lignocellulosic structure and enhance the accessibility of the biomass for microbial digestion. The pretreated solid fractions were characterized for compositional changes, including cellulose (46.4-59.5%), hemicellulose (10.8-22.6%), lignin (12.3-29.9%), and severity index (2.77-5.01). The pretreated liquid fractions were analyzed for reducing sugars (1.07-3.32 g/L), soluble lignin (1.7-5.3%), and COD (3250-35600 mg/L). Fourier Transform Infrared Spectroscopy (FTIR), X-Ray Diffraction (XRD), and Scanning

Electron Microscopy (SEM) analyses were employed to assess structural modifications post-pretreatment.

Subsequent anaerobic digestion experiments were conducted on both the solid and liquid fractions obtained after hydrothermal pretreatment. Biogas production and its composition were monitored over 30 days. Hydrothermal pretreatment of pith at a biomass loading of 10 wt.%, a temperature of 190 °C, and a duration of 20 min yielded the highest biogas production, 368 mL/gVS. The solid fraction at the above-mentioned condition was characterized for cellulose (58.4%), hemicellulose (14.9%), lignin (15.0%), and severity index (3.95). The resulting liquid fractions were analyzed for reducing sugars (3.14 g/L), soluble lignin (3.5%), and COD (17160 mg/L). The experimental data were statistically analysed to determine the adequacy of the regression model. The statistical analysis, including Analysis of Variance (ANOVA), confirmed the adequacy of the quadratic regression model in predicting biogas yield with an R^2 value of 0.9988. The theoretically optimized pretreatment conditions predicted by the model were found to be biomass loading: 8.5 wt%, temperature: 187.4 ℃ and time: 17.4 min with a theoretical biogas yield of 371.6 mL/gVS. The predicted optimization conditions were experimentally validated with a biogas yield of 411 mL/gVS (methane 54%). The biogas production from the unseparated pretreated pith and raw pith was found to be 313 mL/gVS (methane 49.4%) and 132 mL/gVS (methane 36.7%), respectively. Under optimized conditions, the cellulose content and severity index of the pretreated solid fraction was 59.2% and 3.8, whereas the reducing sugar, and COD of the pretreated liquid fraction were found to be, 3.68 g/L, and 15,700 mg/L, respectively. To further improve biogas yield, the study optimized the C/N ratio of the pretreated bagasse pith. The C/N ratios varied from 5 to 45, and their impact on biogas production was evaluated. The optimal C/N ratio was 25, yielding a biogas yield of 474.3 mL/gVS and a methane content of approximately 55%. Beyond this ratio, biogas yield plateaued, indicating that excess nitrogen did not contribute to further improvements. The study also scaled up the biogas production process to a pilot-scale level, utilizing a 300-liter reactor for solid fraction digestion and a 20-liter reactor for liquid fraction digestion. The cumulative biogas yield from the solid fraction reached 4567 L over 98 days, while the liquid fraction produced 219.8 L of biogas over 92 days.

The third objective focused on the valorization of digestate through pyrolysis to generate biochar, bio-oil, and syngas. The digestate obtained after anaerobic digestion was subjected to

pyrolysis at different temperatures (400 °C and 800 °C) with varying moisture contents (10%, 40%, and 80%). The resulting biochar was analyzed for physicochemical properties, including surface area (2.32-254.47 m^2/g), pore volume (0.003-0.14 cm^3/g), elemental composition (C: 34.77-52.16%, H: 0.89-3.46%, N: 0.49-2.11%), and calorific value (19.05-23.31 MJ/kg). The highest biochar yield (75.8%) was obtained at 400 °C with 10% moisture content, while the lowest yield (23.1%) was recorded at 800 °C with 80% moisture content. Scanning Electron Microscopy (SEM) images revealed that biochar produced at higher temperatures exhibited a well-developed porous structure, making it suitable for potential applications such as adsorbents, soil amendments, and energy storage materials.

The final objective was to conduct a techno-economic assessment of the integrated biogas and biochar production processes. The study estimated the energy potential of bagasse pith-based biogas production and assessed the economic viability of integrating anaerobic digestion with pyrolysis for digestate valorization. Factors such as operational costs, energy recovery efficiency, and potential revenue from biochar were considered. The evaluation of scenarios indicated that the two-step process viz., anaerobic digestion followed by pyrolysis at 400 °C without hydrothermal pretreatment, is the most energy-efficient, economically viable, and operationally scalable option. This configuration, validated at laboratory and mill scales, showed consistent biogas yields, effective energy recovery via biochar, and a net financial benefit, establishing it as the optimal method for industrial application.

In conclusion, this research provides a novel approach for the sustainable management of sugarcane bagasse pith through hydrothermal pretreatment-assisted biogas production and digestate valorization. The findings underscore the efficacy of hydrothermal pretreatment in improving biogas yields, and the potential of pyrolysis in converting digestate into valuable biochar. The techno-economic analysis further validates the feasibility of adopting an integrated biorefinery approach for bagasse pith utilization. This study not only contributes to the advancement of waste-to-energy technologies but also supports the broader goal of reducing environmental pollution and enhancing the sustainability of biofuel production in India.

सारांश

यह अध्ययन बायोगैस उत्पादन और डायजेस्टेट का मूल्यवर्धन करने के उद्देश्य से गन्ना बगास पिथ के हाइड्रोथर्मल प्रीट्रीटमेंट का अन्वेषण करता है, और बगास पिथ के कम उपयोग तथा इसके बायोएनर्जी अनुप्रयोगों की संभावनाओं से जुड़े प्रमुख मुद्दों को संबोधित करता है। यह शोध भारतीय सरकार की नीतियों के व्यापक संदर्भ के बारे में है, जिनका लक्ष्य कृषि अवशेषों जैसे नवीकरणीय ऊर्जा स्रोतों का उपयोग कर जीवाश्म ईंधन पर निर्भरता कम करना है। भारत की महत्वपूर्ण कृषि उत्पादन क्षमता के परिणामस्वरूप प्रति वर्ष अनुमानित रूप से लगभग **620** मिलियन मीट्रिक टन लिग्नोसेलुलोज़िक बायोमास के उत्पादन को देखते हुए यह अध्ययन विशेष रूप से प्रासंगिक है, जिनमें से लगभग **50%** का उपयोग नहीं हो पाता है।

बगास पिथ, जो चीनी उद्योग का एक उपउत्पाद है, कुल खोई का लगभग **30–38%** हिस्सा बनता है। पिथ, जो एक अल्प-फाइबर सामग्री है, बगास को कागज़ बनाने के दौरान निकाल दी जाती है। रासायनिक संरचना में बगास के समान होने के बावजूद, ऐतिहासिक रूप से इसे बॉयलरों में निम्न-मूल्य ईंधन के रूप में उपयोग किया गया है, जिससे चीनी उद्योग से होने वाले लगभग **95%** ग्रीनहाउस गैस उत्सर्जन में योगदान होता है। यह अध्ययन एक वैकल्पिक मार्ग प्रस्तावित करता है जिसमें हाइड्रोथर्मल प्रीट्रीटमेंट के बाद एनेरोबिक डाइजेशन (एडी) के द्वारा बगास पिथ को बायोगैस में परिवर्तित किया जाता है, जो इसकी जैव-विघटनशीलता को बढ़ाता है। अध्ययन, आगे संसाधन उपयोग को अधिकतम करने और परिपत्र जैवअर्थव्यवस्था को बढ़ावा देने के लिए एनेरोबिक डाइजेस्टेट के मूल्यवर्धन (वैलोरेटाइज़ेशन) का अन्वेषण भी करता है।

पहले उद्देश्य की प्राप्ति करने के लिए, चीनी के बगास पिथ का एनेरोबिक पाचन किया गया और प्री-ट्रीटमेंट प्रक्रिया का अनुकूलन किया गया। अध्ययन में बायोगैस उपज को बढ़ाने के लिए प्री-ट्रीटमेंट परिस्थितियों के अनुकूलन हेतु बॉक्स- बेह्नकेन डिज़ाइन का उपयोग कर रिस्पांस सरफेस मेथोडोलॉजी (आरएसएम) लागू की गई। पिथ के प्री-ट्रीटमेंट के लिए हाइड्रोथर्मल प्री-ट्रीटमेंट पर विचार किया गया क्योंकि यह प्रक्रिया पर्यावरण-अनुकूल है और कम इनहिबिटर उत्पन्न करती है। हाइड्रोथर्मल प्री-ट्रीटमेंट निम्नलिखित परिस्थितियों में किया गया: ठोस भार **5–15** वेट**%,** तापमान **160–220** डिग्री सेल्सियस, और समय **10–30** मिनट। प्री-ट्रीटमेंट का उद्देश्य लिग्नोसेल्यूलोज़िक संरचना को तोड़कर जैवद्रव्यों के सूक्ष्मजीवीय पाचन के लिए उनकी पहुँच बढ़ाना था। पूर्व-उपचारित ठोस अंशों की रासायनिक संरचना में बदलाव का विश्लेषण किया गया, जिसमें सेल्यूलोज़ (**46.4–59.5%),** हेमिसेल्यूलोज़ (**10.8–22.6%),** लिग्निन (**12.3–29.9%)** और तीव्रता सूचकांक **(2.77–5.01)** शामिल थे। पूर्व-उपचारित द्रव अंशों में घटक-विश्लेषण किया गया— अपचायक

शर्करा **1.07–3.32** ग्राम/लीटर, घुलनशील लिग्निन **1.7–5.3%,** तथा रासायनिक ऑक्सीजन मांग (सीओडी**) 3250–35600** मिलीग्राम प्रति लीटर निर्धारित की गई। संरचनात्मक परिवर्तनों का आकलन करने के लिए फूरियर ट्रांसफॉर्म इन्फ्रारेड स्पेक्ट्रोस्कोपी (एफटीआईआर **),** एक्स-रे विवर्तन (एक्सआरडी**)** और स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी (एसईएम **)** के विश्लेषण किए गए।

हाइड्रोथर्मल प्रीट्रीटमेंट के बाद प्राप्त ठोस और तरल दोनों अंशों पर बाद के अवायवीय पाचन प्रयोग किए गए। **30** दिनों की अवधि में बायोगैस उत्पादन और इसकी संरचना की निगरानी की गई। **10** वेट% बायोमास लोडिंग**, 190** डिग्री सेल्सियस का तापमान**,** और **20** मिनट की प्रीट्रीटमेंट के साथ पिथ ने **368** एमएल/जीवीएस की सर्वश्रेष्ठ बायोगैस उत्सर्जन दी। उपर्युक्त स्थिति में ठोस अंश सेलूलोज़ (**58.4%)** हेमिसेलुलोज़ (**14.9%)** लिग्निन (**15.0%)** और गंभीरता सूचकांक (**3.95)** के लिए विशेषता थी। परिणामस्वरूप तरल अंशों का विश्लेषण शर्करा (**3.14** ग्राम/लीटर) घुलनशील लिग्निन (**3.5%)** और सीओडी (**17160** मिलीग्राम/ लीटर) को कम करने के लिए किया गया था। प्रतिगमन मॉडल की पर्याप्तता निर्धारित करने के लिए प्रयोगात्मक डेटा का सांख्यिकीय रूप से विश्लेषण किया गया था। वैरियेंस के विश्लेषण (एनोवा**)** सहित सांख्यिकीय विश्लेषण ने **0.9988** के आर^2 मान के साथ बायोगैस उपज का अनुमान लगाने में द्विघात प्रतिगमन मॉडल की पर्याप्तता की पुष्टि की। मॉडल द्वारा अनुमान लगाया गया की**,** सैद्धांतिक रूप से अनुकूलित पूर्व-उपचार की स्थिति बायोमास लोडिंग पाई गई**,** जो निम्नलिखित हैं**: 8.5** वेट**%,** तापमानः **187.4** डिग्री सेल्सियस और समय **17.4** मिनट की सैद्धांतिक बायोगैस उपज **171.6** एमएल/जीवीएस के साथ अनुमानित अनुकूलन स्थितियों को प्रायोगिक रूप से **411** एमएल/जीवीएस (मीथेन **54%)** की बायोगैस उपज के साथ मान्य किया गया था। गैर-उपचारित प्री-ट्रीटेड पिथ और प्राकृतिक पिथ से बायोगैस का उत्पादन क्रमशः **313** एमएल/जीवीएस (मीथेन **49.4%)** और **132** एमएल/जीवीएस (मीथेन **36.7%)** पाया गया। अनुकूलित परिस्थितियों में, प्रीट्रेटेड ठोस अंश की सेलूलोज़ सामग्री और गंभीरता सूचकांक **59.2%** और **3.8** ग्राम/लीटर था, जबकि अपचायक शर्करा, और प्रीट्रेटेड तरल अंश का सीओडी क्रमशः**, 3.68** ग्राम/लीटर**,** और **15,700** मिलीग्राम/ लीटर पाया गया। बायोगैस उपज में अधिक सुधार करने के लिए**,** अध्ययन मे पूर्व-उपचारित बगास पिथ के सी/एन अनुपात को अनुकूलित किया। सी/एन अनुपात **5** से **45** तक सीमा में रखा गया था, और बायोगैस उत्पादन पर उनके प्रभाव का मूल्यांकन किया गया था। सर्वोत्तम सी/एन अनुपात **25** पाया गया, जिसके परिणामस्वरूप लगभग **55%** की मीथेन के साथ **474.3** एमएल/जीवीएस की बायोगैस उपज हुई। इस अनुपात से परे, बायोगैस की उपज स्थिर हो गई, जो दर्शाता है कि अतिरिक्त नाइट्रोजन ने आगे सुधार में योगदान नहीं दिया। अध्ययन ने ठोस अंश पाचन के लिए **300**-लीटर रिएक्टर और तरल अंश

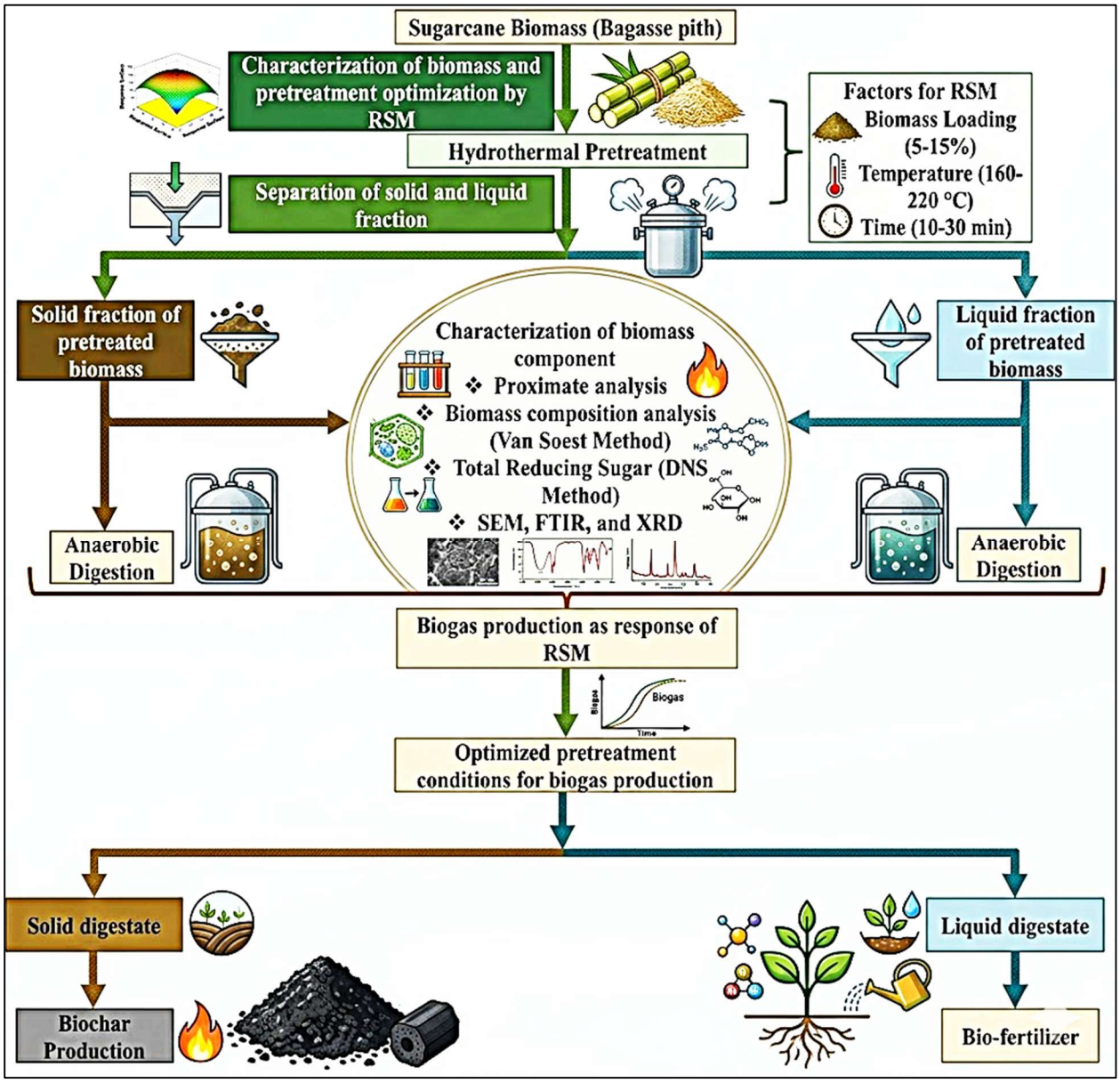
पाचन के लिए **20**-लीटर रिएक्टर का उपयोग करते हुए बायोगैस उत्पादन प्रक्रिया को एक पायलट-स्केल स्तर तक बढ़ाया। ठोस अंश से संचयी बायोगैस उत्पादन **98** दिनों में **4567** लीटर तक पहुंच गया, जबकि तरल अंश ने **92** दिनों में **219.8** लीटर बायोगैस का उत्पादन किया।

तीसरा उद्देश्य बायोचार, जैव-तेल और सिनगैस उत्पन्न करने के लिए पायरोलिसिस के माध्यम से डाइजेस्टेट के मूल्यांकन पर केंद्रित था। अवायवीय पाचन के बाद प्राप्त डाइजेस्टेट को विभिन्न तापमानों (**400** डिग्री सेल्सियस और **800** डिग्री सेल्सियस) पर विभिन्न नमी सामग्री (**10%, 40%** और **80%**) के साथ पायरोलिसिस के अधीन किया गया था। परिणामी बायोचार का विश्लेषण सतह क्षेत्र (**2.32-254.47** वर्ग मीटर प्रति ग्राम) छिद्र मात्रा (**0.003-0.14** सेमी^{3}/ग्राम) मौलिक संरचना (कार्बन: **34.77-52.16%,** हाइड्रोजन **: 0.89-3.46%,** नाइट्रोजन **: 0.49-2.11%)** और कैलोरी मान (**19.05-23.31** मेगाजूल/ किलोग्राम) सहित भौतिक रासायनिक गुणों के लिए किया गया था। उच्चतम बायोचार उपज (**75.8%**) **10%** नमी सामग्री के साथ **400** डिग्री सेल्सियस पर प्राप्त की गई थी, जबकि सबसे कम उपज (**23.1%**) **80%** नमी सामग्री के साथ **800** डिग्री सेल्सियस पर दर्ज की गई थी। स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी (एसईएम) छवियों से पता चला कि उच्च तापमान पर उत्पादित बायोचार ने एक अच्छी तरह से विकसित छिद्रपूर्ण संरचना का प्रदर्शन किया, जिससे यह अधिशोषक, मिट्टी संशोधन और ऊर्जा भंडारण सामग्री जैसे संभावित अनुप्रयोगों के लिए उपयुक्त हो गया।

अंतिम उद्देश्य में एकीकृत बायोगैस और बायोचार उत्पादन प्रक्रियाओं का तकनीकी-आर्थिक मूल्यांकन शामिल था। अध्ययन ने बगास पिथ-आधारित बायोगैस उत्पादन की ऊर्जा क्षमता का अनुमान लगाया और डाइजेस्टेट मूल्यांकन के लिए पायरोलिसिस के साथ अवायवीय पाचन को एकीकृत करने की आर्थिक व्यवहार्यता का आकलन किया। परिचालन लागत, ऊर्जा पुनर्प्राप्ति दक्षता और बायोचार से संभावित राजस्व जैसे कारकों पर विचार किया गया। परिदृश्यों के मूल्यांकन ने संकेत दिया कि दो-चरणीय प्रक्रिया अर्थात् अवायवीय पाचन के बाद हाइड्रोथर्मल प्रीट्रीटमेंट के बिना **400** डिग्री सेल्सियस पर पायरोलिसिस सबसे अधिक ऊर्जा-कुशल, आर्थिक रूप से व्यवहार्य और परिचालन रूप से स्केलेबल विकल्प है। प्रयोगशाला और मिल पैमाने पर मान्य इस विन्यास ने लगातार बायोगैस की पैदावार, बायोचार के माध्यम से प्रभावी ऊर्जा पुनर्प्राप्ति और शुद्ध वित्तीय लाभ दिखाया, जिससे इसे औद्योगिक अनुप्रयोग के लिए इष्टतम विधि के रूप में स्थापित किया गया।

अंत में, यह शोध हाइड्रोथर्मल प्रीट्रीटमेंट-असिस्टेड बायोगैस उत्पादन और डाइजेस्टेट वेलोराइजेशन के माध्यम से गन्ना खोई के पिथ के स्थायी प्रबंधन के लिए एक नया दृष्टिकोण प्रदान करता है। निष्कर्ष बायोगैस पैदावार के सुधार में हाइड्रोथर्मल प्रीट्रीटमेंट की प्रभावकारिता और डाइजेस्टेट को मूल्यवान बायोचार में परिवर्तित करने में पायरोलिसिस की क्षमता को रेखांकित करते हैं। तकनीकी-आर्थिक विश्लेषण आगे बगास पिथ उपयोग के लिए एक एकीकृत जैव शोधक दृष्टिकोण अपनाने की व्यवहार्यता को मान्य करता है। यह अध्ययन न केवल अपशिष्ट से ऊर्जा प्रौद्योगिकियों की उन्नति में योगदान देता है, बल्कि पर्यावरण प्रदूषण को कम करने और भारत में जैव ईंधन उत्पादन की स्थिरता को बढ़ाने के व्यापक लक्ष्य का भी समर्थन करता है।

Graphical abstract



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LIST OF SYMBOLS

Symbol	Description
%	Percentage
µg/g	Micrograms per gram
A	Coded variable (e.g., Temperature)
A/g	Ampere/gram (current density)
Al_2O_3	Aluminium oxide
B	Coded variable (e.g., Reaction time)
C	Coded variable (e.g., Feed concentration)
C/N	Carbon to nitrogen ratio
CaO	Calcium oxide
CO_2	Carbon Di Oxide
Fe_2O_3	Iron(III) oxide
F/g	Farads/gram (Gravimetric capacitance)
g	Gram
gVS	Grams of volatile solids
H_2SO_4	Sulphuric Acid
HCl	Hydrochloric Acid
k	Rate constant
K_2O	Potassium oxide
K_2O	Potassium oxide
kJ/mol	Kilo-Joule per mole
KOH	Potassium Hydroxide
kWh	Kilowatt-hour
L	Liter
m^2/g	Surface area per unit mass
mg/g	Milligrams per gram
MgO	Magnesium oxide
min	Minutes
MJ/kg	Megajoules per kilogram

mL	Milliliters
mm	Millimeter
mmol/L	Millimoles per liter
Mn_3O_4	Trimanganese tetraoxide
MPa	Megapascal
MT	Metric Ton (1000 kg)
Mt	Megatonne (one million tonnes)
n	Reaction order
Na_2O	Sodium oxide
$NaClO_2$	Sodium Chlorite
NaOH	Sodium hydroxide
pH	Hydrogen ion concentration
R_0	severity factor
R^2	Coefficient of determination
SiO_2	Silicon dioxide
SO_3	sulphur trioxide
T	Temperature (°C)
t	Time (min)
Tonne	Metric ton (1000 kg)
wt.%	Weight percent
W/kg	Watts per kilogram (Gravimetric power density)
Wh/kg	Watt-hour per kilogram (Gravimetric energy density)
Y	Yield
ZnO	Zinc Oxide

LIST OF ABBREVIATIONS

Abbreviation	Full Form
AD	Anaerobic Digestion
AHP	Alkaline Hydrogen Peroxide
ANOVA	Analysis of Variance
APHA	American Public Health Association
ASTM	American Society for Testing and Materials
BET	Brunauer–Emmett–Teller
BOD	Biological Oxygen Demand
BPSD	Biopolymer Synthesis and Degradation
C/N	Carbon to Nitrogen Ratio
COD	Chemical Oxygen Demand
CrI	Crystallinity index
DO	Dissolved Oxygen
FTIR	Fourier Transform Infrared Spectroscopy
GC-MS	Gas Chromatography–Mass Spectrometry
HT	Hydrothermal treatment
HTL	Hydrothermal Liquefaction
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
L/S	Liquid-to-Solid Ratio
IRR	Internal Rate of Return
MSW	Municipal Solid Waste
MT	Metric Ton
NMR	Nuclear Magnetic Resonance
NPK	Nitrogen, Phosphorus, and Potassium
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PANI	Polyaniline
PDA	Potato Dextrose Agar

RSM	Response Surface Methodology
SCW	Subcritical Water
SD	Standard Deviation
SEM	Scanning Electron Microscopy
SS	Steam Stripping
SPCN	Oxidized sugarcane bagasse pith-based porous carbon nanosheets
TGA	Thermogravimetric Analysis
TOC	Total Organic Carbon
TS	Total Solids
UV–Vis	Ultraviolet–Visible Spectroscopy
VC	Volatile Compounds
VS	Volatile Solids
XRD	X-ray Diffraction
XRF	X-ray Fluorescence